Doctoral theses at NTNU, 2020:161

Aleksandra Maria Lang

A Geometallurgical Approach Applied to the Tromsdalen Calcite Operation

Doctoral Thesis

NTNU
Norwegian University of
Science and Technology
Faculty of Engineering
Department of Geoscience and Petroleum

NTNU
Norwegian University of
Science and Technology

Aleksandra Maria Lang

Doctoral theses at NTNU, 2020:161

NTNU

ISBN 978-82-326-4670-8 (printed version)
ISBN 978-82-326-4671-5 (electronic version)
ISSN 1503-8181

NTNU
Norwegian University of
Science and Technology

Aleksandra Maria Lang

A Geometallurgical Approach Applied to the Tromsdalen Calcite Operation

Thesis for the degree of Philosophiae Doctor

Trondheim, May 2020

Norwegian University of Science and Technology
Faculty of Engineering
Department of Geoscience and Petroleum

NTNU
Norwegian University of
Science and Technology

NTNU
Norwegian University of Science and Technology

Thesis for the degree of Philosophiae Doctor

Faculty of Engineering
Department of Geoscience and Petroleum

ISBN 978-82-326-4670-8 (printed version)
ISBN 978-82-326-4671-5 (electronic version)
ISSN 1503-8181

Doctoral theses at NTNU, 2020:161

Printed by Skipnes Kommunikasjon as

> Even when on their guard, human beings inevitably theorize.
>
> Stanisław Lem, Solaris

Preface

The work presented in this doctoral research has been carried out at the Department of Geoscience and Petroleum at the Norwegian University of Science and Technology (NTNU) in Trondheim, under the supervision of associate professors Kurt Aasly and Steinar Løve Ellefmo. The work is part of the research project InRec – Increased Recovery in the Norwegian Mining Industry by Implementing the Geometallurgical Concept funded by the Research Council of Norway and co-funded by Verdalskalk AS, Sibelco Stjernøy AS and Brønnøy Kalk AS.

The research comprised a case study and field work at Tromsdalen marble deposit operated by the company Verdalskalk AS. The study focuses on aspects of geometallurgy and implementation of the geometallurgical concept as relevant for industrial mineral deposits. This doctoral thesis is article-based, which means that the core research is presented in two published articles and one unpublished manuscript, attached as Part II of the thesis.

During the PhD research I presented my research at two international conferences:

The SEG 2015 World-Class Ore Deposits: Discovery to Recovery Conference; 2015.10.27 – 2015.10.30, Hobart, Australia: *Lang, Aleksandra; Ellefmo, Steinar Løve; Aasly, Kurt. Establishing the geometallurgical flow sheet for industrial mineral operations;*

The Process Mineralogy '17 conference; 2017.03.20 – 2017.03.22, Cape Town, Republic of South Africa:

Lang, Aleksandra; Aasly, Kurt; Ellefmo, Steinar Løve. Mineral characterization as a tool in the implementation of geometallurgy into industrial mineral mining.

I was also an author of a technical note *Geometallurgical flowsheet development and specification at Verdalskalk. Mineralproduksjon 7 (2016) B17-B24*, and a co-author of a paper: *Steinar L. Ellefmo; Kurt Aasly; Aleksandra Lang; Veena S. Vezhapparambu; Camilo A.M. Silva. Geometallurgical Concepts Used in Industrial Mineral Production. Economic Geology (2019) 114 (8): 1543-1554*

The paper (Ellefmo et al., 2019) and the technical note are not included in the thesis.

During my doctoral studies I attended NTNU university courses relevant to my field: Light and Electron Microscopy, Process Mineralogy, Scientific Writing, Advanced Petrology, Leapfrog Geo short course, PhD seminar, Norwegian Language course levels A1- B2, and an Image Analysis in Geoscience short course at the University of Basel, Switzerland.

Acknowledgement

I would like to express my gratitude to all of those who helped me through my doctoral work both on professional and personal level. First of all, I would like to thank my supervisor, Associate Professor Kurt Aasly and co-supervisor, Associate Professor Steinar Løve Ellefmo for guidance and cooperation. Kurt – thank you for being always ready to help me and for making complicated things easier. Steinar – thank you for all the inspirational discussions on the flowsheet, IDEF0 and geostatistics.

I would like to acknowledge Verdalskalk AS crew for the support and knowledge they shared with me during the numerous fieldworks. Many thanks to the main geologist Juan Rojas Ruiz for his advice and the constant support; to Tor Helge Hillmarsen for coordinating the InRec Project; Marta Martinussen Lindberg for a great help during sampling; Trond Johansen, Arnt Martin Storli, Håkon Mork, Rune Landsem, and Jonathan Ardila Quinonez for their commitment.

I would also like to acknowledge NTNU academic and technical staff: Maria Thornhill, Maarten Felix and Nathan Church for proofreading my articles, conference abstracts and my doctoral thesis; Torill Sørløkk, Kjetil Eriksen and Kristin Bergseth Aure for helping me with the laboratory work; Jonas Dombrowsky for Leapfrog consultations and Rolf Arne Kleiv for our fruitful discussions related to the geometallurgical flowsheet.

My gratitude also goes to my closest colleagues: Zeudia Pastore, Camilo Mena Silva, Veena Sajith Vezhapparambu, Przemyslaw Kowalczuk, Geertje ter Maat, Cyril Juliani, and many others. It feels to me as we have created a very special work environment, in which we were not only colleagues but also friends that trusted and supported each other. It gave me the sense of belonging. Alex – thank you for being the initiator of the most of our social activities. The Tuesday quizzes were something to remember. Mario, Kristian, Ben, Øystein and Bjørn – it was such a joy to play in a band together and to share musical experiences.

Special thanks to Marzena Grindal for being my expat friend, sister, mother, personal coach, economic advisor, and, towards the end of my stay in Trondheim, a great landlord. You are the best!

