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Research paper

Geometallurgy applied to industrial minerals operations

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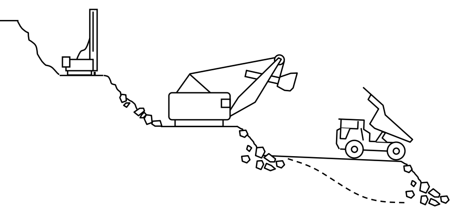
ABSTRACT

The geometallurgical concept shows a high potential for increasing resource efficiency and value from the Norwegian mining industry. By obtaining better control of variations in in-situ properties, (modal mineralogy, mineral textures, ore hardness, etc.) and creating 3D economic block models based on grades and other important properties, it is possible to enhance production by means of capacity and yield as well as other variables specific for the raw material in question. Geometallurgy has globally been thought of as a tool for ore producing mines. Geometallurgy related problems encountered in the industrial mineral industry are both comparable and not comparable to the problems known from the ore mining industry. In this paper we present the Norwegian mining industry in a geometallurgical perspective and aim at identifying and describing some of the issues that are special for the industrial minerals sector.



1. INTRODUCTION

The mining industry is facing numerous challenges. High grade ores are getting depleted and new discoveries tend to be high-tonnage, low grade ores as described by e.g. Lund (2013). At the same time, environmental rules and regulations are being tightened, demanding high cost environmental investigations and monitoring, especially with respect to tailings disposals. As a result of these changes in both the nature of deposits and in regulations for the mining industry, investment- and operational costs are increasing gradually. Thus, the mining industry is forced to improve their working strategies to be able to exploit the full potential of the deposit. Increased detailed knowledge about the deposit is arguably the most important issue. Herein lays not only knowledge about the grade of the valuable minerals and metals and the impurities, but also about inherent properties like e.g. mineralogy, textures and grindability. These parameters will have a paramount influence on the processing performance, and thereby the financial result. In the future, pressure will also be on the mining industry to find alternative use of waste rocks and tailings from primary ore production.

Based on the characteristics of the Norwegian mining industry and the original scope of the geometallurgical concept, this paper investigates the similarities and differences between the metallic ore- and industrial mineral sectors. Further it studies how they are utilizing and possibly can strengthen their utilization of the inherent possibilities in the geometallurgical concept. Background data are gathered from scientific publications, mineral statistics of different countries and company information.

2. TRENDS IN THE MINING INDUSTRY

It is interesting to look at the relationship between the metallic ore sector and industrial mineral sector in order to understand the dominating parties and look at how focus is aimed. The basis for this paper is the Norwegian mining industry and data for the more mining intensive neighboring countries Sweden and Finland is given below for reference.

2.1 The Norwegian mining industry

The Norwegian mining industry has over the last decades been characterized by a dominating industrial mineral sector over the metallic ores. This can be seen from the annual mineral statistics presented by the Directorate of Mining and the Geological Survey of Norway (2013), see Table 1 for summary of statistics. Table 1 shows that industrial mineral production dominates when it comes to the number of production sites, whereas metallic ores constitute a large share of the total monetary values relative to the low number of production sites.

Table 1. Annual mineral statistics from 2010 to 2012. Data compiled from Neeb et al., (2011), Neeb et al., (2012), and Neeb et al., (2013). NOK in Billions. Metallic ores are tonnes ore delivered to concentrator.

	Metallic Ores			Industrial Minerals			Aggregates		
Year	Production sites	NOK (billions)	Mt ore	Production sites	NOK (billions)	Mt prod	Production sites	NOK (billions)	Mt prod
2010	4	1,8	9,9	35	2,6	11,2	1048	4,0	64,0
2011	3	2,5	10,0	37	2,9	9,2	952	4,7	76,7
2012	4	3,0	11,2	29	2,8	10,8	1012	5,2	79,4

The metallic ores are dominated by iron oxide and ilmenite production. Except for these mines, there are no other metallic ores mined in Norway, such as base- or precious metals. The last base metal mine in operation in Norway, Bleikvassli

Gruber, was closed in 1997, after an incident where a water leakage filled the mine with water. Since then there has been no such mine in operation in Norway.

However, the main sector in Norwegian mineral production, dominating significantly over the metallic ores and industrial minerals, is, as seen from Table 1, aggregate production. This sector alone accounted for 72 % more produced tonnage from the mine from 30 times more sites, but less than 90 % of the value compared to the combined numbers from ore and industrial mineral production.

