

## DIMENSION STONE: THE LATEST TRENDS IN EXPLORATION AND PRODUCTION TECHNOLOGY

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### ABSTRACT

*The dimension stone industry is not widely known or appreciated within the mainstream mining industry. This is in spite of the fact that the industry has grown at an average of over 7% per annum since 1980, and is estimated to now have a global turnover in excess of US\$ 60 Billion per annum.*

*Production technologies, particularly in the developed world where labour costs are high, have developed rapidly over the past two decades. Aligned with this, there has been a significant trend in adoption of a more professional mining approach in the exploration for and operation of dimension stone quarries. In fact, in the experience of the authors, mining a dimension stone deposit successfully is often more challenging from a mining engineering point of view than many conventional surface mines.*

*This paper gives an overview of the industry and then proceeds to discuss best practice in exploration for dimension stone and to outline the latest technologies applied in mining of dimension stone. These technologies are varied and the specific combination of technologies applied in any given quarry is determined by both the physical properties of the material as well as the influence of geology which significantly impacts on the recovery of saleable material and hence the economics of the quarry.*

### 1 INTRODUCTION

Dimension stone is a collective term for various natural stones used for structural or decorative purposes in construction and monumental applications[1]. The defining feature of dimension stone is that unlike other mineral commodities which have value mainly as a result of their physical properties, the physical properties of a rock are merely the minimum qualification in determining whether it is fit for use in dimension stone applications. The ultimate success in marketing a natural stone as a dimension stone lies firstly in its appearance, and secondly in the possibility of producing rectangular blocks of suitable dimensions [2] (hence the term dimension stone - some authors prefer the term “ornamental stone” [3], emphasising the decorative aspect of its use) to allow for successful production of the final product in the required sizes. Indeed, the USBM defines dimension stone as “naturally occurring rock material cut, shaped or selected for use in blocks, slabs, sheets or other construction units of specialised shapes and sizes”[4]. A dimension stone block thus has value as a result of its dimensions and appearance, underlain by a set of minimum physical properties (among these are various strength parameters, workability, ability to take a polish, and resistance to physical and chemical weathering).

The major application of dimension stone is within the construction sector, which accounts for over 80% of consumption, with the funerary monumental industry accounting for 15%, and various special applications for around 3% (see Figure 1). Consumption patterns are thus cyclical in line with the world economy, but production of dimension stone has nevertheless exhibited annualised

growth of 5% over the last 75 years. The growth in use of dimension stone products has accelerated in recent years, with annualised growth of 7.5% since 1986 (see Figure 2). This has been attributed to more frequent discoveries of new stone deposits, a more conscious stone culture (particularly in countries without a long tradition of stone use), technical advances in extraction and beneficiation techniques, and the fact that new enterprises in the field require quite limited investments[5], as well as a “new stone age” where the use of natural stone is once again enjoying a renaissance[6], [7]. In spite of this growth however, dimension stone quarrying still only accounts for under 0.5% of worldwide quarrying tonnages [8], with sand, gravel, aggregate and limestone for cement accounting for most of the remaining volume. In terms of value however, the industry is an important one, with the total value chain estimated at over US\$ 60 billion worldwide.

A common sub-classification scheme separates dimension stone into calcareous materials (marbles, travertines, limestones etc), siliceous materials (granites, quartzites and sandstones) and slate. Note that dimension stone sold as “granite” includes all feldspathic crystalline rocks of mainly interlocking texture and with individual grains [9] that are visible to the naked eye and includes fine, medium and coarse-grained, igneous rocks and some metamorphic rocks [10].

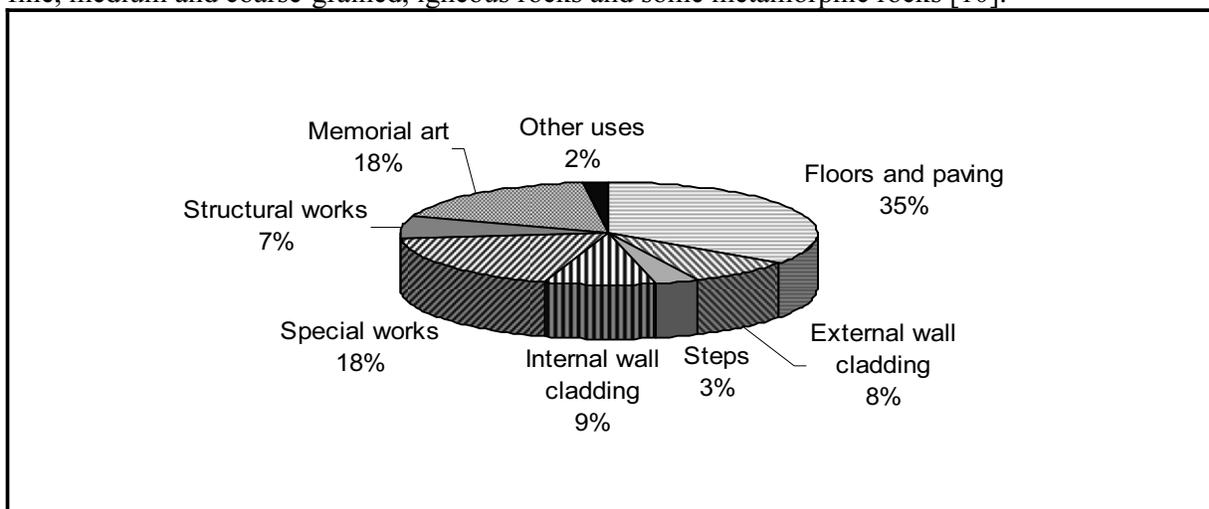
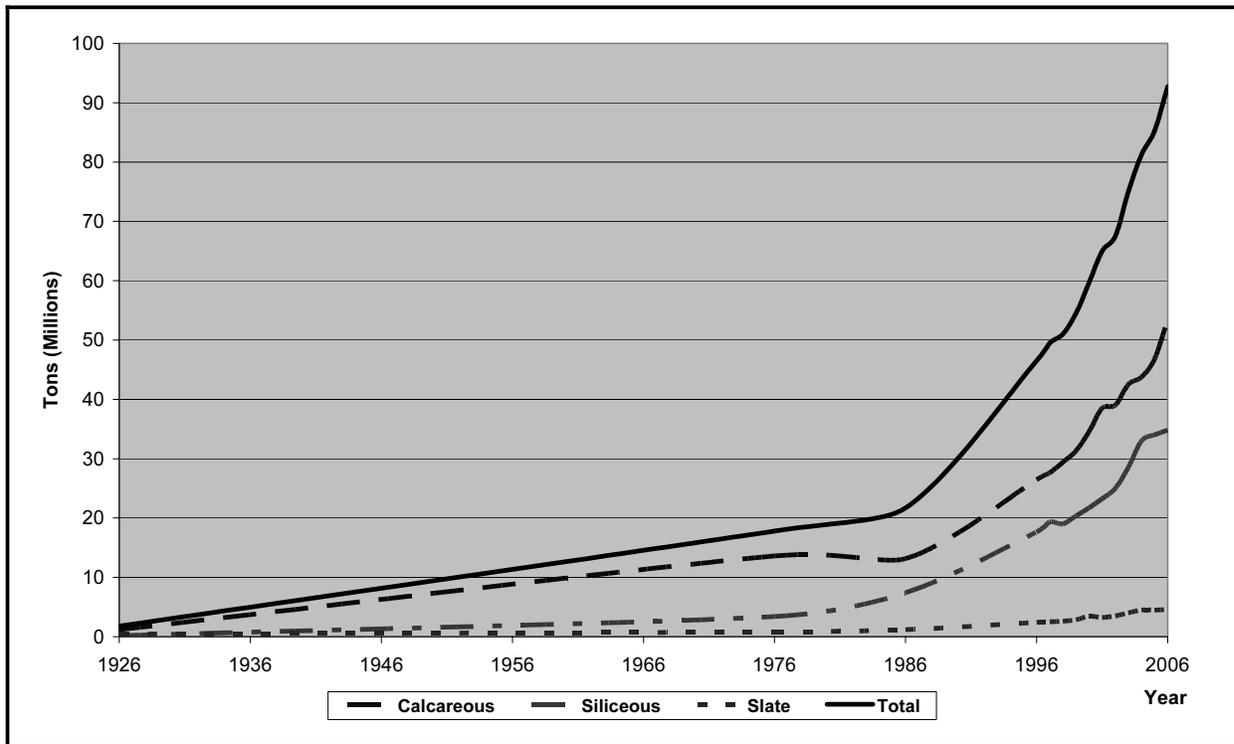


Figure 1 Main uses of dimension stone

Marble is defined commercially as any crystalline rock composed predominantly of calcite, dolomite, or serpentine that is capable of taking a polish [9]. Calcareous materials account for approximately 57%, siliceous materials for around 38% (of which granites account for probably over 95%), and slates for around 5% of total world production of around 93 million tons in 2007 [8]. A major feature of the growth in the industry has been the growth in siliceous material relative to calcareous materials and slates, with the former category having increased its share of world stone production from less than 10% in 1926 to over 40% in the 2004, with a 199 fold increase in absolute tonnage produced[8]. Over the same period, production of calcareous stone has increased 45 fold and slates only 10 fold. The major producers of raw natural stone are China, India, Italy, Iran, Turkey, Brasil, Egypt, Portugal, the USA, Greece, France and South Africa, while the major consumers of finished products are China, the USA, India, Italy, Spain, , South Korea, Germany, France, Japan, Taiwan, Brasil and the UK [8]. It can be seen from this that the concentration of production has historically tended to be in the countries where the most stone is consumed, and where there has been a long history of use of natural stone in construction, particularly in the Mediterranean and Eastern countries. In terms of trade in raw



**Figure 2** Growth in world stone production

stone, calcareous materials are generally processed in large volumes in their countries of origin (mainly the Mediterranean countries, China and Korea), while siliceous materials tend to be mainly produced in countries which are relative newcomers to the stone industry, and hence have not historically had large beneficiation capacity. The major exporters of raw stone are thus India, Turkey, Spain, Brasil, China, Egypt, and South Africa. Italy has long been the dominating force in the natural stone industry, not only in terms of consumption of finished products and production of raw material, and also the beneficiation of imported raw materials and export of finished products. However, its dominance has been overcome by dramatic increases in all facets of the Chinese market, while Indian production and importation of raw stone for processing and re-export is also increasing rapidly.

The stone industry has historically been extremely fragmented in terms of the size and numbers of companies involved, with most dimension stone operations being small under-capitalised owner-operated businesses [11]. This has been the case particularly in the production of raw material, where a modern quarry can be established with an investment of between US\$ 1 and 5 million, depending on the scale of operation. In countries such as India, China and Brasil, where labour is cheap, and SHE legislation virtually non-existent in terms of enforcement, the investment required can be as little as 10% of these figures. In comparison, a modern beneficiation facility of medium size producing slabs for the construction market requires an investment of at least US\$ 15 million, which is around 4 to 5 times the investment required in a quarry that will produce the volume of material consumed by the factory. The global nature of the dimension stone business, combined with the lack of concentration necessitates a complex system of trading through intermediaries (block traders) in order for a quarry's product to reach the factories. This is because factories need to offer a wider choice of product range to their customers, and consequently often need to source material from many locations. As blocks are generally inspected by the factory prior to purchase, it

is difficult for direct trade to take place economically between any but the largest quarrying companies and factories. The block trader thus fulfils an important role in that he will travel around the world selecting large quantities of blocks from quarries which are then shipped to stock yards close to the major processing districts, where they are available for inspection by the small factory customer. This obviously requires a large amount of working capital in order to fund the purchase and transportation costs (at today's freight rates, the transport costs may be substantially higher than the ex-quarry purchase price), as well as capital invested in the land and handling facilities at the stock yards. The larger investment required, and thus larger companies involved has resulted in the beneficiation and block trading companies having greater control of pricing and material selection than the raw material producers. In addition, the quarry is several steps removed from the end user and has little or no control over the promotion and marketing of its product, and often little knowledge of changing fashion trends in the industry. However, market knowledge and the ability to reach out is considerably more important in the dimension stone business than in both the metals and industrial minerals sectors [12].