Kasia – thank you for being there for me during difficult periods and thank you for our chill balcony nights.

My gratitude goes to my family and friends back in Poland. I could always count on you. Thanks to my Mother for believing in me and supporting me at all times, for being always cheerful and optimistic, and for welcoming me in Warsaw anytime I had opportunity to visit.

Last but not least - thank you Piotr for all the love and support you gave me.

Abstract

The motivation behind the thesis was to increase the knowledge and to expand the possibilities within industrial mineral mining, an important mining sector in Norway. This was done through extensive deposit study and an implementation of the geometallurgical concept into Verdalskalk AS's calcite operation. Verdalskalk operates an open-pit calcite mine in Tromsdalen. The Tromsdalen deposit is a Middle Ordovician metalimestone of high purity. Most of the raw material is calcined in a furnace to calcium oxide (CaO) and used to produce precipitated calcium carbonate (PCC).

The main focuses of the study were mineralogical and textural studies of the raw material, rock surface hardness tests and conceptual work on the development of a geometallurgical flowsheet. The studies and tests were designed to follow the concept of geometallurgy, which merges geological and processing information along the mining value chain. The objectives of the study were to expand the knowledge of the geological drivers of processing parameters in the mine, and to implement the geometallurgical approach, used widely in metalliferous mining, to industrial mineral operations through a development of a geometallurgical flowsheet. The research was summarized in three papers.

The mineralogical studies mostly used transmitted and reflected light microscopy, with additional use of scanning electron microscopy. The surface hardness tests were conducted with the use of an Equotip 3 D rebound hardness tester on the rock in the pit and on the drill half cores. The conceptual work on the geometallurgical flowsheet used the IDEF0 function modelling methodology, followed by an investigation of the company's value chain, quality check procedures and possible bottlenecks. The research also consisted of logging the company parameters to investigate on potential areas of operation where the geometallurgical concept can be applied. Additionally, a literature review was conducted to clarify and unify geometallurgical terms and definitions.

Mineralogical studies using transmitted and reflected light microscope revealed differences in calcite grain size, trace mineral assembly and grain boundary shape between two types of marble (K2 and K5) of the same purity class. It was concluded that better mineralogical and textural control of the raw material is needed for better prediction of the kiln process.

Surface hardness tests were done in-situ and on halved drill cores. The tests done in-situ followed the mineralogical investigations of marble types K2 and K5. Rebound hardness values of type K2 were higher than K5, and that finding was interpreted as being related to the presence of silica minerals. Type K2 rebound hardness data also had higher standard deviations which were related to limonitic staining of the rock. It was concluded that research should be continued on half-cores as surface smoothness and accessibility was hypothesized to be an important factor.

The surface hardness tests on drill core material were preceded by core logging that allowed classification of the marble into 14 types. The highest rebound hardness values were obtained for types M10 and M8, both characterized by the presence of dispersed graphite that is usually associated with fine-grained calcite. The coarse-grained white calcite was characterized by much lower values. A positive correlation between core diameter and mean result and between core diameter and standard deviation was found and a need for an appropriate correlation factor was highlighted, as the correction factor mentioned in the literature did not compensate for the differences in the results.

Another focus of the study has been the development of the general and the case-specific geometallurgical flowsheet. The geometallurgical flowsheet was defined as a tool for designing and communicating a geometallurgical program to establish a geometallurgical predictive model. It was proposed to be used on site, for enhanced communication between specialists. The geometallurgical model definition was clarified as a function that links georeferenced in-situ geological characteristics and georeferenced measure of performance in a processing plant, emphasizing the positioning of the geoscientific data. The term *a priori model* was introduced for a preliminary model that is checked and validated during the execution of a geometallurgical program. It was concluded that the IDEF0 methodology was a tool that integrates with the idea of enhanced interdisciplinary communication, which is one of the key features of geometallurgy.

Thesis structure

The presented doctoral work comprises the summary in Part I and the papers in Part II.

The summary presents motivation, research objectives and background of the thesis, and is followed by a brief summary of each of the papers. Furthermore, the outcomes, synthesis of work and recommended future research is presented to the reader.

The second part of the thesis presents the three papers that are the main contribution to the doctoral work. The papers comprise two published articles and one manuscript:

Paper I

Mineral characterization as a tool in the implementation of geometallurgy into industrial mineral mining

Aleksandra Lang, Kurt Aasly, Steinar Løve Ellefmo

Published in Minerals Engineering 2018; Vol. 116, 114-122

Paper II

Geometallurgical flowsheet as a tool for designing and communicating geometallurgical programs

Aleksandra Lang, Steinar Løve Ellefmo and Kurt Aasly

Published in Minerals 2018; Vol. 8, 372.

Paper III (manuscript)

Application of rebound hardness testing to assess spatial lithological and textural variations of calcite marble

Aleksandra Lang, Steinar Løve Ellefmo and Kurt Aasly

Abbreviations

BSE – backscattered electrons

BWI – Bond Work Index

CT – computed tomography

EDS – energy-dispersive X-ray spectroscopy

GCC – ground calcium carbonate

HL – Leeb's hardness number

IDEF0 – Integration Definition for Function Modelling

InRec – Increased Recovery in the Norwegian Mining Industry by Implementing the Geometallurgical Concept

KPI – key performance indicator

LOI – loss on ignition

LOM – life of a mine

NFR – The Research Council of Norway (Norges forskningsråd)

NGU – Geological Survey of Norway (Norges geologiske undersøkelse)

NTNU – Norwegian University of Science and Technology (Norges teknisk-naturvitenskapelige universitet)

PCC – precipitated calcium carbonate

PSD – particle size distribution

SEM – scanning electron microscope

TOC – total organic carbon

XRF – X-ray fluorescence

Contents

Part I: Summary

Chapter 1: Introduction

1.1 Motivation behind PhD research

This research, as a part of the NFR-funded InRec project dedicated to mining, was conducted with the aim to increase the knowledge and expand the possibilities within industrial mineral mining in Norway. Currently, the mining sector worldwide faces many challenges including high-grade deposit depletion and growing awareness of the environmental concerns (Prior et al., 2012). Our needs to consume Earth's natural deposits grow steadily, and a shortage of non-renewable resources is only a matter of time. One way to address this problem is to seek alternative renewable energy and material sources (Lund, 2007), and another way that should be carried out in parallel is to grow the awareness of more efficient and sustainable exploitation of mineral commodities (Moran et al., 2014).