Figure 1 shows the sales value in MNOK for the main mineral sectors from 2001 to 2012. The aggregate sector has had a steady increase, whereas the industrial mineral- and the dimension stone sector have been more or less stable. The metallic ore sector has increased rapidly from 2009 and had a higher sales value in 2012, compared to the industrial minerals sector.

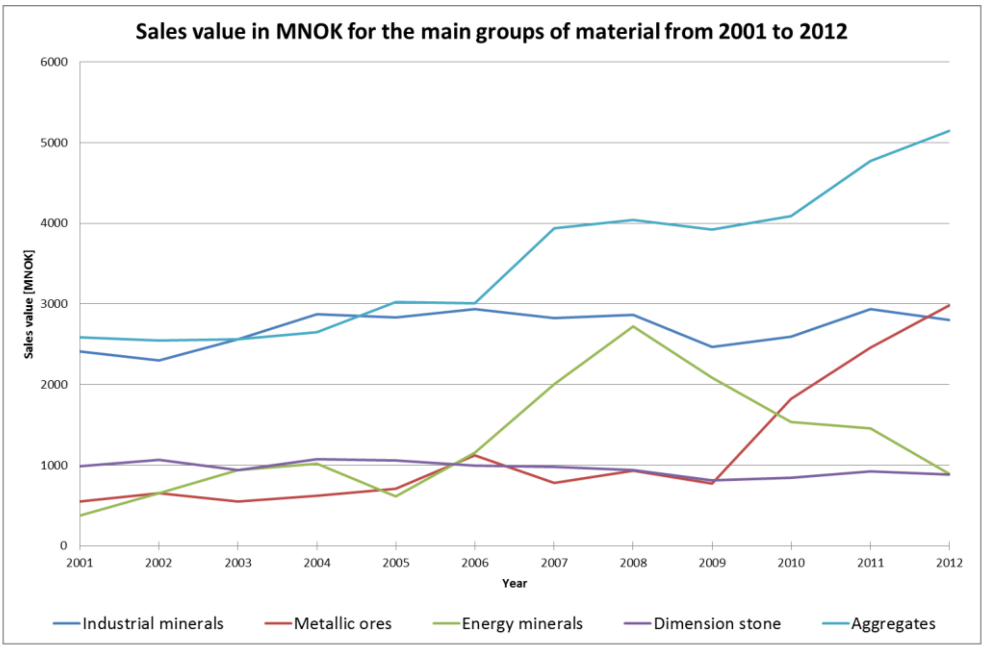


Figure 1. Sales value for the main groups of material in the Norwegian mining industry. Data compiled from Neeb et al., (2013).

Figure 2 presents the number of production sites in Norway for the main mineral sectors. The number of production sites producing metallic ores was nearly constant from 2006 to 2012, varying between 2 and 4. The large increase in sales value from 2009 in figure 1 is not a result of many new mines, but the result of one new mine replacing a mine practically without any production at all.