There has however been substantial consolidation of the industry at the raw material production level over the past ten years, to the extent that the biggest producers worldwide now rival the larger beneficiators and block traders in terms of the volume of stone produced/processed, if not in terms of the number of companies. However, in turnover terms, no single company has yet reached even one percent of the world market, with the twenty biggest companies in the industry probably having a combined market share of around 10%. Growing realisation of the importance of market knowledge and ability to reach out to customers further down the value chain has also resulted in a trend for these larger raw material producers to move into the distribution and beneficiation arena. Similarly, several of the large beneficiators and block distributors have integrated backwards into raw material production in order to ensure reliable and sustainable supplies of key products.

What is surprising given the large value of the industry (several times larger than platinum production for instance), is the minimal attention it has attracted from capital markets, the mainstream mining industry and academia. Only a handful of dimension stone companies have ever been listed on stock exchanges around the world, and while South Africa probably had the greatest number (as many as 6 listed companies in the late 1980s), not a single listed company remains today, and the authors are only aware of one publicly traded dimension stone company worldwide currently. In terms of interest from large mining companies, only South African mining houses have ever taken a stake in dimension

stone companies. During the 1980s, Anglo American bought a 30% stake in Deutsche Steinindustrie AG, a German company which was probably somewhat ahead of its time (see discussion above regarding industry trends) in that it had production interests on five continents as well as a block trading company and beneficiation interests. This stake was later converted to a 30% stake in Finstone s.a.r.l., today the most vertically integrated and probably the largest company in the industry. Anglo however sold this stake to Finstone's remaining shareholder in 2002 after bowing to pressure from financial analysts to dispose of so-called non-core assets. Gencor bought a controlling stake in Keeley Granite (later renamed Kelgran) during the early 1990s, although given their subsequent exit after a fairly short period, this was probably largely aimed at stripping out the PGM minerals rights held in Kelgran's quarries in the western lobe of the Bushveld complex. While the importance of the industry has been recognised by the Society of Mining Professors [13], academic interest has in the past come largely from the Italian universities, although over the past 10-15 years there has been an increasing volume of research from China, Eastern Europe, Turkey, Portugal, Spain and India in the fields of dimension stone exploration, non-explosive cutting and splitting, assessment of the quality and exploitability of stone deposits, ore reserve estimation, rock mechanics in dimension stone mining and environmental impacts and reclamation.

## 2 EXPLORATION FOR DIMENSION STONE

Historically prospecting and exploration for dimension stone was the domain of non-professional prospectors, who because of lack of knowledge of the market and industrial requirements of the processing industry, coupled with the absence of professional exploration skills seldom conducted formal investigations or evaluations prior to opening quarries [14], [15]. It has however become good practice, especially in the more developed stone producing countries, to perform a thorough geological investigation prior to making a decision to open a quarry, as the deposit is the one factor that cannot be changed in a dimension stone project, while the initial investment in geological study is small compared to other mining endeavours [16]. However, like other basic construction materials which are extensively available, common in nature and appear at low depths, dimension stone is not the object of huge exploration investment, nor does it permit the investment in complex exploration techniques utilised in discovering metallic ores or hydrocarbon deposit, given the fact that dimension stone deposits generally represent a high- volume, low-value commodity, and as a consequence, adequate exploration methodologies have not been researched in spite of the high level of technological development that has been achieved for exploitation operations [3].

How should we therefore go about conducting exploration for dimension stone deposits? In order to arrive at this answer, we need to consider the relevant properties of required of successful a dimension stone. According to Carvahlo et al [3], and as discussed above, the aesthetics of a stone is the intrinsic factor on which depends its use as construction material with decorative functions. While it may be strongly subjective, aesthetics can be used for the technical evaluation of a dimension stone because it is the result of the conjoined perception of a set of criteria, namely the colour, the texture, and the presence or absence of discontinuities [3]. Similarly, Luodes et al identified three major criteria for use in evaluating a dimension stone [17], namely the appearance, the soundness of the deposit and the market demand for that type of stone. In terms of appearance, it is important that the colour should be as uniform as possible across the entire deposit. If a stone is classified as a one-coloured type, stripes, inclusions, or veins of a differing colour are not accepted in that stone by the market, while if the stone is classified as a multicoloured type, an appropriate variation of the colours is required, even to the extent of the inclusion of “defects” mentioned above [17], However, the colour and pattern of the stone must be homogeneous across the deposit that the market can identify different blocks as being one and the same product. The soundness of a deposit is defined by the use of the stone and by the demands of the processing industry [17], so that for example blocks for construction application which are sawn by gangsaws are typically required to have dimensions of 240-330cm x 120-190cm x 70-180cm, requiring that the deposit should have a minimum spacing of fracturing of at least 2 to 3m. It thus the homogeneity of a dimension stone deposit in terms of colour, texture and discontinuities that is particularly relevant during geological surveys as it is the base for establishing the limits of a dimension stone deposit [3], and Carvalho et al have proposed the following decision criteria on exploration for dimension stone:

<b>Dimensioning</b>	<b>Homogeneity</b>	<b>Fracturing</b>
<ul style="list-style-type: none"> <li>• Thickness of productive units ( sedimentary beds, metamorphic facies etc)</li> <li>• Volume of the deposit</li> <li>• Spatial Disposition</li> </ul>	<ul style="list-style-type: none"> <li>• Colour</li> <li>• Texture</li> <li>• Discontinuities</li> </ul>	<ul style="list-style-type: none"> <li>• Preferential directions</li> <li>• Frequency</li> <li>• Density</li> <li>• Intensity</li> <li>• Type and morphology</li> </ul>

**Table 1 : Decision criteria on the exploration of dimension stone [3]**

According to Carvahlo et al, these criteria can be evaluated by the basic geological tools of geological mapping and fracturing survey and they state that thematic geological mapping, with strong support from the techniques of structural geology and diamond core drilling, is fundamental for the research and evaluation of data that are intrinsic to the dimensioning and homogeneity qualification of the deposits [3]. Geophysical methodologies can also be complement to the in situ fracturing surveys, and can give valuable information with regard to the frequency and intensity of fracturing in particular. While Carvahlo et al have focused exclusively on the above mentioned tools in proving viable marble quarrying areas within the Portuguese Estremoz Anticline, we believe them to be insufficient in general for taking a dimension stone quarry to full production levels with a high degree of confidence. Taboada et al have distinguished between the quality and the exploitability of a granite [18]. They define the exploitability of a granite as being determined by structural characteristics such as orientation, family, extension, persistence, and continuity and discontinuity densities—irrespective of whether the fractures or joints are of primary or secondary origin, while the quality depends on various factors such as grain size, colour, the presence of black-knot flow structures, and weathering. Similarly, Venkat Reddy has identified the following defects which affect the quality and exploitability of a dimension stone deposit [15]:

- Colour variations
- Textural characteristics and textural variation
- Structural and macro-discontinuities
- Micro-discontinuities
- Intrusives
- Inclusions
- Accessory minerals
- Contact zones
- Alterations

While mapping and geophysical methods may help to define structural and macro discontinuities such as fractures and joints, as well as contact zones, intrusives, and larger inclusions, core drilling is required to give a full picture of colour variation and textural variations as well as micro-discontinuities and weathering. The disadvantage of core drilling however is that that a dimension stone prospect cannot be drilled as densely as an ore body because the drill holes can spoil otherwise suitable stone [17], while economic spacing of core drill holes will be vary large when compared to the size of blocks required to be produced, while many defects are small enough to be missed by drilling, but closely spaced enough to affect block quality. Luoden et al have proposed an exploration sequence consisting of the desktop study, field mapping, detailed mapping, geo-radar survey, core drilling, reserve assessment, test quarrying, test processing, and quarry planning [17]. We are in substantial agreement with this sequence, but would split the test quarrying into a bulk sampling (including test processing) and a test quarrying phase. We would thus recommend the following approach to the phases of a dimension stone exploration, where completion of each phase prior to test quarrying does not guarantee a successful quarry, but provides sufficient information to make an informed decision as to whether or not to proceed to the next stage taking the risks of a negative outcome into account:

1. Desktop Study
2. Field evaluation
3. Detailed mapping
4. Drilling
5. Geophysical methods
6. Bulk Sampling

## 7. Test Quarrying

Each of these phases is discussed in more detail below.

### 2.1 Desktop Study

The first phase of any dimension stone exploration should comprise a desktop study. Target generation should be accomplished by thorough investigation of available geological maps and reports, with focus placed on desired rock types. For example, when looking for black granite, gabbros, norites, diorites and dolerites would be suitable target lithologies, while if a multicoloured patterned material is sought, regional metamorphic provinces should be examined for potential outcrops of suitable stone. Marble is found in belts of regionally metamorphosed sedimentary rocks or adjacent to a specific suite of intrusions, which have thermally metamorphosed carbonate beds [19].

Common remote-sensing tools including satellite imagery and aerial photographs as they are good aids in the initial surveying stages. The Indian Geological Survey carries out the first phase of regional evaluations and resource inventories by identifying potential belts of dimension stone using satellite imagery, aerial photographs, and geological maps [9]. A further tool that can be used during target generation is GIS (Geographical Information Systems) which can facilitate desktop studies by generating topographical and geological maps of identified targets. The Google Earth™ mapping service is a recent remote-sensing tool with tremendous capacities as it grants the user a simulated three-dimensional view with zoom capabilities and the ability of an interactive management of the orientation view. Although not being geographically precise, it can be a very effective tool for the selection of exploration-target areas of dimension stones as a function of the fracturing degree of the rocks [3].

A desktop study should ideally also contain an indication of the economic factors that will affect the project, or “exploitability” of the prospect. It is also important to bear in mind at this stage the likely physical properties of the target rock, as it is necessary that these conform to the minimum requirements for dimension stone. As pointed out above, a requirement for a good dimension stone deposit is the market demand for a stone type [17]. Even if the appearance and soundness are at an acceptable level, the stone has no value without demand from the market, which is again dependent upon the ever-changing fashion. The geologist conducting exploration should thus have a good idea of the stones that are currently in demand and be abreast of trends in the market. Aspects such as infrastructure and basic services should be researched at this point in the exploration phase. For example, an arid environment (e.g. Namibia or Northern Cape Province) will have a water scarcity. An investigation as to what the availability of water is in the area most proximal to the project or an investigation of what costs will be involved to transport water to the site should be undertaken. The availability of electricity infrastructure should also be investigated, especially in South Africa where there is an electricity scarcity. Another factor to take into account during this phase is the likely transport costs for blocks of the stone to port or to processing factory, and compare this with the likely range of prices for stone of the colour being sought.

After selecting targets, it is ideal to research the legal requirements and strive for compliance. In South African legislation, there is somewhat of a dilemma for the dimension stone prospector in terms of the legal process. While an initial field evaluation could be done under the auspices of a reconnaissance permission, there are two problems with this. Firstly, a reconnaissance permission does not entitle the holder to remove any samples, even if these are small hand samples which are necessary to verify the colour and appearance of the polished stone, and secondly, a reconnaissance

permission does not convey any exclusive right (unlike the Exclusive Reconnaissance Licence in Namibia) to apply for or be granted a prospecting right or mining right. It would seem that the safest option at this stage would be to apply for a prospecting right for any prospects identified which may be of value, even though they could be discarded after the initial field evaluation.

## **2.2 Field Evaluation**

During this phase, the general soundness and appearance of the stone are defined [17]. The first step in field evaluation is to identify the colour of the stone. Often, the weathered outside surface of a rock is in no way indicative of the colour inside, and it is thus necessary to use a hammer to expose a fresh surface of the stone. If the colour is not acceptable, then the prospect could be discarded at this stage, while a truly exceptional colour may be pursued to further stages even if the stone's formation is not ideal. It should be noted that even the colour of a freshly exposed surface may differ from that shown by polishing, and so if the stone appears of acceptable colour and the formation is in good physical shape, it will be necessary to remove several small samples to cut and polish for further evaluation.