Communication is the key parameter for successful and efficient process management (Lewis, 1987). In any process engineering, it is important to understand a need for efficient interdisciplinary communication (Riemer, 2007). Lack of communication is an issue that prevents the development, full understanding and predictability of performance of the mining value chain (Munro and Tilyard, 2009).

With the challenges and concerns mentioned, the concept of geometallurgy shows its potential, as it is one of the solutions allowing for sustainable development (Dominy et al., 2018), and at the same time promotes interdisciplinary communication (Cropp, 2014). Geometallurgy is in its broadest sense the integration of geological and metallurgical knowledge during the life cycle of a mine to maximize the benefits and minimize the risks of the operations (SGS, 2019).

The geometallurgical concept shows a high potential for increasing resource efficiency and value. By obtaining better spatial control of variations in in-situ properties (e.g. modal mineralogy, mineral textures, ore hardness) and processing performance (e.g. liberation rate, leachability), and by creating 3D models, it is possible to enhance production by means of capacity, yield and other variables specific for the raw material.

While the term geometallurgy is currently used mostly in relation to metallic minerals deposits, this PhD thesis explores the idea of using the geometallurgy concept in industrial minerals operations, as there is a need to expand the knowledge and the possibilities within this sector of the Norwegian mining industry.

In this doctoral research a case study of the Verdalskalk AS calcite marble open pit operation in Tromsdalen is presented. This operation was selected to check possibilities for implementation of a geometallurgical approach in industrial minerals operations, and to observe and address possible differences between geometallurgy applied to industrial mineral and metallic ore operations.

The aspect of enhanced interdisciplinary communication in geometallurgy raised a need for a tool that would communicate geometallurgical operations along the mining value chain in a clear and systematic way. The term geometallurgical flowsheet was introduced as a preliminary concept and developed through the investigations of the Verdalskalk AS operation and of the Tromsdalen deposit variations.

1.2 Research questions and objectives

In this work, an implementation of geometallurgical approach is tested on an industrial mineral commodity, specifically a calcite open pit operation. It was hypothesized that for implementation, as with metal deposits, a first essential step is to obtain a thorough understanding of the geological and quality variations within the deposit. Here, the objective was to improve mineralogical and textural knowledge of the marble variations through extensive sampling and microscopic studies and to check whether the marble types distinguished by the company reflect the actual variability.

Another important statement is that, as with metallic ore deposits, an understanding of the relationship between geology and processing performance is vital to implement geometallurgy to new deposits. Therefore, a second objective of the study was to increase the knowledge of the relationships between in-situ marble, the company's processing parameters and final product quality. The research questions related to this part of the study included whether and how the in-situ marble variations influence the product quality; how the in-situ and processing parameters are related; and whether the relationship could be quantified and predicted.

Another hypothesis established for this doctoral study was related to the rebound hardness parameter. It was assumed that as with metal deposits, surface hardness can be a proxy for mineralogical variations and an Equotip 3 D testing instrument can serve as a geometallurgical tool in the case of marble deposits. According to this hypothesis, the objective of the study was to assess the use of surface hardness parameter as a proxy for marble variations and to assess Equotip 3 D as a tool to collect geometallurgical data. Here, it was essential to answer research questions such as: how does the surface hardness change with respect to different marble types; do rebound hardness values reflect the changing lithology; and how to use the Equotip 3D in a best possible manner.

Since communication is one of the key concepts for geometallurgy, the last but not least main hypothesis of the research states that enhanced communication along the mining value chain can be addressed by building a so-called geometallurgical flowsheet – a tool that would help to communicate the geometallurgical program along the mining and processing operations. Here, the main objectives were to propose and to define both a generic and a case-specific geometallurgical flowsheet, seen as a set of procedures, their visualization and associations that would contribute to create a process model based on a geometallurgical approach. A case-specific flowsheet would incorporate the processes and parameters of the Tromsdalen operation, as studied during research. A set of research questions was addressed, including how to communicate and visualize clearly; what are the main steps of the flowsheet, what is a goal /end product of the flowsheet.

The co-objective relevant for the research was a detailed literature review of the state of the art for geometallurgy and related methodologies and terminology.

1.3 Thesis contribution

The idea of geometallurgy is well known and by no means new. However, extending the geometallurgical approach beyond the metallic ores is still in an early research phase. In Norway, the research on incorporating elements of geometallurgy into industrial minerals sector has been conducted, but without addressing geometallurgy directly, rather referring to process mineralogy (Bunkholt, 2015). In the current research, the geometallurgical approach was directly addressed and implemented in an industrial minerals operation for the first time.

The main novelty of the research is the establishment of the geometallurgical flowsheet with the use of IDEF0 modeling language. The term, its definition and proposed use as a way of establishing the geometallurgical model is presented for the first time. The introduction of the concept of the *a priori* model as an initial idea of the dependencies between in-situ variabilities and the performance indicators is new.

The use of Equotip as a tool for the rock characterization and use of rock surface rebound hardness as a geometallurgical proxy has already been documented. However, in this research a new, geostatistical approach based on variogram modelling was proposed to support rock classification.

The mineralogical studies and drill core logging allowed for expanding current knowledge on the mineralogy and lithology of the deposit.