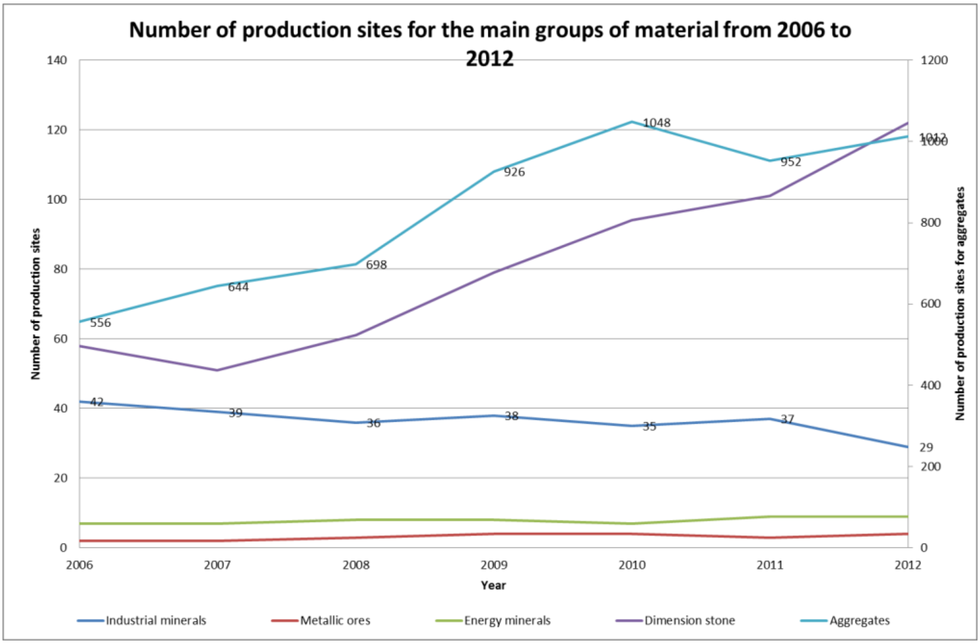


Figure 2. Number of production sites for the main groups of material. Data compiled from Neeb et al., (2013)

2.2 The mining industry in Sweden and Finland

To compare, statistics for mining in Sweden has been compiled from Åkerhammar et al., (2011), Islamović and Norlin, (2012) and Åkerhammar et al., (2013) and presented in Table 2. Here it is obvious that metallic ores dominates the Swedish mining industry in tonnage to another extent than in Norway. The number of metallic ore producers is more than three times the number in Norway. Also the number of industrial mineral producers are higher, although only slightly. However, mined tonnages from industrial mineral mines are less than 70 % of the mined tonnages in Norway.

The numbers for the Finnish mineral statistics have been compiled from GTK‘s web services (GTK, 2013). A threefold higher number of industrial mineral producers in Finland produce between 75 and 90 percent of the equivalent metallic ore.

Table 2. Minerals statistics of Sweden years 2010-2012. The Swedish mining industry is dominated by metallic ore producers in tonnage but the number of industrial mineral producers are higher.* x+y = “none iron ore” + “iron ore”. Data has been compiled from Åkerhammar et al., (2011), Islamović and Norlin, (2012) and Åkerhammar et al., (2013). Monetary values for metallic ores were not readily available.

	Metallic Ores			Industrial Minerals		
Year	Producers*	SEK (billions)	Mt	Producers	SEK (billions)	Mt
2010	10+3	n.a.	60.6	42	3,2	8,9
2011	10+3	n.a.	66.7	41	3,4	9,7
2012	11+3	n.a.	70.6	38	3,5	9,0

Table 3. Mineral statistics of Finland, years 2010-2012. Compiled from GTK web services (GTK, 2013). Monetary values were not available.

	Metallic Ores			Industrial Minerals		
Year	Producers*	EUR (billions)	Mt	Producers	EUR (billions)	Mt
2010	10	n.a.	18,2	35	n.a.	15,6
2011	12	n.a.	17,2	34	n.a.	16,0
2012	12	n.a.	19,6	29	n.a.	15,1

3. THE GEOMETALLURGICAL CONCEPT

The term geometallurgy describes a concept within mineral production planning and optimization that originated about four decades ago (Hoal, 2008 and references therein) and can be related to another frequently used term “From mine to mill” concept (e.g. AusIMM, 1998) However, the latter is a holistic approach towards a better fragmentation and process optimization and tend to lack the spatial relationship to the deposit. Geometallurgy is a structured attempted to establish a “better” link between in-situ (hence the spatial relationship) quantifiable parameters and the recovery. In this case “better” means more precise. Hence, a better link between in-situ quantifiable parameters and the expected recovery and profit.

The Geometallurgical concept has received increasingly more attention during the last two decades, due to fewer easy accessible, high grade ores in production and the nature of new ore discoveries that tend to be characterized as low-grade-high tonnage deposits (e.g. Lund, 2013).

Although geometallurgy have been defined differently by different authors, see e.g. Hoal (2008) and Dunham et al. (2011), in general geometallurgy can be said to combine geological and metallurgical information to create spatially-based predictive models for mineral processing plants to be used in production management (Metallurgical in this context relates to physical separation of minerals (mineral processing) or hydro metallurgy (chemical separation)). Geometallurgy is applied along the entire value chain from exploration for new or extended resources through mining to the separation of valuable minerals from gangue minerals.

Geometallurgy has over the past few decades extended to become an important concept in the mining industry.