The second step is to study the formation of the rock outcrop in order to ascertain the possibility of producing blocks of a commercial size. In some circumstances this is fairly easy, as there are solid outcrops on which the joint and vein spacing can be readily evaluated. Where there are no solid outcrops, the size of boulders on the surface can give some indication of the possibility of producing blocks. Where there are only very small boulders present, it is unlikely that it will be possible to produce blocks of marketable size, as in general the jointing and veining in the host rock controls weathering that produces boulders. Small boulders are usually indicative of closely spaced joints and veins in the underlying solid rock. The size of the outcrop and its consistency should also be evaluated at this stage.

Should the colour appear acceptable, and the formation appears healthy, the next step should be to remove several samples of the stone for cutting and polishing. Small boulders which can be carried by hand can be removed, or else samples of approximately 30cm cubic can be extracted from the solid rock or large boulders by means of a petrol powered rock drill and plugs and feathers or expansive mortar. By removing these at several points around the formation, an idea of the consistency of the colour can also be gained. These samples can be compared against existing products on the market, and used to obtain feedback from customers as to the demand and expected price for the material. These samples will also give some idea of whether or not the stone can be polished to an acceptable finish, as well as giving an indication of the hardness of the stone from a sawing and finishing point of view.

## **2.3 Detailed Mapping**

Should initial field evaluation indicate a potentially economically viable resource, detailed geological mapping of the deposit should be conducted. Mapping traverses should be planned, and if necessary cleaned by mechanical means, compressed air or pressurized water jets [17]. After cleaning and washing, the traverses should be measured (a tachymeter or GPS can be used for this purpose) and mapped in detail on a scale of between 1:100 and 1:250 according to the size of the deposit. During detailed mapping, special attention was paid to the composition, colour, and structure of the stone, as well as the fracturing [17]. Important portions of the traverses should also be photographed. A geological map should be constructed as a record of field results and also to give a basis for further evaluations of the physical extent and morphology of the prospecting area.

Geological maps of this sort could also give a basis for calculation of reserves[18] or even indications of regional discontinuities.

During the detailed mapping phase, several samples of the stone for cutting and polishing should be collected, preferably along the traverses. Small boulders which can be carried by hand can be removed (it is important to determine the effect of weathering on these and whether they are reflective of fresh rock), or else samples of approximately 30cm cubic can be extracted from the solid rock or large boulders by means of a petrol powered rock drill and plugs and feathers or expansive mortar. By removing these at several points around the formation, an idea of the consistency of the colour and mineral composition can also be gained. These samples can be compared against existing products on the market, and used to obtain feedback from customers as to the demand and expected price for the material. These samples will also give some idea of whether or not the stone can be polished to an acceptable finish, as well as giving an indication of the hardness of the stone from a sawing and finishing point of view.

It should be noted that in the South African mining legislation a prospecting right and Environmental Management Plan (EMP) are required for the removal of these small samples even though the environmental impact is negligible.

## **2.4 Geophysical Methods**

While the previous steps give an indication of the deposit from a surface point of view, a thorough three-dimensional assessment is a prerequisite prior to taking the risk of bulk sampling and test quarrying, which entail significantly higher expense and are far more environmentally disruptive than the previous stages of exploration for dimension stone. Indeed, Luodes et al concluded that for a successful evaluation study, the discontinuous and varied nature of geological features in three dimensions must be clearly understood [17]. Geophysical methodologies are important in the more detailed research stages as a complement to the in situ fracturing surveys [3], [20] and are significantly cheaper than core drilling. In particular, the very low frequency electromagnetic/radio frequency electromagnetic (VLF-EM/RF-EM) and the ground-penetrating radar (GPR) techniques are useful for dimension stone [3]. Geophysical resistivity surveys can reliably locate travertine deposits, because travertine has a higher apparent resistivity than the bedrock, which is usually weathered [9].

The VLF-EM/RF-EM method is based on the propagation of low- to very low-frequency radio waves that generate a secondary electromagnetic field dependent on the lithology. The detection of this secondary field allows the acquisition of data about the propagation environment and its heterogeneities: clay-filled fractures, karst, paleo-channels, lateral facies variations, etc. [3]. This method has a low investigation depth but can be quickly carried out with a very low cost, allowing the acquisition of data related to major structures and the delimitation of suitable area targets for more advanced ornamental-stone exploration stages [3].

In general, the advantage with of an GPR survey is that it gives a penetration depth of 10-25m, gives a large cross section of the subsurface fracturing and can determine zones of significant weakness, dykes, contacts etc. [20]. There are however limitations, as small and closed cracks do not show up well in the radar profiles [17]. The geo-radar survey is however a more feasible method in homogeneous rock types than in heterogeneous types. In the latter case, the proper interpretation of the results is more difficult as different internal structures of the stone are often seen in the radar profiles [17]. If the material is strongly deformed and folded, these structures can be falsely

interpreted as fractures, as was the case in a GPR survey conducted on the highly deformed Parys granite by the CSIR on behalf of one of the authors in the mid 1990s.

Nevertheless, in spite of the limitations, the use of geophysical methods can be used to evaluate whether or not to proceed to drilling, which is significantly more expensive, particularly in homogenous (single coloured) rock types.

## **2.5 Drilling**

If the outcome of field evaluation and geophysical investigations (if conducted) is positive, the next step should be to drill the formation in order to demarcate the ore deposit as well as to provide information on the vertical extent of the formation and possible defects with depth; which has implications on the recovery. Generally diamond core drilling is preferable, as the core can be evaluated not only for colour consistency, but also for defects such as joints, veins and banding which may influence the recovery of marketable blocks. Percussion drilling is cheaper than diamond core drilling, but has the limitation that chips of stone are produced which are only indicative of colour consistency. Core drilling may be economically achieved by lightweight air powered core drills such as the Metre-Eater™, which are capable of drilling at least 100m with a TBW sized core barrel which produces 45mm core, and at least 30m at NQ size (65mm core). Core should be split and polished in order to log the colour as well as joints, veins and very fine veinlets which may affect the acceptability of the stone in the market.

Vertical holes may be drilled in order to test the consistency of the colour and texture of the stone at depth, as well as to identify possible mining cut-offs and horizontal or sub-horizontal joints which may affect recovery, or assist with mining access. Horizontal or inclined holes should be planned at right angles to the major joint sets in order to evaluate the spacing of these in order to get an idea of recovery, and if there are two strongly defined joint sets, consideration should also be given to several horizontal or inclined holes at right angles to the former holes. Depending on the size of formation and the nature of the joint sets, initial hole spacings of the order of 50m could be considered, with possible in fill drilling at a later stage. In practice, it is not economic to drill at a spacing that will identify every single joint, and this would in any case destroy the reserves by creating a hole through every block that could be recovered. Also, with strongly deformed multi-coloured stones, and porphyritic granites, drilling may not be able to give a satisfactory indication of the textural consistency of the stone. Drilling can however provide information that will lead to a no go decision on the prospect.

In South Africa a prospecting right and EMP are required for drilling activities. If drilling is properly planned, the major environmental impact is the access roads which need to be constructed to gain access to the site for the air compressor and water truck. If the distance to actual drilling site is not extreme, environmental damage may be limited by constructing pipelines for the supply of air and water to the drill rig, thus minimising disturbance of the site, as the rig itself can be carried by hand to the drilling site.

## **2.6 Bulk Sampling**

Should the results of drilling prove positive, the next phase is to conduct bulk sampling to remove several blocks in order to test market acceptance. The number of blocks required will depend on the marketing strategy and whether or not the prospector has access to a factory which can cut slabs of the material. In general, most non-vertically integrated companies will need to remove around twenty blocks for distribution into the market, while a vertically integrated company may get away

with as few as two blocks, as it is able to distribute slabs into the world market in order to evaluate response to the material.

Many operators confuse the stage of bulk sampling with the stage of test quarrying. It should be emphasised that the aim of bulk sampling is to get sufficient representative sample blocks of the stone in order to test the market reaction to the material, and that it is not necessary to open a full blown quarry for this purpose. Bulk samples extracted under the scenario described above in South Africa should fall within the definition provided in Section 20(1) of the MPRDA, and it should not be necessary to get permission in terms of Section 20(2) of the Act to remove and dispose of minerals. However in view of the authors' experience of inconsistent application of the law by the Department of Minerals and Energy, it would however be wise to consult apply for the Section 20(2) permission simultaneously with the application for a prospecting right. This application should clearly state the amount of material for which permission for removal and disposal is sought.

It should also be noted that in the case of a new deposit of an established material, it is possible to skip the bulk sampling stage and proceed directly to test quarrying.

## **2.7 Test Quarrying**

In the case of a successful market feedback to bulk samples, or in the case of an established material, the final phase of prospecting is test quarrying. The aim of test quarrying is to fully evaluate the recovery of saleable blocks within the formation in order to determine whether full scale mining is economically viable, as well as to evaluate the implications of extraction methods on the economics of quarrying. Test quarrying is required, as other methods described above can only give an indication of the range of possible recovery, and the actual recovery possible can only be established by actual mining of the formation and recording the resultant production and costs. It also allows for the adjustment of extraction methods in order to determine the most feasible method to be employed. While recent advances in dimension stone quarry evaluation [3], [18] have shown that there is potential for geostatistical methods to provide reasonable assessments of potential exploitability of a quarry, the authors would be somewhat hesitant to use this as a substitute for test quarrying before proceeding the development of a full scale quarry, which has significant cost implications, as well as being substantially more disruptive to the environment.

Test quarrying should however be conducted on as small a scale as possible in order to minimise the environmental impacts in the event of a final decision not to proceed with further quarry development. In terms of requirements under South African mining legislation, test quarrying could be carried out under the auspices of a prospecting right, provided that the permission in terms of Section 20(2) of the MPRDA referred to above is acquired. However, in the authors' experience, delays in the processing of mining right applications could result in the quarry having to be closed for up to a year after the volume for which Section 20(2) permission has been obtained and before a mining right is issued. Given the ever changing nature of the market for dimension stone, and the requirement from the market for a consistent supply, this could have disastrous implications for the prospect in terms of missing the market opportunities. In the author's view, it would be recommended that an application for a mining permit (currently limited to 1.5 Ha and 2 years duration, but expanded to 5 Ha in the draft Minerals and Petroleum Development Amendment Bill) be made immediately it appears that there is a reasonable chance of a successful quarry. Such applications are significantly cheaper than mining right applications since they do not require a Social and Labour Plan, have much less restrictive environmental requirements and timeframes, and they are processed significantly more quickly than mining right applications, and would allow for

test quarrying and the transition to full scale production to occur while a mining right is awaited, without the risk of market disruption.

### 3 DIMENSION STONE MINING

In mining dimension stone it is necessary to split or cut the stone into successively smaller pieces until the final desired block size is achieved, and saleable blocks are produced. The mining methods utilised in the extraction of dimension stone range from relatively simple and low technology methods to some quite technologically advanced methods. In general, marble is extracted using relatively advanced non-explosive cutting technologies, and is even quarried in underground situations, while granite tends to utilise more low-tech drilling and splitting technologies, although this is changing. Mining of slates and quartzites generally utilises the simplest technologies. The impact of historical climatic conditions on mining methods is also evident, as in the northern hemisphere, loose boulders were removed by glaciation during the last ice age, and so stone is extracted from relatively solid formations, while in the southern hemisphere warm wet conditions favourable for weathering have in many cases left large reserves in the form of loose boulders. Slates and quartzites for paving and roofing purposes are quarried by splitting blocks or slabs from the body of the stone using drilling, and splitting with plug and feathers, or in some cases sawing these loose. These are then cleft along the bedding planes to produce thin sheets for paving or roofing purposes. The technology is simple, and quarrying generally on a very small scale. Small earthmoving equipment is used for moving and transporting the blocks or slabs. Final products consist of roofing tiles, sawn tiles of regular shape, and approximately regular thickness, and irregular sheets used for crazy paving.

For most rocks, the mining stage of dimension stone extraction conforms to one of two general strategies [21]. In the first of these, large volumes of rocks (usually in the 1000s of m<sup>3</sup> range) are loosened by means of primary cuts, and then divided stepwise into smaller pieces until commercial blocks are obtained, discarding waste material as the process is performed. This is the main method employed in most granite and marble quarries. Under the second strategy, commercial blocks are directly cut from the rock body. This strategy is often employed in the production of sandstone, where blocks are often extracted from relatively thin layers or between bedding planes. In case where natural slabs, kerbs, paving stones etc are produced is considered a special case, where cautious blasting is employed and suitable pieces are selected from the muckpile [21]. This latter case is often applied in the extraction of slates, quartzites and prophyoids and ignimbrites [22]

A summary of the different extraction methods for dimension stone and the technologies involved is given in Table 2 below.