1.4 Scope

The scope of the thesis encompasses the geometallurgical approach in industrial mineral operations, with focus on discovering potential factors needed to establish the geometallurgical models. The thesis comprises a case study of the Verdalskalk AS open pit operation. Part of the work is the investigation and description of the geological and mineralogical characteristics of parts of the deposit. However, a discussion of the detailed metamorphic drivers of the deposit variability and unlocking of metamorphic conditions is beyond the scope of the thesis.

Several definitions of the term geometallurgy exist, revealing varying areas of focus and ranging from broad to narrow view. Therefore, it is important to scope the presented research according to one of the definitions of geometallurgy. Here, the geometallurgical approach was narrowed down to defining the links between geology and production, and, specifically, to observing and defining the links between specific geological properties and the mine key performance indicators (the KPIs). The environmental and economic aspects that are present in a broader view of geometallurgy are not addressed. Since the case study was conducted on an existing mine in operational phase, geometallurgy in a broad sense that encompasses the exploration and closure phases was not addressed here either. The scope was schematically presented in Figure 1.

The geometallurgical model is discussed conceptually both as a general idea as well as the deposit-dependent model. In the second case, some findings were useful to create a basis for the modelling. However, the actual geometallurgical modelling is beyond of the scope of the work.

The Verdalskalk AS produces three qualities of the material: pure, standard and aggregate rock. The analysis of Verdalskalk AS activities and deposit sampling, leading to the results presented in papers I and II, were focused on the pure quality material and did not encompass the standard and aggregate rock quality value chain. Paper III, however, discusses the variations within the deposit with no direct relationship to a specific value chain line and it encompasses rock of potentially pure, standard and aggregate qualities as well as rock types that are beyond the currently operated pit.

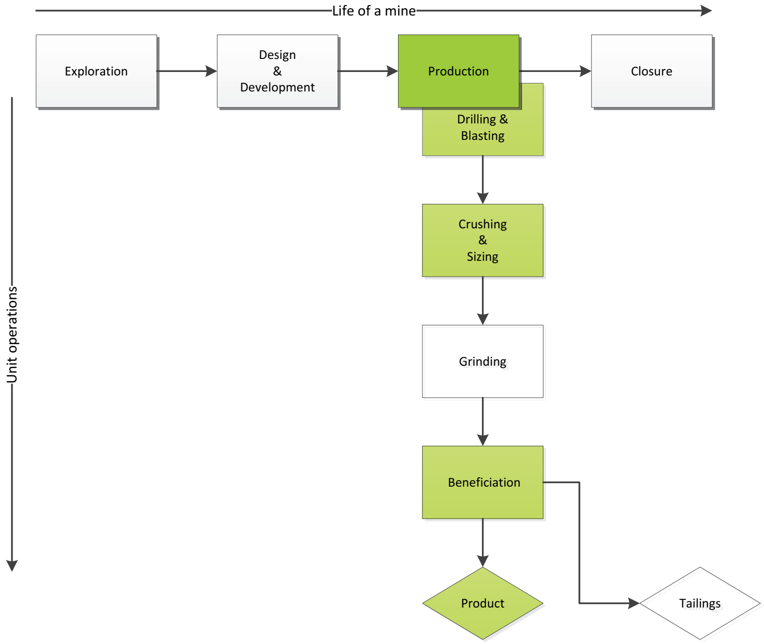


Figure 1. Geometallurgy, or elements of geometallurgy can be implemented along life of a mine as well as along unit operations. The processes addressed in this thesis are related to a mine in production phase and are highlighted in green.

Chapter 2: Background

2.1 *Geometallurgy*

Geometallurgy is a cross-disciplinary approach to mining and mineral processing, where the geological information is merged with processing information along the value chain to gain a better knowledge of the orebody, to increase the mine performance and to lower the risk factors. The term geometallurgy was first used around 1970 (Hoal, 2008) but came into common usage around 2000 and onwards (Williams, 2013).

There are several definitions of geometallurgy, depending on the broad or more specific view on the matter. The narrow view focuses on understanding the relationships between geology and mineral processing (Bowell et al., 2011), while geometallurgy in the broadest view incorporates environmental and economic factors (SGS, 2019). The view on geometallurgy may also vary depending on the ultimate goals of the geometallurgical approach. The aim may vary from the ore recognition and increased information availability along the value chain, to establishing fully predictive georeferenced models. Dominy et al. (2018) distinguish "classical" geometallurgy as a collaboration of geology and process mineralogy teams for a better understanding of the orebody, and "modern" geometallurgy that goes beyond the "classical" view by integrating geology, mining engineering, metallurgy, mineral economics and geoenvironmental parameters to create predictive 3D block models. The geometallurgical framework was conveniently shown by Jackson et al. (2011) where several important aspects were presented together with different levels of applications. The application of geometallurgy could vary from reactive understanding through process evaluation and design, to full scenario-based financial assessment. The geometallurgical approach can be used at all steps of the life of mine (LOM) and can be split into a strategic approach with the long-term LOM view, and as a short- to medium-term tactical approach (Dominy et al., 2018). The geometallurgical approach has also been applied to waste rock management (Parbhakar-Fox, 2017).

The most important factor in geometallurgy, regardless of the applied definition, is the holistic view of the mine operations along the life of mine, and increased predictability. According to Dominy et al. (2018), holistic orebody knowledge is gained through integration of:

- Core logging – i.e. collection of information on e.g. lithology, alteration, surface hardness, rock quality designation (RQD)
- Mineralogical analyses (e.g. automated mineralogy systems and X-ray micro CT)
- Bulk- and mineral chemical analyses
- Physical testing
- Metallurgical recovery – e.g. leaching, gravity recovery, floatability index

Interdisciplinary communication is a well-recognized aspect of geometallurgy. Geometallurgy as an interaction between geology, mining and mineral processing disciplines requires interaction of multi-disciplinary teams and effective information flow (Cropp, 2014, Dominy and O'Connor, 2016).