4. THE VALUE CHAINS AND BLENDING PROCEDURES

4.1 Introduction

The production process must be planned carefully, not only to ensure the right quality to the right time and place, but also for securing an optimal resource utilization and economical profit from the operations. The fundamental input into the planning process is the 3D geological model describing the geometry of and the quality variations in the deposit. This model must be reconciled during production to be as close to the truth as possible. The planning process outputs mine plans and schedules, either by using scheduling and blending software or manually. These plans include information on what quality to blend from where in the pit at what time. This blending is somewhat different whether an industrial mineral deposit or a metal ore is mined. These differences are sought explained in the following sub-chapters:

4.2 Customer relations in the different value chain

There are some main differences in the customer relations through the value chain for industrial minerals producers and metallic ore producers. A metallic ore's main value is given from the metal grade and some penalty elements. Valuable metals are the main metal(s) that "carries" the project as well as elements that give additional value to the ore as it is produced. The penalty elements are elements that if contained in one of the final concentrates, are unwanted by the customer because it will affect the result of downstream processes. I.e. they will generate problems in the refinement process or even be difficult to remove ending up as a constituent of the final product. A content of penalty elements, as lies in the word, gives reason to put a penalty fee on the delivery of the ore concentrate to the customer. Thus the level of the penalty is calculated from the actual content of the respective element in the concentrate. This, in reality, decreases the value of the concentrate. However, the content of such elements rarely lead to a ban from delivery of concentrate.

On the other hand, in industrial minerals production, it is more typical that unwanted elements (or even specific minerals) have an upper limit that can be tolerated. This limit can be experienced as high or low by the producers. The result of “off-spec” production, where an element is of higher content than tolerated, is that the customer cannot receive the shipment and the production has to be disposed as waste. The term penalty element or mineral does not exist in the industrial minerals sector as it does for the metallic ores, although, in some cases the element content can lead to differentiation in qualities and thus reduced prices for the concentrate. The outcome of quality differentiations is that the concentrates are used in different types of end-products. Thus, the price reduction can be seen as some sort of grade independent penalty if the grade is within some specifications.

Often customers have additional requirements to the product or concentrate besides the element grade. This could for example be mechanical strength of the product or whiteness. The requirements also often come as sets of requirements, not only Cu-grade, but for quartz deposits for example, minimum SiO2 content combined with maximum contents for e.g. Al2O3, Fe2O3 and TiO2 and mechanical strength. These combinations of requirements create a broad source of variation and thus more complex block modelling where issues related to for example additivity are important.

For processing and refinement plants, stability in raw material (feed or concentrate) properties is important. Stable grade, chemistry or mechanical properties are important for producing end products down the value chain with equal stability in grade or chemistry.

4.3 Blending in a metallic ore mine

The customer of a metal mine is primarily interested in the metal grade. That said, mineralogy, textures and grindability etc. are other decisive parameters. If the grade of a block is above some cut-off and thereby labeling the ore as at least marginal, the mining block can be extracted as long as it can be blended with a block that has a high enough grade to ensure that the average is above some required average grade. The cut-off is a result of a more or less complex estimation that includes costs and recoveries. The usage of this simple principle is dependent on capacities in the mine and in the processing plant.

In modern scheduling and optimization tools, a dollar value is used as input instead of grade. The dollar value of a given mining block is estimated from the size of the block, the grade, the recovery and the commodity prices and the costs. The recovery would typically be dependent on grindability, textures and mineralogy. The costs are dependent on the grindability, which influences the amount of energy that one has to invest to liberate the valuable metal containing minerals. In cases like this, one would have a cut-off on the dollar value instead of the grade. Mining blocks could be blended if both blocks have a dollar value above the cut-off, based on operation costs, and the average dollar value exceeds the required average dollar value (including required rate of return). The value of the block is always defined and quantifiable.

Again, a prerequisite for this kind of blending is that one is not faced with any limitation in the production capacities.

The dollar value concept is implemented in most scheduling and blending software. In these software, the optimum scheduling and blending is the one that maximize the net present value.

4.4 Blending in an industrial mineral mine

In an industrial mineral deposit, the blending and the required input are somewhat different. The interesting grades are normally not the valuable mineral in itself, but the impurities. A cut-off can be applied both on the average and on the value in one single block. It might not be sufficient that the average impurity levels in a blend are below some specified level. Possibly must also the level in all blocks that are included in the blend be below some level. This is not because the block with high levels of impurities will dilute the good block, but because it might totally destroy the product.