<b>Extraction method</b>	<b>Cutting</b>	<b>Splitting</b>	<b>Cautious Blasting</b>
<b>Method of separating blocks/slabs</b>	Blocks separated by means of kerfs	Blocks separated by fractures induced in pre-determined planes	Blasting with minimal breakage – suitable pieces selected from muckpile
<b>Technology</b>	Sand wire (helicoidal wire) Diamond wire	Explosives: Detonating cord NG based explosives	Explosives

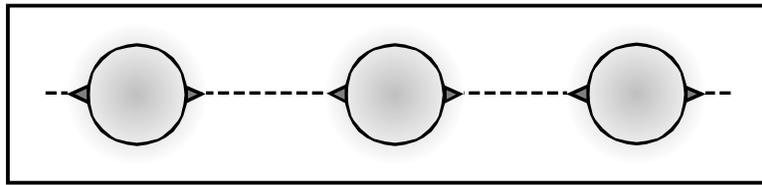
	Chain saw Disc cutter Diamond belt cutter Flame jet Water jet	Blasting gunpowder Plug & feather Expansive mortar Hydraulic wedges	
<b>Products</b>	Commercial blocks	Commercial blocks	Natural slabs Kerbs Paving stones Cobbles Building blocks Tiles

**Table 2 : Summary of dimension stone extraction methods (adapted from Mancini et al [22])**

While marble has in the past (as far back as Roman times) been quarried by various splitting techniques, the last century has seen the advent of sawing techniques to loosen the stone and form blocks. Initially, sawing was achieved using helicoidal wire with sand or some similar abrasive added to perform the cutting. The last 30 years or so have seen the development of diamond wire, to the extent that sawing with diamond wire is the main method of both primary and secondary cutting as well as block squaring in marble quarries today. Chain cutters with tungsten carbide picks are used extensively to perform blind cuts, especially in underground situations, as well as for primary cutting in soft marbles and limestones, although recently diamond belt cutters have been introduced to perform the same function. The latter can be quite technically advanced, with automatic programming of cutting being a possibility. In some of the marbles with higher quartz content, diamond wire life is not as favourable as in the softer stones, and so drilling and splitting methods are still sometimes used, although generally non-explosive splitting methods are used. Depending on the quarry geometry, handling of blocks is either by means of gantry cranes or front-end loaders. Marble is generally extracted in fairly large blocks, and so fairly large earthmoving equipment (Caterpillar 988 or Komatsu WA600) is generally the order of the day, particularly in first world producing countries. However, as is the case with granite, in poorer countries smaller machines (the Caterpillar 966 is the standard machine used in Brasil) or even timber gantries are used to lift and move blocks.

### 3.1 Splitting Techniques

The splitting techniques are generally the oldest of techniques used in dimension stone extraction. The earliest techniques involved chipping a V-shaped groove in the stone using hand tools, and then either filling this groove with wooden wedges which expanded when wet, or in colder climates filling this groove with water which froze to ice overnight in order to split the stone. Today, all of the splitting techniques involve drilling of a series of small diameter co-planar holes in the stone in order to introduce a splitting agent. In many cases, holes are notched using a special tungsten carbide drilling bit in order to enhance the direction of split (see Figure 3)

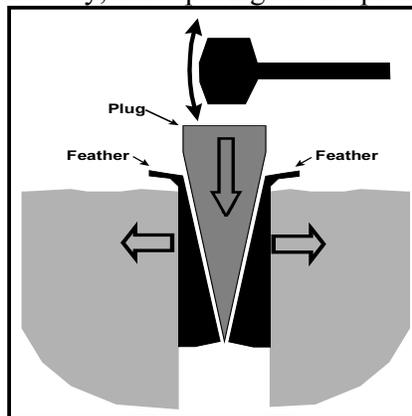


**Figure 3** Use of directional notches to assist splitting

In the case where the stone has one or more grain or cleavage directions along which it splits preferentially, the use of splitting technologies on these directions is often both effective and economic. While it is possible, especially with the use of high VOD explosives to split in two or more directions simultaneously, splitting techniques usually rely on the stone being loose and free from the solid formation, either in the form of boulders, as a result of loose bedding planes between layers of sandstone or slate, or having been loosened from the solid formation by cutting techniques.

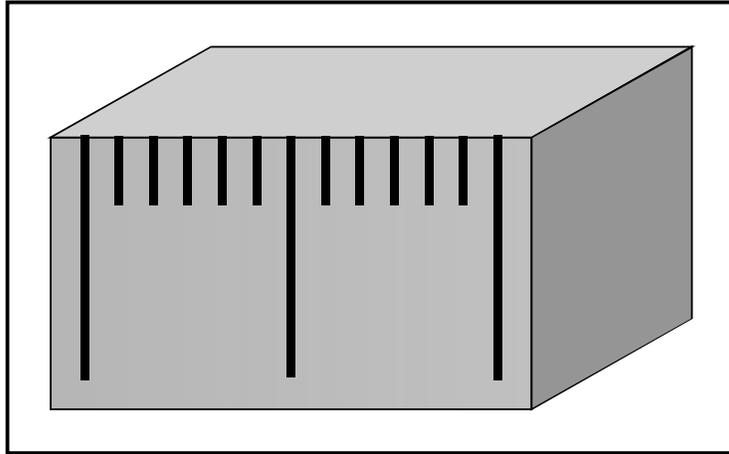
### 3.1.1 Plugs and Feathers

The use of plugs and feathers involves the drilling of a line of co-planar holes in the stone and introducing into these two shaped steel feathers (half round steel strips) with a steel plug or wedge in between them. These are orientated along the direction of the intended split, and the wedges are driven with a hammer causing a lateral force in the hole, which causes splitting of the stone (see Figure 4). The use of directional notches as described above may assist in splitting in the desired direction, especially in a stone where there is not a distinct cleavage direction. In stones where there is a distinct grain direction, the line may be cut using plugs and feathers at up to 10° from this direction. Spacing of holes depends on the presence of a grain direction, and the strength of the stone. In harder stones with no grain, the required holes spacing may be as little as 10cm, while in a stone with a strongly developed freeway, hole spacing on this plane may be as much as 25cm.



**Figure 4** The use of plugs and feather to split stone

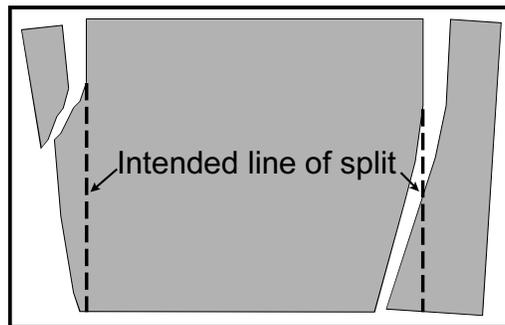
In general, where there is no grain, or where cutting off the grain direction it is advisable to drill all holes to the full length (approximately 90% of the height split), while on a strongly developed freeway, it is only necessary to drill every 5<sup>th</sup> or so hole to the full depth, while intervening holes may be drilled just deep enough to accommodate the plugs and feathers (see Figure 5). When using plugs and feathers, a better split is obtained when all of the plugs are tensioned slowly and evenly, rather than hitting too hard and too fast.



**Figure 5** Drilling for plug and feather in stone with a strongly defined cleavage direction

### 3.1.2 Mechanical Splitting

With mechanical splitting, the same principles are applied as with plugs and feathers. The equipment consists of a hydraulic cylinder which forces a steel plug between two feathers, causing the lateral force which splits the stone. Although higher forces can be generated, allowing for much bigger splits, caution must be exercised in terms of the speed at which the force is applied, as too quick an application may result in a split which runs off the desired direction (see Figure 6). Often, as many as 30 hydraulic splitters may be positioned of a jib carried by a tractor or other mobile equipment to allow for rapid positioning of the splitters and splitting of large cuts (see Figure 7).



**Figure 6** Poor splitting from too quick application of splitting force



**Figure 7** Hydraulic splitters carried on jib to mechanise large splits

### **3.1.3 Expansive Mortar**

Expansive mortars (limestone based compounds which set and swell after mixing with water) have been around for some time. Their drawbacks in the past have been that they have been expensive, and have taken several days to work. However, over the past 12 years, they have become extensively used in the dimension stone industry, especially in the splitting of granites, as the pricing has become more competitive, and splitting times have been reduced to as little as a few hours. Times of as little as a few minutes can be achieved, but in practice, the heat generated by the reaction causes the water to boil, with the resulting steam pressure either ejecting the material from the hole, or causing a split due to the gas pressure similar to the effect of gunpowder, often negating the benefits of using expansive mortar. This can also have significant safety effects, as the ejected material is both very hot and caustic, causing both thermal and chemical burns, while fragments or slabs of rock may be forcibly ejected unexpectedly, injuring workers.

Expansive mortars work to split rock in much the same basis as blasting gunpowder. The swelling effect of the mortar generates a pressure which is applied evenly around the circumference and over the length of the hole. When several holes within a plane are loaded simultaneously, the resolution of the forces involved yields a resultant force at right angles to the line through the holes. When this force exceeds the tensile strength of the material, splitting occurs. For Fract-Ag®, the first commercial expansive mortar to be widely applied in dimension stone, tests have determined that the pressure generated on the sides of the drillhole is of the order of 80Mpa after 24 hours at 20°C (at higher temperatures, the time is less, and it is likely that over longer times far higher pressures may be achieved). In theory then, hole spacing can be determined by the following formula:

$$s = (p \cdot h \cdot d) / (\delta t \cdot h')$$

Where s = hole spacing

p = pressure exerted (Mpa)

h = depth of hole (m)

$\delta t$  = tensile strength (m)

h' = depth to be cut (m)

For Rustenburg material which has tensile strength values of about 6.5MPa on freeway, 8MPa on secondway and 9MPa on toughway, theoretical considerations result in hole spacings of the order of 25cm on the latter two directions. At this spacing, splitting occurs long before maximum pressures are generated, and in practice, even with spacings as large as 40cm, or at 25cm with only every second hole filled, splitting occurs even though in theory it should not be possible. This is probably due to the fact that splitting is not instantaneous as the formula above assumes, but occurs gradually over time. Because the pressure is built up slowly and evenly over a long period of time,

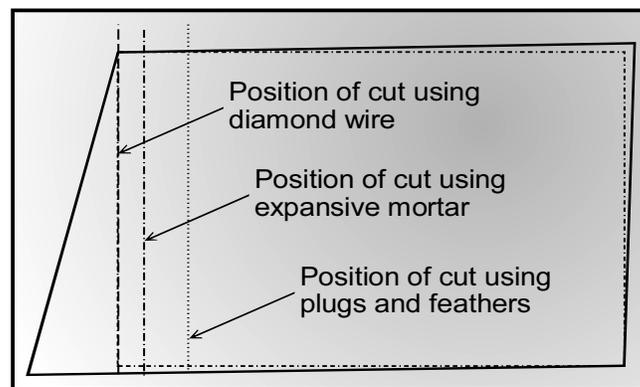
splitting starts long before the theoretical splitting force is reached, due to tensile strength being exceeded in the immediate vicinity of the hole, aided by the directional notching. As this split slowly extends over time, the area remaining to be split becomes ever smaller, resulting in a reduction of the splitting force required. At the same time, more and more pressure is being generated, increasing the rate of splitting, and consequently the split occurs long before the theoretical force is reached. The Fract-Ag® however continues swelling after the split is complete, displacing the loosened material by as much as 13mm.

The major advantage of expansive mortar over plug and feather or mechanical splitting is that the force is applied evenly over the entire length of the hole, rather than just at the top of the hole. This results in more even splitting, avoiding the problems shown above. In addition, it is also possible to split a thinner piece of stone off when trimming a block (see Figure 8). Expansive mortar also has advantages over explosives in that there is generally no shock effect on the stone surrounding the hole, and when the reaction is not too fast (as described above), there is no gas pressure which escapes into and extends existing fractures, and so better recovery of saleable material is often achieved in quarries which have many existing open fractures.