The geometallurgical approach to mining uses solutions like geometallurgical tests, geometallurgical modelling, process mineralogy, proxies, statistics and geometallurgical domaining of the orebody. The recent progress in geometallurgy is driven by factors like advances in analytical techniques or computing power (Dunham et al., 2011).

The ore characterization combined with laboratory metallurgical testwork leads to the creation of the geometallurgical model, which should aid in updating or reviewing the resource model and mine plan (Sola and Harbort, 2012). A geometallurgical model is a georeferenced predictive tool to be used in planning and management along the mine value chain (Lamberg et al., 2013). A geometallurgical program is a way to establish a geometallurgical model and is performed through geometallurgical operations. According to Lischuk et al. (2015), a geometallurgical program is defined as an industrial application of geometallurgy. Geometallurgical testwork leads to assigning geometallurgical domains that are types of rock having similar processing properties (Deutsch et al., 2016, Gregory et al., 2013).

2.2 Carbonate raw materials

2.2.1 Industrial minerals

Industrial minerals are usually defined as any rock or mineral of economic value excluding metal ores, fuels and gemstones (Harben and Bates, 1990). This definition extends also to those metallic minerals that are exploited and processed for the use of their non-metallic content, for example ilmenite and bauxite (Kogel et al., 2006). In Norway, the definition of industrial minerals is narrower , and does not comprise construction materials and dimension stone (NGU, 2015).

2.2.2 Carbonate raw materials

Carbonate rocks include limestone, chalk, marble, travertine, shells, vein calcite, aragonite sand, dolostone and carbonatite. Of those, most are sedimentary rocks, while carbonatite is an example of igneous rock and marble of metamorphic rock. The common feature is the major (50 – 100%) content of carbonate minerals. The most typical chemical compound is calcium carbonate (calcite, aragonite) $CaCO_3$, or calcium magnesium carbonate (dolomite) $CaCO_3 \cdot MgCO_3$ (Haldar and Tišljar, 2014).

Deposits of carbonate raw materials are carbonate rocks or minerals that have favorable chemical and/or mineralogical characteristics allowing for specific industrial usage (Harben, 2002). Carbonate rocks are usually available at low cost and have a broad range of industrial applications both for their physical and chemical characteristics. Most commonly they are used as aggregates, dimension stone or ground calcium carbonate (GCC). The ground calcium carbonate is used in paper production as filler, as pigment in plastic production, as coating, adhesives and sealants, and as pharmaceuticals and abrasives (Carr and Frederick, 2014).

Carbonate rocks are also a source for chemical lime (CaO) that is a calcined form of calcium carbonate, whose main use is neutralization, coagulation, causticization, dehydration, and absorption. One of the main roles of quicklime is production of PCC (precipitated calcium carbonate) that is used as a coating and brightening agent in paper production, a strengthening agent and pigment in plastic and rubber production, an absorption agent in paints, a soil stabilizer, a desiccant , and a reaction agent in carbonates and hydroxides for the production of calcium-based chemicals (Harben, 2002). In metallurgy, and in the glass and ceramics industry, carbonate compounds act as a purifying- and flowing agent. In environmental applications, calcium carbonate is used as organic sulfur neutralizer and SO_2 emission control (Mineralstech, 2015).

2.2.3 Theory of calcination

Calcium carbonate is calcined at high temperatures in shaft or rotary kilns to obtain calcium oxide (CaO), commonly known as quick lime or burnt lime. Quick lime is created via the reaction:

$CaCO_3$ + Heat → CaO + CO_2

Three conditions must be fulfilled during production:

- The rock must be heated to the temperature of carbonate dissociation
- This temperature, and in practice, a higher temperature, must be maintained for a certain period of time
- The CO_2 gas that is released during reaction must be removed.

Decomposition of $CaCO_3$ into quick lime is an endothermic reaction with a heat consumption of 178 kJ/mol (Rodriguez-Navarro et al., 2009). It needs a temperature of 898°C at 760 mm Hg pressure and 100% CO_2 atmosphere. The dissociation temperature is higher at higher CO_2 pressure. The decomposition occurs from the surface to the center of the rock lumps and from the surface to the center of a single grain (Boynton, 1966). CaO crystals form after decarbonization. The phase transformation was studied and described by Rodriguez-Navarro et al. (2009). The research showed that the dissociation process is influenced by the chemistry, physical properties and conditions during sedimentation or metamorphism of the rock. A medium to strong correlation was found between calcite crystal size and decarbonization heat, with influence of rock microstructure-related diagenesis (Všianský et al., 2019). Hedin (1954) conducted a series of experiments showing significant differences in the CO_2 liberation rate, and hypothesized that in limestones with dense, coarse microstructure, CO_2 diffuses through the crystal lattice at a slower rate. Details about lime technology was summarized by Boynton (1966) and Oates (2008).

2.3 Industrial minerals in Norway

In Norway, industrial minerals are an important sector in mining. They constituted 15% of the total raw minerals turnover in 2018 (DirMin, 2019). The most mined industrial minerals and rocks are carbonates (calcite and dolomite), olivine, quartz, ilmenite and nepheline syenite (NGU, 2015). Norway produces 6-7 Mt/a of calcitic marble, limestone and dolomite, and is Europe’s major producer of calcium carbonate for the use as GCC. The deposits are mostly calcite and dolomite marble with one exception of low-grade metamorphosed limestone. They are used for agricultural purposes, fillers, raw material for GCC production, and as raw material for lime and cement production.

The industrial mineral sector in Norway was addressed by the two other work packages of InRec research project. The research on Brønnøykalk AS calcite deposit and Sibelco Stjernøy AS nepheline syenite deposit is summarized in Vezhapparambu et al. (2018) and Mena Silva et al. (2018). The differences between the industrial mineral and metaliferous mining in a geometallurgical perspective were discussed by Aasly and Ellefmo (2014).

2.4 Fieldwork area

This PhD focuses on the Verdalskalk AS open pit carbonate raw material mine and furnace plant located in mid Norway in the municipalities of Verdal and Inderøy. The mine operates on the Tromsdalen calcite marble deposit (Figure 2).