A calculation of a dollar value could be somewhat more cumbersome in an industrial mineral deposit. Given that a block has impurity levels below the cut-offs, the dollar value is often set to one price. This price does not depend on the "grades". If the impurities levels are somewhat elevated above the cut-offs, the block can possibly be assigned a full dollar value if and only if the block can be blended with another block with impurities levels so good, that the average is within specification. Again, the dollar value does not depend on the impurity level.

The dollar value concept is for this reason not used to any great extent in production planning. One prerequisite would be to be able to somehow punish a high level impurity block by some factor, possibly a probability. More research must be done to develop a well suited factor. Instead of using the dollar value concept, the life time is normally used to find the optimum schedule and blending. The optimum schedule and blend is the one that maximizes the mine life time and at the same time produces products that are within specifications.

5. CASE DESCRIPTIONS

The current use of geometallurgical elements in the Norwegian mining industry is illustrated here through a set of brief case descriptions from selected industrial mineral producers.

5.1 Åheim Olivin – Sibelco Nordic

The main products from Sibelco Nordics plant in Åheim are crushed olivine with different particle size distributions. The olivine is mined in an open pit operation. Quality control through sampling and analysis of drill cuttings assures that the olivine quality is within the grade specifications. In addition to the geochemistry is the strength of the olivine rock a decisive quality parameter. A number of techniques have been tested to try to assess and spatially quantify the strength variations. The tested techniques included measurement while drilling (Sandøy, 2011), Schmidt hammer mapping and core logging and rock type classification based on subjective assessment of the rock type strength. Preliminary tests have been performed to implement the strength parameters in the block modelling, but no block model including both geochemistry and strength has been established. The processing plant is simply a crushing and sieving plant. Blending of high grade loose and lower grade hard raw material based solely on geochemistry will therefore produce a small grain sized, high grade product and one course grained, lower grade product, where the wanted result would be a stable high quality of both small and course grained products. Implementing geometallurgical principles where both strength and geochemistry are included in the block model, would therefore potentially increase the value-add.

5.2 Brønnøy Kalk

Brønnøy Kalk is situated near Brønnøysund in North-Norway and produce calcium marble raw material for production of ground calcium carbonate (GCC) at Hustadmarmor’s GCC plant at Elnesvågen, Western Norway. Brønnøy Kalk has since more than 15 years been working with an idea of mining and quality assurance which is similar to the geometallurgy concept (Watne, 2001). A 3D model based on geological mapping and drill core logging is the basis for all mine planning. Quality parameters are among others whiteness, reagent consumption and flotation loss in a laboratory scaled processing procedure (Bunkholt, 2011).

A MSc project was recently finished at NTNU, where the quality parameters was block modelled (Hilmarsen, 2012) and an optimal final pit was found using scheduling software (Hilmarsen, 2013). The results from these projects show that such optimization can be used on such problems, but that special care must be taken due to the nature of the blending procedures.

5.3 Elkem Tana

Elkem Tana AS produces quartzite for metallurgical production of Ferrosilicon and Silicon in electric arc furnaces. Mining method is open pit ranging from sea-level to around 350 m above sea level (Brenden-Veisal, 2009). Several quality requirements need to be met in order to have a saleable product. Different quartzite qualities are produced, with Fe2O3 and Al2O3 as the main quality parameters. In addition, there are requirements to the content of other elements like Ti, Ca and Al (Schei et al., 1998). The SiO2 content is defined by impurity contents and no fixed specification is set from customers. Besides specification of impurity content, there are quality parameters related to particle size which typically ranges from 10 to 150 mm (Schei et al., 1998) as well as mechanical- and thermal strength.

According to Al2O3 and Fe2O3 content, the resources are defined as product qualities. Mainly, these qualities are intended for different end products and the less content the higher the quartzite quality.

A 3D resource model is developed for the deposit and is the main tool for planning and follow-up of production (Brenden-Veisal, 2009). All production is planned according to three main chemical qualities that are modelled in the 3D model based on the chemical content. Average chemical compositions from neighboring drill cores are used to define the quality of the quartzite around one drill core intersection. The qualities are planned according to existing and future mining levels (Brenden-Veisal, 2009). An important input to the model is faults and fracture zone which affect the production tonnages dramatically. The particle size requirement results in a relatively low yield from the crusher plant compared to similar industrial mineral production. This is because all undersize material is regarded waste as there are no alternative marked for this sizing locally. Thus, fracture zones and faults will affect the yield even higher if the fracture density or fault by nature result in less in-spec size distribution of the product.