An important factor to consider in the use of expansive mortar is the diameter of the drill hole. In practice, no additional pressure is generated on the wall of the drill hole in larger holes, and while the resulting force increases proportionally to the diameter, expansive mortar consumption increases with the square of diameter. In practice in the Rustenburg quarries, no difference is observed between 32mm and 34mm diameter holes, while consumption of expansive mortar increase by 13% in the latter case.

### **3.1.4 Explosive Splitting**

Extraction of granite has in the past relied heavily on the use of explosive splitting techniques. The earliest of these relied on the use of blasting gunpowder (hereinafter referred to as “BGP”) to achieve a soft split blast. In more recent times, the use of decoupled high velocity explosives has become prevalent, especially in Scandinavia and parts of the USA.

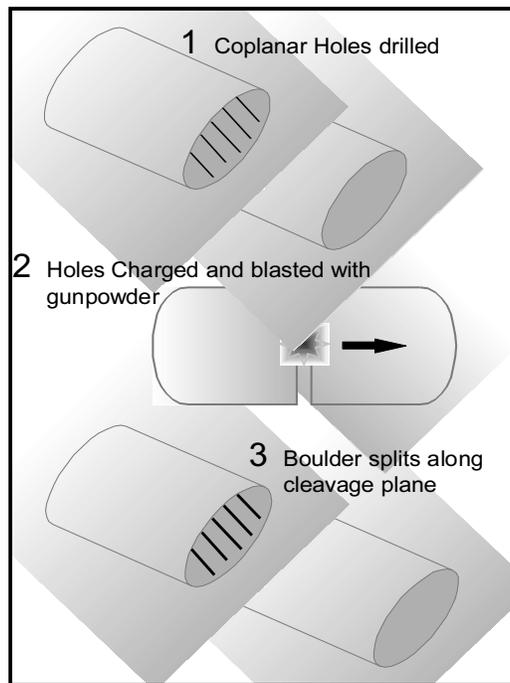


**Figure 8** Position of cut with alternative trimming methods

### *Blasting Gunpowder*

Blasting gunpowder is a deflagrating, rather than a detonating explosive. It thus works by means of the pressure generated by confined the product gases of deflagration, and has virtually no shock energy. In practice, this is achieved by means of igniting the BGP in a suitably tamped drillhole. In

the early days, the lack of any technology for simultaneous ignition of the holes meant that this was often achieved with a single hole drilled as to take advantage of the natural cleavage direction or grain of the stone. Where it was not possible for a variety of reasons to utilise the natural cleavage direction of the stone, or where this was absent, use was made of line drilling and splitting with plugs and feathers (see above). Extraction of granite with this method required a high degree of skill from the quarryman, which verged on an art form. With the advent of electric initiation, it became possible to drill a series of co-planar holes which were charged with BGP and initiated simultaneously to achieve a precise split, which made it possible to accurately split stone without strong cleavage directions. The resultant force generated by the combined holes result in splitting of the rock along this line due to its tensile strength being exceeded. This effect can be enhanced through the use of directional notching of the drill holes (see above), to force the direction of the split (a technique pioneered in dimension stone in Rustenburg material, but well known in explosive theory). In Rustenburg material, BGP works exceptionally well due to the three co-perpendicular strongly defined grain directions, all of which have substantially lower tensile strength than a random direction. These are such that on freeway for instance, a perfect cut can be made over many square metres using only a single drillhole.



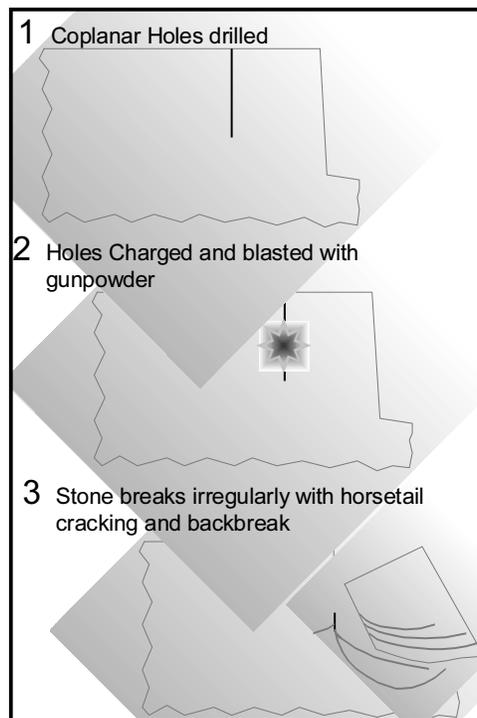
**Figure 9** Splitting of boulder with BGP

A drawback of splitting with BGP, is that the stone must be loose and free to move in order to achieve a good split. This is generally the case with loose boulders (see Figure 9) above, and while BGP performs highly satisfactorily in the hands of a skilled quarryman in boulder formation, the same cannot always be said for solid formations.

The use of BGP to successfully split (straight and without damaging the rock) dimension stone is a highly specialised task relying heavily on the experience and judgement of the quarryman - while powder factors can be calculated in theory, the slow nature of the cutting (compared to high VOD explosives) has implications not taken into account by theoretical calculations (see discussion on

expansive mortars). The calculation is further complicated by the influence of the degree of confinement (tamping) on the pressure generated. In practice, it is not desirable to tightly confine the BGP in a point charge, as although it will cut, the extremely high pressures generated at the point where the charge is placed can cause cracking of the rock around the hole, which is further extended by the escaping gases. Many techniques have been developed, which are well known to quarrymen and are beyond the scope of this discussion, to ensure that every split made is perfect. However, such are the number of variables to be taken into account, that even the most experienced quarrymen produce some poor splits, which inevitably impact on recovery. In the solid formations, this becomes even worse, as there are many geological features such as unloading joints and veins which are partially open but not completely loose (in boulders, these are by definition weathered and loose). These features, the exact position of which is not always known in the drillhole (if this is known, they can be compensated for by deck loading) allow for the escape of deflagration gases from the drillhole in undesired directions, often causing significant blasting damage to the material, and reducing recoveries.

In solid stone formations attempts to split using BGP are generally not successful, as the blast tends to run towards the nearest free face, often with the development of horsetail cracks and back damage which result in significant losses of material (see Figure 10) hereunder. While it is possible to counteract this to a certain extent by drilling and blasting in two or more directions simultaneously, this is often not successful with BGP, due to the slow burning speed and anisotropic nature of the stone. BGP is thus mainly used in loose boulder formations in the southern hemisphere.



**Figure 10** Blasting in solid formation

### *Decoupled High VOD Explosives*

In the northern hemisphere, a range of blasting techniques have been developed using high VOD explosives to split the stone. In the Scandinavian countries, decoupled nitroglycerine based charges in small diameter tubes (11mm or 17mm) are used in holes of 30-40mm in diameter. While use of natural joints in the rock is often made in order to facilitate splitting, techniques for two, three and even four way simultaneous splitting have been developed. In the USA and other European countries, detonating cord is normally used for split blasting, often with the holes filled with water to assist transmission of the shock wave. In the USA, a special gel filled with microscopic air bubbles has been developed to aid transmission of the shock wave, while cushioning the effects. Different stones however have differing sensitivities to different types of blasting and a method that is used in one material successfully may not be suitable in another, or even later in the life of the same deposit, as blasting may cause the release of inherent stresses within the stone in deeper parts of the formation. The advantage of using high VOD explosives, compared to BGP, is that as the splitting does not rely on the gas pressure generated, the associated problems related to solid formations discussed above fall away. In addition, high VOD explosives are more suited to splitting in more than one direction simultaneously, and are therefore indispensable in key cuts where two perpendicular directions must be split at the same time.

In theory high VOD detonating explosives work by means of their shock energy to produce a splitting effect in the rock. This is achieved by drilling a series of co-planar holes, which are then charged and detonated simultaneously. The resulting compression shock waves are superimposed along the line between the drillholes, increasing the compressive forces generated along this line. The compressive forces induce tensile forces in the rock at right angles to their direction of action, and thus a split is caused along the line between the holes as a result of the tensile strength of the rock being exceeded. The secret behind successful splitting with high VOD explosives lies in arriving at the optimum balance of hole spacing and powder factors which result in tensile strength of the rock being exceeded only where there is superimposition of the shockwaves, i.e. on the line between the holes. Splitting with high VOD explosives is not an easy business - too high a powder factor, and cracking will occur in many random directions in addition to the intended split line; too low a powder factor, and the split will not occur perfectly, with much of the detonation gas energy then dissipated into the surrounding rock in the form of cracking [23].

Another problem in attempting to split with high VOD explosives is that their shock energy is such that they pulverise the rock immediately surrounding the borehole (compressive failure zone), followed by a zone of radial cracking (tensile failure zone) where the compression wave is still strong enough (intensity reduces with distance travelled) to induce tensile forces exceeding the tensile strength of the rock. These cracks are then extended further by the gas pressures generated. These effects are partially overcome by means of using decoupling (using a charge of much smaller diameter than the drillhole, allowing for an air or water gap to absorb the worst of the shock energy) and by not tamping the holes. In the dimension stone industry, specialised low energy explosives have been developed to provide additional compensation for these effects.

Powder factors for splitting in dimension stone are traditionally prescribed by the manufacturers in terms of a weight of explosives per cubic metre of rock to be loosened [24][25][26]. Conceptually, this makes no sense in terms of the theory described above, and it can lead to large benches being overcharged or small benches being undercharged, especially if the ratio of the three dimensions varies dramatically from that used to determine the ideal powder factor. Much work was conducted in the Rustenburg quarries of Finstone by one of the authors in the mid 1990s, using both Finnish nitroglycerine based explosives especially developed for dimension stone blasting (F, K, G and KK pipecharges), as well as Energex Barrel™, an product of AEL Ltd for smooth blasting in tunnelling

and shaft sinking. After consulting with Espley-Jones [27], it was decided to base the determination of powder factors on a weight per square metre basis, which seems more conceptually correct. This has the advantage of optimising the powder factor to the splitting mechanism independent of bench geometry. It does however have the drawback of not taking into account the (desirable) movement of the loosened bench which is effected by the gas energy of the explosion. Based on the results of extensive testing, powder factors of 100-120g/m<sup>2</sup> on the freeway direction and 130-160g/m<sup>2</sup> in the secondway and toughway directions have yielded the best results in terms of minimising blasting induced fractures as well as achieving successful two-way splitting using both F11 and F17 pipecharges and Energex Barrel™. Satisfactory results were not obtained with the K, KK and G formulations of pipecharges at 17mm diameter, and these at 11mm diameter did not split the stone at all. Previous testing conducted in the Rustenburg quarries in the early 1990s with Dynatrim™ (a now discontinued AEL product based on the K pipe performance parameters) yielded optimum reported results for two-way splitting at around 180g/m<sup>2</sup>, although no study of blast induced fracturing was done.

One weakness however of a powder factor based solely on the square metres split is that it makes no provision for displacement of the rock mass that is split. A three term powder factor formula which attempts to make some compensation for the above deficiencies has been developed [21] based on empiric observation in Italian granite quarries. The formula is as follows:

$$C = a + b.S/V + c.s$$

where C = overall powder factor (g/m<sup>3</sup>)  
S = split surface area (m<sup>2</sup>)  
V = volume (m<sup>3</sup>)  
s = displacement (m)  
a = minimum effective powder factor (10.52 g/m<sup>3</sup>)  
b = specific surface consumption of explosive (26.47 g/m<sup>2</sup>)  
c = displacement efficiency coefficient (28.74 g/m<sup>4</sup>)

The first and last terms of this formula account for the displacement effect, while the middle term accounts for the splitting effect. This formula was developed in three way blasting in granites with tensile strengths of around 15MPa. It was also developed using detonating cord (PETN explosive). Typical reported powder factors for the Italian quarries observed range between 60 and 100g/m<sup>2</sup> when converted to a powder factor based on surface area. While slightly lower than the results obtained in the Rustenburg quarries, this is likely to be a result of the fact that holes were stemmed with water, which increases shock wave transmission, but also increases the likelihood of cracks forming around the holes.