2.4.1 Geological setting

The Caledonides of central Norway comprise volcano-sedimentary successions of the Lower and Upper Hovin and Horg Groups (Roberts et al., 1984). The Tromsdalen marble deposit belongs to the Hovin Group of the upper Allochthon within the Trondheim region (Norsk Kalkforening, 2005), and is a Middle Ordovician unit (460 Ma) of low-grade metamorphism caused by the Caledonian orogeny (Gautneb, 2012, Korneliussen et al., 2014).

The Tromsdalen area is a part of an overturned fold where the units are inverted compared to the stratigraphic order of their protoliths. The unit underlying the marble is classified as greenstone and greenschist with local transition to amphibolite, while the unit overlying the marble is defined as greyish-green phyllite and calc-phyllite, locally interlayered with metasiltstone, metasandstone and tuff. The marble unit is also referred to as metalimestone (NGU, 2019). The units have an approximate dip of 35-55° towards the southeast in the area of the pit.

The marble is generally a medium to light grey fine crystalline marble. The deposit is regarded as very pure, having approximately 55% CaO (with stoichiometric calcite having 56.03% CaO) and impurities that are present in the deposit consist of Fe-oxides and hydroxides, pyrite, quartz, mica and chlorite (Gautneb, 2012). Some parts of the rock appear darker due to some content of finely dispersed graphite (Korneliussen et al., 2014).

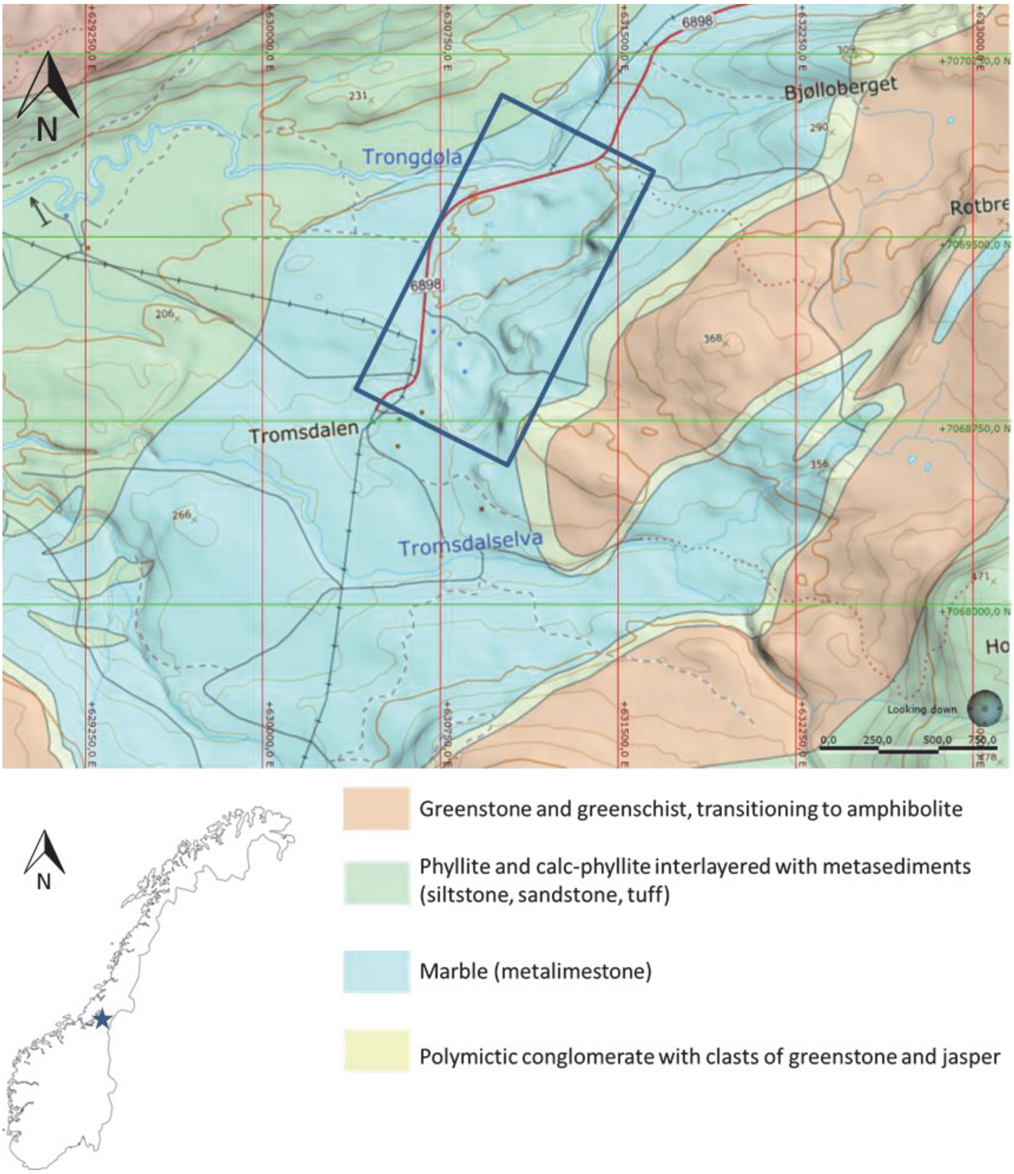


Figure **2**. Geological map of the Tromsdalen area with location on the map of Norway. The blue rectangle marks the current pit area (NGU, 2019).

2.4.2 Operation

The Verdalskalk AS operation consists of three facilities: Tromsdalen, where a pit (Figure 4A), a crushing and screening plant and a main laboratory is located; a plant in Hylla, where the raw material silos, storage, a kiln, product storages, drill core archive and an on-site laboratory are located; and a harbor in the municipality of Verdal, where products are stored and shipped to customers.