6. DISCUSSION

The summary of mineral production in Norway shows that industrial minerals are important in the mineral industry, although metallic ore production stands for the highest values generated. The high number of industrial mineral producers has a dominating appearance on conferences and arrangements for the mineral industry, and at the same time, this sector spend most money on research and development as shown by the number of research programs and PhD candidates co-financed through the years 2000 to 2013 (Aasly, 2008, Hestnes, 2013, Jacamon, 2006, Moen, 2006, Sandøy, 2003, Sørensen, 2007, Watne, 2001) and additional ongoing PhD projects. The Strategic University Program on The Value Chain from Mineral Deposit to Beneficiated Product with Emphasis on Quartz (Malvik, 2005) was the main funding source for PhD programs in the period. On the other side, metallic ore producers were involved in only one PhD project (Ellefmo, 2005) in the same period.

The graph presented in Figure 3 tries to illustrate the difference in relationship between grade (metallic)/quality (industrial minerals) parameters and block dollar value for the two mineral segments. As shown in the graph, metallic ores have no value as long as the grade is below cut-off and this part of the ore cannot be used in blending schemes. The blending is done with marginal ore with in-grade ore in order to maximize the value of the operation. This is quite different from the strategies used by industrial mineral producers, where cut-off is rarely a topic, rather most low-grade raw material can be blended with high-grade raw material in order to produce in-grade product. However, blending may decrease the value of the high-grade part of the blend, but the profit lies in higher utilization of the ore and less waste rock. In some cases, the low-grade raw material may have to be drilled and blasted anyway, in order to gain access to higher-grade raw material and thus producing this part of the raw material as part of a blend may be profitable. This type of mine planning requires good geological and mineralogical knowledge and it shows that industrial mineral producers have been working with elements of geometallurgy for a long time. However, the concept has not been fully embraced. Some people even regard some of the largest industrial mineral producers as best-in-class working with geometallurgy (Jens Gutzmer, pers. com. February 6th, 2014). The way of working has been developed because of the nature of the industrial minerals sector, where prices and quality requirements have forced a high focus on optimization in order to secure revenue.

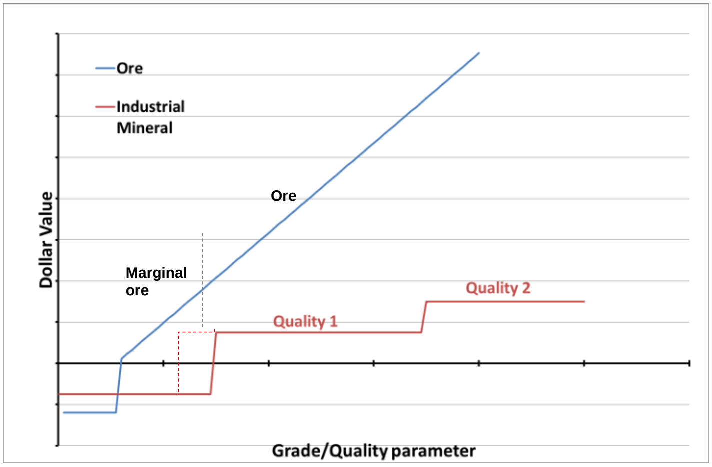


Figure 3. Constructed curve indicating Grade/Quality parameter related to Dollar Value.

Figure 3 shows that the grade is not as important in industrial minerals production as in the mining of metallic ores. In contrast to the metallic ores, where grade is the main factor for defining ore value and some commodities are really high priced, tonnage is the most important factor in industrial minerals. The relatively low priced (high cost) commodities show small price differences on quality improvements and the up-side is often related to tonnages.

7. CONCLUSION

The following conclusions can be drawn:

- The geometallurgical concept has been developed to be used on metallic ores.
- Geometallurgical principles can be used on industrial mineral deposits.
- Strength variations point out as a more important parameter in industrial mineral production.
- Block modelling strength variations cause potential additivity issues that must be resolved.
- The Norwegian mining industry has until recently been dominated by industrial mineral producers if aggregate production is not taken into consideration.
- The Norwegian industrial mineral sector has frequently been working with geometallurgical elements without reference to the geometallurgy concept.

- Some also consider the large industrial mineral producers to be best in class, in Norway, when it comes to implementing elements of geometallurgy.

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