In general, the sources quoted above prescribe a fixed powder factor independent of the type of explosive. This seems strange, as there is a very wide range of properties of these various explosives, and it seems logical that a powder factor which has been found to work well with one type of explosive will not necessarily work well with an explosive of vastly differing parameters. In practice therefore when testing was performed in Rustenburg, powder factors were adjusted between explosives relative to their heat of explosion (the only parameter which is a reliable indicator of relative strength which was available for all explosives), while still trying to balance the volume of detonation gases side of the equation (In practice, it may be that relative weight strength may be a better correcting factor if it is available for all explosives). The results obtained in testing of various explosives listed in Table 3 below have however justified this approach.

Explosive	VOD (m/s)	Vol Det Gas (l/kg)	Heat of Expl (MJ/kg)	Density (kg/dm <sup>3</sup> )	Diameter (mm)	Charge (g/m)	Vol Det Gas (l/m charge)	Heat of Expl (kJ/M charge)
Det Cord 40g/m PETN	6500	780	5.9	n/a	n/a	40	31	236
Det Cord 20g/m PETN	6500	780	5.9	n/a	n/a	20	16	118
Det Cord 10g/m PETN	6500	780	5.9	n/a	n/a	10	8	59
Det Cord 8g/m PETN	6500	780	5.9	n/a	n/a	8	6	47
F-17 Pipecharge	2500	335	2.8	0.95	17	216	72	604
K-17 Pipecharge	1900	160	1.5	0.95	17	216	35	323
KK-17 Pipecharge	1700	130	1.2	0.9	17	204	27	245
G-17 Pipecharge	1800	409	2.0	0.9	17	204	84	409
F-11 Pipecharge	2500	335	2.8	0.95	11	90	30	253
K-11 Pipecharge	1900	160	1.5	0.95	11	90	14	135
KK-11 Pipecharge	1700	130	1.2	0.9	11	86	11	103
G-11 Pipecharge	1800	409	2.0	0.9	11	86	35	171
Energex Barrel	3200	906	2.37	0.95	18	242	219	573
Dynatrim	1700	800	1.38	0.9	18	229	183	316

**Table 3 : Properties of various high VOD explosives tested for splitting Rustenburg Grey Gabbro**

The properties of the particular stone quarried have significant implications for the type of explosive used and the success of splitting with minimal blast induced fracturing. The testing conducted in the Rustenburg material was able to limit radial cracks from blasting to as little as 7-8mm in random directions (tensile strength approximately 18MPa) at the optimum powder factors. However cracks on the secondway and toughway which have much lower tensile strengths extended for up to 20cm, probably due to extension of the shock wave induced fractures in these directions by the gas pressure. However, in the author's experience, in stones which are fairly isotropic and do not have significant cleavage directions, cracking can be limited to only radial fractures induced by the shock wave.

### 3.2 Cutting Techniques

The techniques of cutting stone have been developed in relatively recent times. They were developed initially in response to the problems incurred when splitting relatively solid formations of stone, where the necessity of splitting in more than one direction simultaneously often lead to damage to the stone as a result of one splitting line running past the other into the remaining stone. One of the earliest developed techniques, the use of helicoidal wire sawing was the forerunner of the development of diamond wire sawing which is now the most prevalent of the cutting techniques. Helicoidal wire is now seldom used, and only in soft sandstones and marbles, and involves the use of a twisted three strand cable pulled through the stone and using sand or similar abrasive as the cutting agent. The remaining cutting techniques are described below.

### 3.2.1 Jet Flame Cutting

Jet flame cutting involves the use of diesel or paraffin with compressed air to produce a hot flame jet (around 2500°C) which spalls a channel in the stone. The technique was developed in the 1950s, and is most effective in granites with a high silica content, as these are prone to fracturing and spalling off at these temperatures. In stones with lower silica content, cutting rates are far slower, and there is a tendency for the flame to melt the other minerals rather than spalling them off., and the operator must exercise caution in order not to clog the slot. Jet flame torching is still widely used in the USA where fuel costs are significantly cheaper than elsewhere and where acceptance of diamond wire has been slower among conservative operators. However, slow production rates (1-1.5 square metres per hour), high fuel consumption (40to 50 litres per hour) and high noise levels (130dB) militate against its use.

### 3.2.2 Slot Drilling

Slot drilling involves the drilling of a coplanar line of large diameter (typically 64mm) holes at a centre to centre spacing of just less than twice the hole diameter using a line drilling rig to ensure accuracy. Guides are then inserted into adjacent holes to stabilise the drill head as the webs between holes are drilled out.

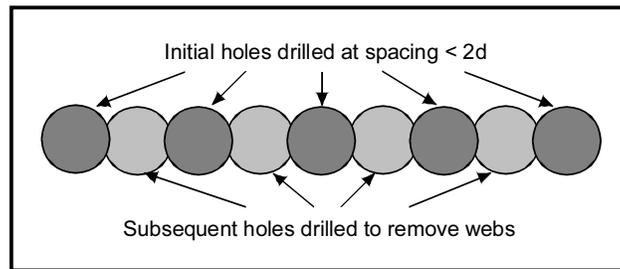


Figure 11 Slot Drilling

Slot drilling is now mainly utilised in the development of keycuts in soft sandstones, slates and marbles, as the drilling costs make it economically unviable in granites compared to alternative methods.

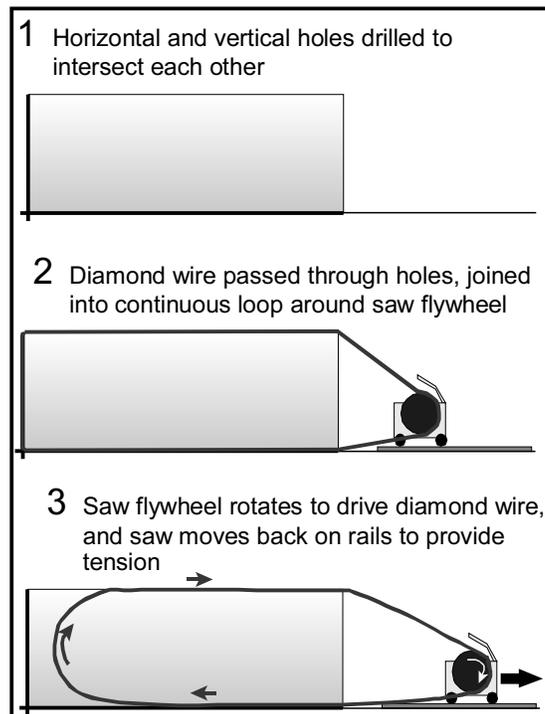
### 3.2.3 Diamond Wire Sawing

The progress in diamond wire sawing technology, both in terms of sawing equipment and the diamond wire itself, over the past fifteen years has lead to the stage where diamond wire sawing is now almost universally the best method of cutting, even in the hardest of granites for loosening of benches at least, although adoption has been slower in countries such as India, China, Finland and the United States where it has been perceived as expensive compared to blasting methods. Studies have shown however that the use of diamond wire sawing has potential for reducing noise and air pollution, enhancing recovery and reducing transport costs by reducing the waste transported [28].

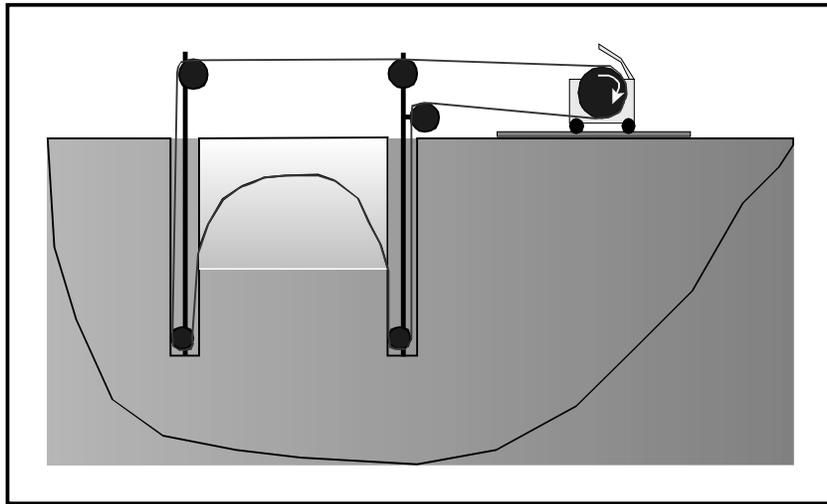
Using this method, two holes are drilled to intersect each other, commonly over distances of up to 25 metres and vertical height of 6 to 12 metres. Experience has shown that while down-the-hole hammer drilling at 75 –90mm diameters gives good results in marbles and the true granites, gabbroic rocks are extremely tough in terms of percussion drilling, with significant accuracy problems. Consequently small diameter diamond core holes are used in these rocks. This has the

added advantage that the core can be studied for the presence of veins, joints and cracks which are not apparent on the exposed faces. The diamond wire is then passed through these holes and joined to form a continuous loop, which is placed over the flywheel of the saw (see Figure 12).

As the flywheel rotates driving the diamond wire through the stone, the saw moves backwards along a track in order to maintain tension on the wire. Current sawing rates achieved are of the order of 2-4 square metres per hour in granites and up to 10 square metres in marbles. A wire life of 6-10 square metres per linear metre of wire is achieved in hard granites, ranging to between 15 and 25 square metres in softer granites and over 40 square metres in some marbles. The average cost of diamond wire is around US\$100 per metre. As a result of the improved economies of diamond wire sawing, it has replaced jet flame torching, slot drilling and multi-direction split blasting in many areas. An important development in recent years has been the development of plunge cutting in granite mines (see Figure 13), which has considerably aided the establishment of keycuts (see mining layout below).



**Figure 12** Diamond Wire Sawing



**Figure 13** Plunge cutting a blind cut with diamond wire.

### **3.2.4 Water Jet Cutting**

Machines have also been developed for cutting the stone loose with high-pressure water jets using suspended abrasives and while these are technically feasible, their high capital costs and long set-up times make them economically unviable in most quarry configurations. While no recent results for water jet cutting could be found in the literature, in 1995 satisfactory results were reported [21] in softer stone, but cutting speeds of less than  $1\text{m}^2$  per hour in gneiss. A drawback of abrasive water jet cutting is that the water needs to be softened and filtered 1 micron, while the life of the sapphire nozzle was less than 24 hours.

### **3.2.5 Chain Cutters**

Chain cutters make use of a jib of approximately of up to 8m in length on which runs a chain fitted with tungsten carbide tipped picks. The machine cuts a slot of approximately 100m in width, 8m in depth, and length limited only by the setup of the rails on which the machines travel. These cutters are used mainly in marble and limestone quarries, and may be used for primary cutting, for cutting the blind cut in keycuts, or even in underground quarries to advance roadways into the solid stone. Cutting speeds of up to  $10\text{m}^2$  per hour may be achieved in marbles.

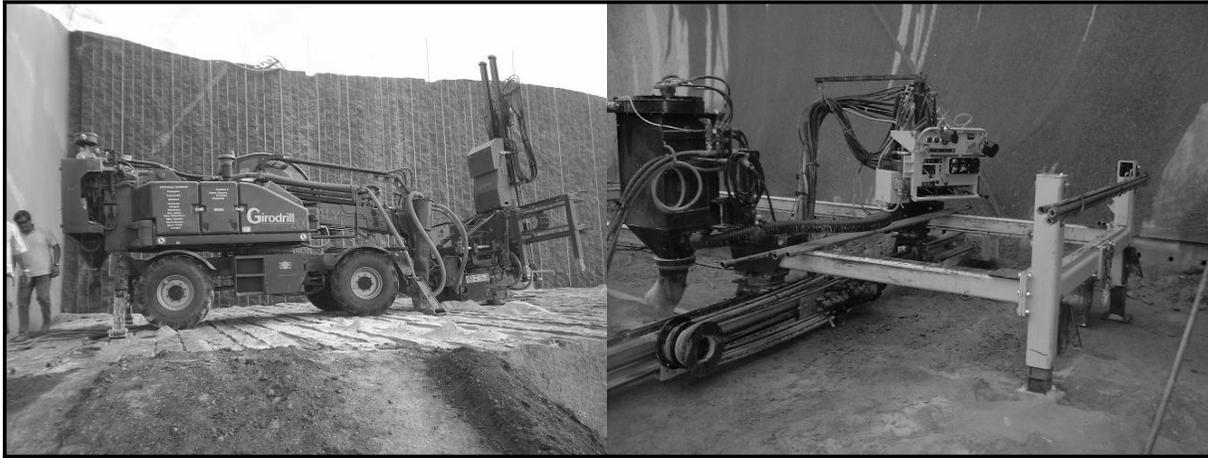
### **3.2.6 Diamond Belt Cutters**

Diamond belt cutters operate on the same principle as chain cutters, but have a rubber belt fitted with diamond segments instead of the toothed chain. They are also used mainly on softer stones such as marble and limestone.