The Tromsdalen deposit is operated as an open pit mine with current dimensions 850 x 500 meter. The lowest pit floor is 165 meter above sea level. The yearly production is about 1.4 million tonnes of marble and the expected remaining lifetime of the mine is approximately 70 years (Rojas Ruiz, J., pers.com. 10.07.2019).

The company divides the raw marble into 6 subtypes based on characteristics given in Table 1 (Rojas Ruiz, J., pers.com. 10.03.2015). The characteristics are related to color and purity by visual inspection.

Table 1. Visual characteristics of the raw material types

Type	Characteristics
K1	Light grey, pure
K2	Dark grey, pure
K3	Dark grey, impure
K4	Light grey, impure
K5	Black, pure
K6	White, impure

The schematic value chain is presented in Figure 3. Drilling (Figure 4B), charging and blasting are used to detach the rock from the orebody and to fragment the raw material. The production blasts (Figure 4C) are then assigned to three qualities: pure, standard and cement, depending on the weight percent of CaO and impurities (Table 2). The rock is used either as kiln feed in production of PCC (pure and standard quality) or as cement raw material when the impurities exceed desired levels.

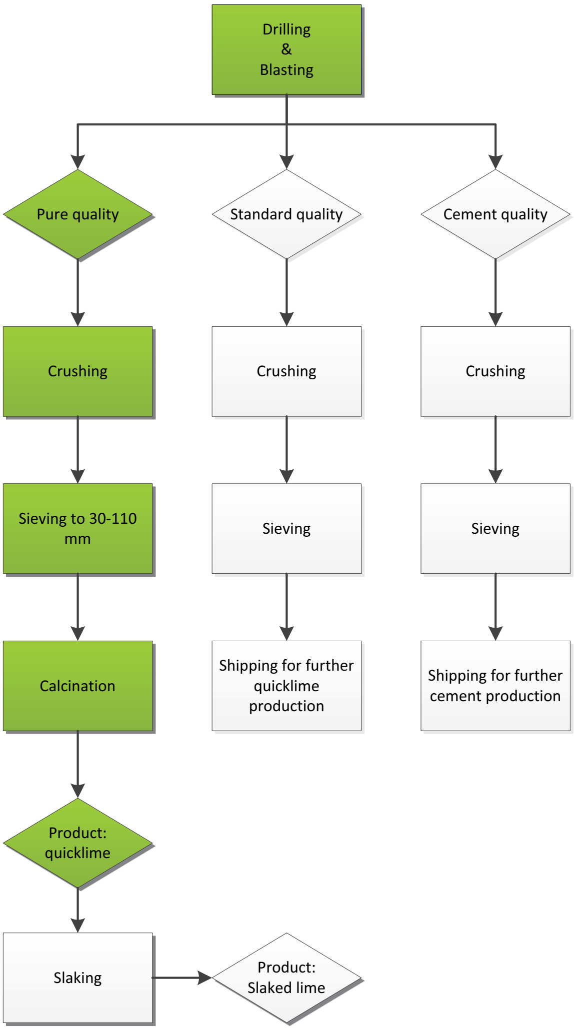


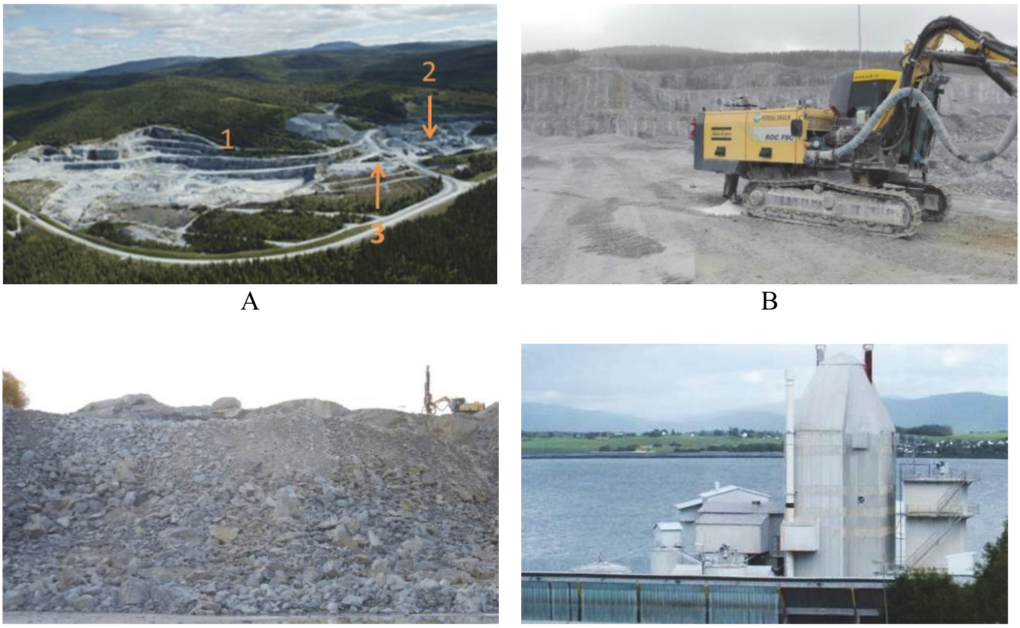
Figure 3. A schematic presentation of Tromsdalen calcite operation. The company's main value chain (highlighted in green) is the main focus of this research.

Table 2. Raw material quality requirements. The pure quality is used as kiln feed.