## **3.3 Drilling in dimension stone quarries**

It is clear from the discussion above that drilling plays an important role in dimension stone extraction methods, particularly the splitting methods, where fairly high drilling densities are required (hole spacings are generally between 12 and 40cm and are usually drilled to 80-90% of the depth of the split). While hand held pneumatic rock drills have traditionally been applied, in the past 20 years, there has been wide scale adaptation of mechanised drill rigs using both pneumatic and hydraulic drills. These have been both skid mounted types which can be moved around by hand or by block handling equipment as well as fully mobile self propelled rigs (see Figure 14). The use

of these rigs can dramatically increase productivity. Hand held drilling in Italian quarries reported yields gross productivity of 15m per hour, while skid mounted pneumatic rigs reportedly achieve gross productivity of 23m per hour [21], resulting in production of 5-10m<sup>2</sup> per hour of split surface.



**Figure 14** Mobile line drilling rig (Verde Ubatuba, Brasil) and skid mounted line drilling rig (Blue pearl, Norway)

Drilling rates however vary widely according to the stone type, and the authors have observed instantaneous penetration rates of 20cm/min for hand held drilling in Rustenburg material, compared to 40cm/min in Parys and African Red granites and 100cm/min in Giallo Ornamental granite in Brasil. In particular, black granites (gabbros, norites, dolerites) do not drill easily with percussion drilling. While drilling rates of up to 150cm/min have been recorded by hydraulic drill rigs in African Red granite, only 70cm/min has been achieved with the same rigs in Rustenburg material. Another factor to take into account is that in these difficult to drill materials, drilling accuracy may be adversely affected by too high a thrust on the drill in order to achieve higher drilling rates. Indeed Italian quarry operators have claimed superior accuracy for hand held drilling rigs than skid mounted rigs [21]. An acceptable deviation is considered to be to 50% of the hole spacing, or 1.5% of the drilling depth for long holes [21], while according to the same source 0.5% of hole length is achieved with a 25kg manual pneumatic rock drill with instantaneous penetration rate of 40cm/min.

### **3.4 Stone Handling**

Depending on the quarry geometry, handling of blocks is either by means of tower cranes or front-end loaders. Marble is generally extracted in fairly large blocks and fairly large earthmoving equipment (Caterpillar 988 or Komatsu WA600) is generally in the order of the day, particularly in first world producing countries. However, as is the case with granite, in poorer countries smaller machines (the Caterpillar 966 is the standard machine used in Brasil) or even timber gantries are used to lift and move blocks.

Front end loaders are commonly fitted with a quick coupler attachment which allows for fast interchanging of the bucket with a fork or boom attachment. While the bucket is generally used for handling waste material and for cleaning up the quarry, the fork attachment is used for handling of blocks (see Figure 15), and the boom for pulling block down from the face.



**Figure 15** Block handling using fork attachment on front end loader (Rustenburg, RSA)

Hydraulic excavators are widely used in dimension stone mining, both for the removal of overburden, as well as within the quarry itself to pull or push split blocks off the face. Generally units in the 20-30 ton class are used, although in the authors' experience, 45 ton units are more productive and less subject to damage in larger quarries where the additional expense can be justified by the utilisation. Transport of waste material to the waste dump has traditionally been accomplished by means of the front end loader, but more and more dump trucks are being used in the industry as operators realise the cost of this improper usage of the loader compared to the savings achieved by using dump trucks for the transportation. In boulder quarries and developing quarries where there are not yet permanent roads, the articulated dump truck is favoured for its flexibility. However in well developed quarries where the cost of maintaining permanent roads is justified, rigid off-highway dump trucks in the 50 ton class with a cut down bowl are proving to be most efficient given the large sizes of waste blocks (15-25 tons), and the matching with the loaders used to ensure that waste is not dropped into the bowl causing excessive shock loading on the truck (see Figure 16).



**Figure 16** Caterpillar 773 Dump Truck with cut down bowl (Springbok Quarry, Rustenburg, RSA)

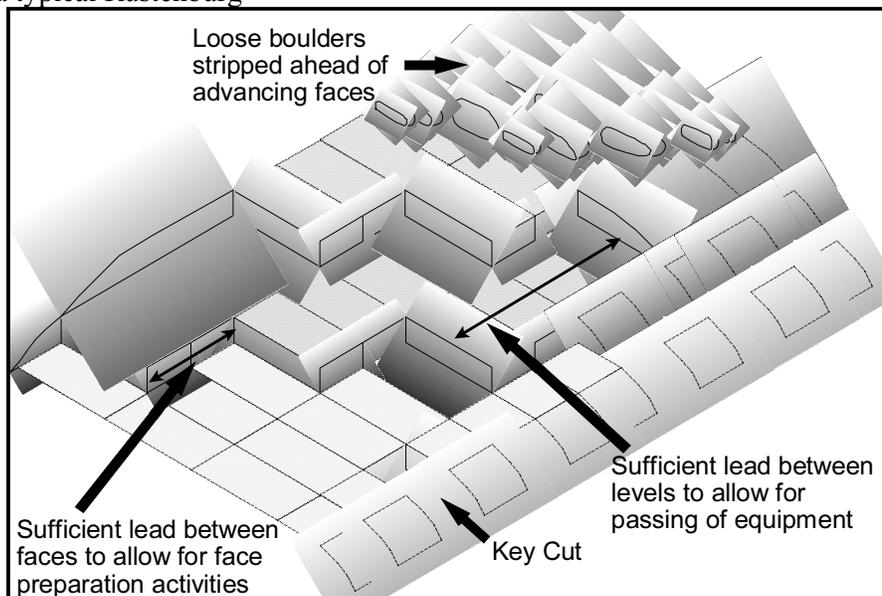
### **3.5 Mine Layout**

An important issue in the development of such a quarry is the layout of the faces and levels. In many boulder operations, scant regard is paid to layout, as once a high recovery boulder has been mined, the mining moves to another high recovery boulder elsewhere, until all of these are depleted

and the next lower range of recovery is mined. This practice is not sustainable, as it effectively sterilises underlying reserves in the solid formation and production of consistent quality and quantities is difficult. This practice has given boulder mining a bad name, both among professionals [29], as well as among environmentalists. However, the mining of loose boulders is unavoidable in most southern hemisphere deposits and if done in a properly planned and systematic way, can aid initial cash flows from the project without prejudicing future development. Planning and developing the quarry on one or more levels, with a saw-toothed face shape (see Figure 17) on each level, allows for sufficient access for all preparation activities for loosening benches without interference from benches being extracted and allows for continuous production and blending of recoveries and qualities.

Where possible, it is best to start from one end of a hill, but where this is not possible, key cuts can be made in the middle of the formation. These have historically been difficult and have been avoided because they have required two way blasting. Recent advances now allow for blind sawing of the back cut. It is also possible to key cut downward into solid stone where the deposit progresses below the surrounding ground level.

An important factor to bear in mind with regard to the planning and development of a dimension stone quarry as depicted in Figure 17, is the impact of the sequencing and scheduling of the various operations involved in loosening and quarrying a bench, as well as the requirement for sufficient space between levels. In practice, as a result of the time taken to intersect the drill holes and perform a saw cut (approximately two weeks if no problems are encountered), three benches are required (one being quarried, one being loosened and one being already loose) for each production team in order for the team to be in a position where they always have loose stone available to work. It is also a good idea to have at least one spare face between every two teams to allow for some blending of different recovery areas in order to stabilise recovery. When one considers that the minimum lead between two levels to allow bench preparation to take place without interfering with tramming of earthmoving equipment, is at least 40 metres (or four bench widths), it is evident that a fairly large area is required to be developed to support production. The idealised layout depicted above would support two production teams, yielding about 3000 to 3500m<sup>3</sup> of production per annum in a typical Rustenburg



**Figure 17** Isometric view of idealised quarry layout

formation (at 10-12% recovery) and would take about 18 to 24 months to develop to this stage. If the formation allows in terms of its size and depth, additional teams could be added at the rate of about one per 8-10 months for operations above surface (hillside quarrying) and one per 12-15 months for sub-surface operations (see Figure 18).

### **3.6 Choice of mining method**

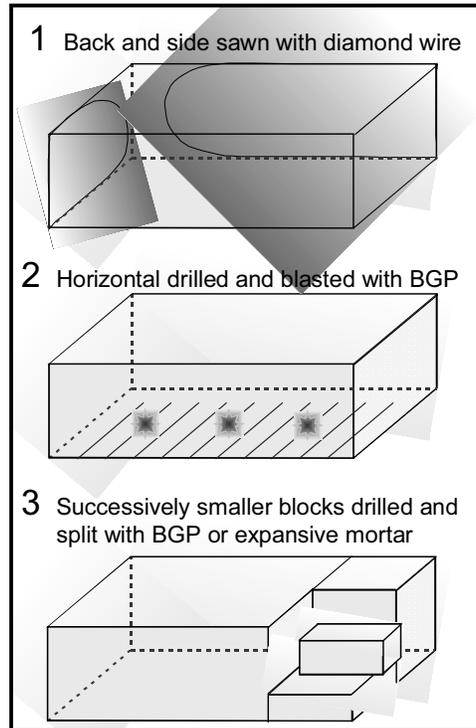
The choice of mining method in a dimension stone quarry is largely affected by the geology of the deposit. Boulder formations will largely be quarried by means of splitting methods, especially by means of the use of blasting gunpowder, while solid formations will require the at least some application of one or more cutting methods in order to loosen large benches from the solid formation. In general, in marbles, slates, sandstones and quartzites mining will be



**Figure 18** Subsurface quarrying in solid formation (Emerald Pearl Quarry, Norway)

by non-explosive splitting and cutting techniques, while in granites blasting techniques may be applied. The physical properties of the stone are likely to determine what type of explosives will be applied. In stones without prominent cleavage directions, the high VOD explosives are often very successful and economic in splitting the stone, while BGP is often the favoured explosive in cases where the cleavage is prominent. The use of explosives should be applied with caution in stones which display sensitivity to blasting, as blasting may cause undesirable cracks in the material.

Conventional mining of solid formations of marble and granite will make use of diamond wire sawing to loosen large benches, which are then split into successively smaller blocks until these are of a size that can be handled by the loader or crane (see Figure 19). The dimensions of a bench such as that shown in Figure 19 are determined by several factors. The length is typically restricted by the limits of accurate drilling for the intersecting holes of the diamond wire cuts. This is generally between 20 and 30m. The width of the bench is determined by the limits of accurate drilling and blasting (generally around 9-12m for available drillsteel and most stone types). The height of the bench is commonly



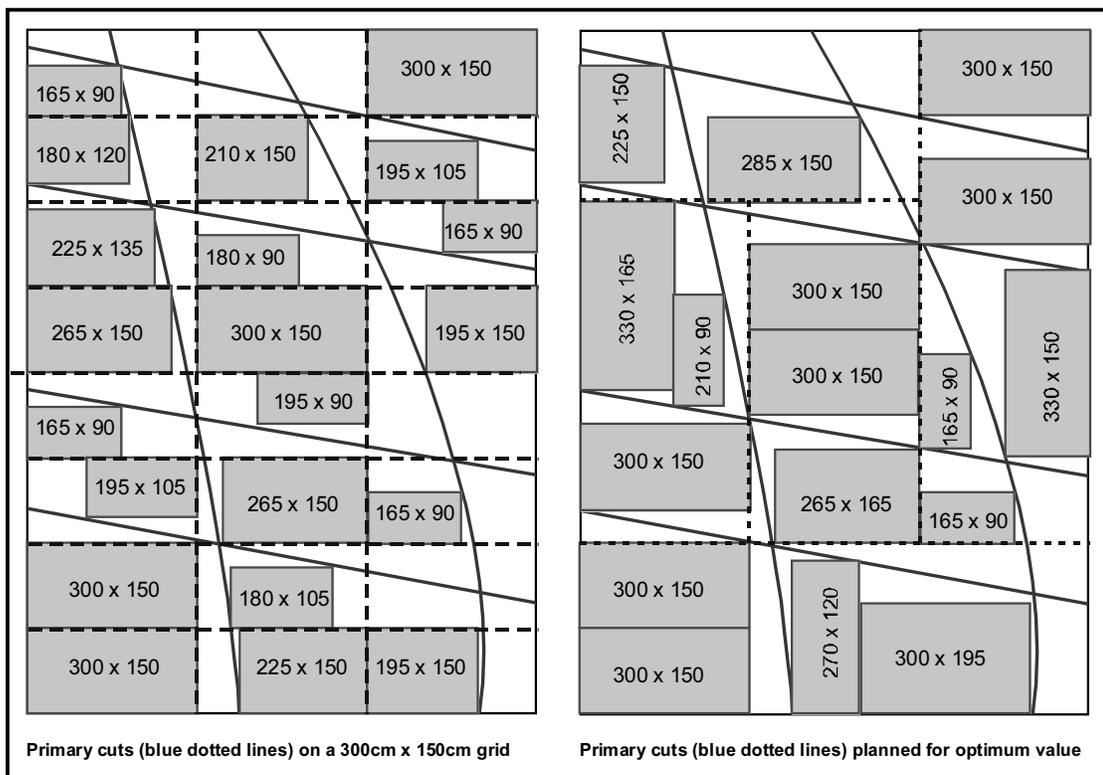
**Figure 19** Conventional mining of a solid formation

determined by the block handling equipment, with the most common large front end loaders in used today able to effectively remove blocks at a bench height of 6-7m. During this splitting process, cognisance must be taken of the defects within the stone in order to determine the position and sequencing of splitting lines in order to maximise the recovery and value of saleable blocks as described below. The blocks are then removed from the face, and trimmed if necessary to square them and remove any remaining defects

The defining feature of dimension stone described in the introduction has important implications for the production process at the quarry, which results in significant additional cost compared to the mere extraction of stone for its physical properties. Indeed, when it is the intention to merely blast and remove stone for its physical properties, recovery can be almost 100% of the volume removed, while when the same stone is quarried with the intention of producing dimension stone blocks, recovery of saleable blocks is typically between 3% and 30%, while the cost of removal material is typically of the order of 10 to 15 times the cost in the former case. This increased cost results from the techniques used to split or cut the stone without damage and the special attention that must be given to carefully extracting rectangular blocks of material from between flaws in the stone (such as cracks, joints, veins, banding or accumulations of a single mineral or colour) which render it unsuitable in terms of the market requirements, rather than just simply extracting blocks of a standard size without regard to these flaws.

It is important to note that these defects often do not affect the physical properties of the stone, but merely its appearance. Further, these flaws constitute a tiny proportion of the volume of the stone. For instance, a block of Rustenburg material of 300cm x 150cm x 150cm with a calcite vein of thickness 100 microns crossing from one corner to the other would be 99.9926% pure gabbro-norite from a chemical and mineralogical point of view. For most extractive industries, the attainment of such a high level of purity of the pure mineral concerned would more than satisfy the market. As dimension stone however, the block would be worthless!

A complicating factor is that the stone often has one or more preferential grain or cleavage directions (freeway, second/easy way, tough way) along which it splits preferentially, even when attempting to split oblique to these directions. The flaws in the material however often run oblique to the grain direction, with the result that recovery of saleable blocks is compromised. 0 below depicts a two dimensional representation of face in a granite quarry, where defects such as veins or joints cross the bench at an angle to the cutting directions of the stone (parallel to the edges of the bench) which are determined by the natural grain or cleavage of the stone. In the first case, the initial cutting is made on a standard grid of 3 metres by 1.5 metres, as depicted by the dotted lines, while in the second case, the initial cuts are planned in such a way as to yield an optimum recovery and size of blocks produced. The second case yields a total volume of final blocks 15% higher than the first case, but with a total value that is 43% higher due to a



**Figure 20** Impact of flaws and primary cutting on recoveries

higher proportion of large blocks. In addition, in the second case, 88% of the production is in large block sizes which are in greater demand in the market, compared to only 44% in the first case. Although this simple two dimensional analysis shows the significant impact on volume, value and

saleability of applying carefully sequenced cutting, in three dimensions, the impact of the initial cutting decision far more significant.

It is further possible that poor quarrying practice could result in the production of blocks which although they might be defect free, may have no or significantly lower commercial value due to the size and orientation of the blocks with respect to the pattern and textural appearance of the stone. For instance in Rustenburg material, relative to the freeway direction, which is the direction that is typically cut and polished, a block of 240cm x 120cm x 120cm would have a significantly higher commercial value than one of 120cm x 120cm x 240cm. Although these two blocks have the same volume, the former block could be sold for at least five times the value of the latter block, which indeed would have only a limited potential market, and once this market has been satisfied, any further blocks of this size produced would be of no value whatsoever, as they could not be sold. Similarly, in a multicoloured material with a flow pattern, a block where this pattern flows at an angle of approximately 30° to the length of the block could be sold for a higher price than one of the same dimensions where the pattern flows along the length of the block. In the case of a block of the same size having this pattern flowing across the width of the block, the block would be virtually worthless.

A further factor influencing the value of a block is its size. In general, blocks for processing into slabs for ultimate use in the construction market must have minimum dimensions across the cutting direction of 240cm x 120cm, since final artefacts typically have dimensions which are multiples of 60cm. Blocks smaller than these dimensions would thus result in significant wastage when cutting the final artefacts. For a material which only has application in the construction market, blocks smaller than the above dimensions would effectively be unsaleable. Further since larger blocks yield increased processing efficiencies, these attract a premium price.

A mining technique which has long been applied in marble quarries, where large slabs of stone are sawn loose from the solid formation and then overturned so that they lie horizontal on the quarry floor where they are further cut into saleable blocks is finding wider application in granite quarries as the cost of diamond wire sawing becomes more economic and operators see the benefits of increased recovery (see 0). Using this technique, slabs of between 170cm and 190cm (this dimension would commonly become the width or height of the final block) in width, and commonly 6-10m in height (slab heights of 7-9m have been reported as optimal [30]) are sawn loose. Either airbags pumped by compressed air at 600-800kPa or steel hydrobags pumped with water at 7MPa are inserted into the kerf and expanded to start tipping the slab. If the slab is sufficiently high and thin, it may be tipped completely by alternately pumping one of two bags and lowering the other further into the slot as it opens, or else hydraulic jacks are inserted into the slot and used to push the slab until it falls. It has been reported that the height of the bench should be increased when the thickness is increased to make tipping easier, and that the length should be decreased in this case so that the total mass of the slab does not exceed 1000 tons [30]. While it is true that a higher bench is easier to tip than a lower one of the same width, this is purely a function of geometry – a higher slab rotates through a smaller angle before the centre of gravity passes the point of rotation and it falls under gravity. The tipping forces required to start rotating the slab are independent of the height of the bench, being described by the following formula:

$$F=1/2w^2.l.\rho.g$$

Where

w = slab width

l = slab length

ρ = rock density

g = acceleration due to gravity



**Figure 21** Slab mining (Marikana Quarry, Rustenburg, South Africa)

In terms of this formula, where only a finite tipping force is available, it is necessary to reduce the length of the slab as the width increases, but the height can be made as high as is convenient and safe, and given that geometry favours the tipping of higher benches we would recommend a height as high as possible. However as the typical widths quoted above are convenient production of typical block sizes required for gang saws, the available equipment has been tailored to suit these dimensions, and has a maximum practical tipping width of around 230cm at a typical length of 10m.

There are many benefits of slab mining in this manner. Diamond wire cuts of high faces are typically more accurate than drilling, and especially where explosives are used for splitting, this may result in significant reduction in material lost, as well as less trimming and reworking of blocks. In addition, there is no damage caused by explosive gases penetrating existing fractures and extending these. This may be significant in many solid formation quarries, especially as quarrying progresses deeper into the formation and more residual stress in the rock is encountered. Further, the cost of sawing may be lower than the cost of drilling and using expansive mortar in countries with higher wage rates, or where pneumatic drilling is conducted using diesel powered air compressors. Once the slab has been tipped, cuts or splits that would not have been possible in the vertical orientation may be made, and so commonly small diamond wire saws are used to further cut up the slab, or splits may be made that would not have been technically possible with the slab in the vertical orientation. For example in Figure 21 above, the second phase split of the slab has been achieved by drilling a line of vertical holes on the freeway direction. This line would have had to have been drilled horizontally some 8m above the quarry floor if the slab was in its original position. This can be of great value in increasing recovery when natural flaws run at an oblique angle to the natural cleavage direction of the stone. There is also a benefit in terms of block handling – the blocks are produced at a height where they can be far more easily handled by the front end loader than is the case in conventional mining. This results in improved equipment productivity, less equipment damage, and less damage to blocks.

There is however a caveat. As with any mining method applied in a dimension stone quarry, slab mining cannot be applied without careful consideration of the geology of the stone. In Rustenburg

for example, Kelgran converted many of their quarries to slab mining after management had seen the method in Europe. Since European equipment was used for the tipping, slabs were sawn at the widths described above, and perpendicular to the most prominent direction of natural flaws. However, the final polished direction of Rustenburg material lies horizontal in the quarry, and in many areas the spacing of the natural flaws is less than 2.4m. This resulted in the slab width becoming the length of the final block rather than the width, with the result that the proportion of large blocks produced for the construction market fell to around 40% of total production, compared to a typical value of around 63% for a convention Rustenburg quarry (and ideally 75% in terms of market demand). At Finstone's Rustenburg quarries it was realised that given the geological



**Figure 22** Prototype slab tipping device (Marikana Quarry, Rustenburg, RSA)

constraints, successful application of slab mining would require slabs of 300 – 330cm in width to be tipped. This required the slab length to be reduced to around 4-5m in order to be able to tip the slab with existing equipment. Since most defects lie at around 70° inclination, this would have meant that many of the advantages of slab mining in terms of higher recovery would have been lost. As a consequence, a hydraulic tipping device which attaches to the quick coupler of the front end loader and uses the loader's hydraulics was designed (see Figure 22 above). This tipping device allows for slabs of 330cm wide by 12m in length to be tipped easily, as well as more safely, since no personnel are required in the vicinity of the slot after it has initially been opened by means of hydrobags.

#### **4 CONCLUSION**

The dimension stone industry is relatively large in value when compared to non-fuel minerals, and consumption of natural stone is growing a rate significantly faster than most mineral products. In spite of this, the industry is extremely fragmented, although there is a trend towards consolidation and vertical integration. Possibly as a result of this fragmentation and consequent lack of financial support for research, the industry has been largely neglected by academics, especially at the quarrying technology level. This however is changing, and there are increasing numbers of papers related to dimension stone quarrying being published, especially from China, India and Eastern Europe, where state institutions have given priority to the development of the industry.

While in the past, quarrying of dimension stone was carried out by traditional methods developed over many centuries, it is becoming increasingly challenging from a technical point of view, requiring inputs from geology and many branches of mining engineering, ranging through blasting

technology, non-explosive rock breaking, rock mechanics, mine design and scheduling, geostatistics and reserve evaluation.

There is no one universally applicable mining method, and the engineering involved in planning and operating a dimension stone quarry must be well versed in a variety of cutting and splitting techniques, as well as have a thorough understanding of both the geology and the physical properties of the material he is extracting in order to design an optimum mining method for that quarry.

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