Oxide (wt%)	**Pure**	**Standard**	**Cement**
CaO	>54.5	> 54.0	>50.4
MgO	<0.6	No requirements, given the purity of the deposit	
SiO_2	<0.5		
Al_2O_3	<0.2		
Fe_2O_3	<0.06	0.06-0.12	>0.12
Na_2O	<0.015	No requirements, given the purity of the deposit	
K_2O	<0.04		
MnO	< 0.005		
P_2O_5	<0.04		
TiO_2	<0.01		
SiO_2	< 0.5		
SO_3	< 0.02		
$CaCO_3$	>97.3	96.4-97.3	>90.0

The crushing is performed on site, with the use of jaw crushers and two crushing lines. The current output size of material for the PCC production is 30 – 110 mm. The pure quality material is then transported to the Hylla plant where the crushed rock is stored and fed to the vertical 2-shaft Maerz furnace (Figure 4 D). The rock is calcined in temperatures reaching 1000 – 1200°C inside the burning zone (Storli, A.M., pers.com. 07.03.2015). The burnt lime is processed to a variety of different sizes ranging from 0 – 0.2 mm to 0 – 40 mm (Mork, H., pers.com. 20.02.2018). Apart from burnt lime, hydrated lime (calcium hydroxide, slaked lime) is also produced on site.

The standard quality raw material is transported to a kiln operated by a different company with less tight purity requirements of the raw material feed. The cement quality raw material is sold to customers or transported to the Verdal harbor for onward shipping. The quality control in the mine is performed at every step of the value chain and includes XRF analysis of chemistry on drill cuttings prior to blasting, XRF analyses of the raw material after blasting and particle size distribution (PSD) quantification of crushed material prior and after screening. On one specific type of product, a Whiteness Index measurement is carried out. The produced quicklime is tested on CaO activity and CO_2 residue, particle size and its distribution and loss on ignition (LOI) and major element XRF analysis. In case of slaked lime, PSD, CaO activity, soundness, free water and particle density analyses are performed (Landsem, R., pers.com. 06.03.2015).



A B

C D

Figure 4. Verdalskalk AS operations. A: the Tromsdalen facility (1: the open pit area; 2: the crushing and screening plant; 3: main office); B: the drilling rig disposing the drill cuttings that are used in quality control, C: a production blast at the Tromsdalen open pit mine, D: a vertical kiln at Hylla, used for calcination.

Chapter 3: Materials and methodology

3.1 Overview

The challenge typically addressed by geometallurgy is insufficient knowledge of the relationships between geological and mineral processing parameters. Additionally, geometallurgical approach should aim at improving communication of full material characteristics along the mine value chain and back to the deposit block model. Therefore, research conducted during several fieldtrips was carried out to understand the possible challenges present in the Verdalskalk AS mine. A field study consisted of in-situ and blasted rock observations and sampling (Figure 7 A, B and E) and inspection of all mine facilities. Visits to the open pit, crusher facilities, main laboratory, kiln and kiln laboratory were followed by consultations with the mine geologist and laboratory staff. This investigation was essential to obtain the necessary knowledge of the raw material variations, mine value chain, its possible bottlenecks, information flow regarding the quality control and sampling methods. Once the challenges were identified, the research encompassed sampling and data collection, laboratory work and literature study.

Deposit sampling and mineralogy descriptions as well as in-situ surface hardness measurements were used in paper I. Paper II encompassed information collected during several visits to the facilities, long-term data collection and geometallurgical literature study. Results of paper I were also important for the development of paper II.

Conclusions from paper I together with extensive drill core logging were used in the work for paper III. The overview of the methodology used for the articles is presented in Figure 5.

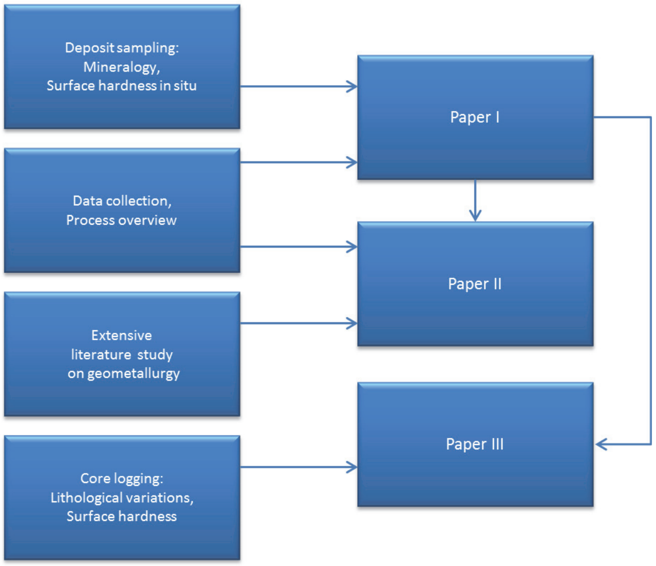


Figure 5. Schematic presentation of the methodology and paper information inputs.

3.2 Microscopy

For the microscopy study, 75 hand specimens were collected from different parts of the pit, both in-situ and from production blasts during several sampling campaigns. A total of 75 thin sections were prepared by NTNU, University of Warsaw and Miekinia Lab company.

The methodology of research consisted of optical microscopy, both transmitted and reflected light mode to observe textures, mineral assemblage, and grain size of the samples; some samples were additionally examined in SEM. BSE observations and EDS semi-quantitative microanalysis was performed on part of the samples to confirm the light microscopy observations. Light microscopy and SEM studies were performed at NTNU. The main focus of the research was the comparison of mineralogy and textures in four production blasts that comprised two different marble types (K2 and K5). The details are provided in Lang et al. (2018b).

3.3 Surface hardness tests

The surface rebound hardness tests were performed with the use of a portable Proceq Equotip 3D device. The Equotip device measures rebound hardness during rock indentation, by calculating the ratio of rebound velocity to the impact velocity of an impact body (Proceq, 2017). The unitless values are presented as Leeb's hardness number (HL).

The tests consisted of in-situ measurements in the deposit and drill core measurements with the use of single impact method (Aoki and Matsukura, 2007). The in-situ Equotip measurements were performed on fragmented rock, after blasting (Figure 7 C, D), at several locations in the deposit. A total number of 110 sample surfaces of 10 production blasts of marble types K2 and K5 were tested. The details are provided in Lang et al. (2018b).

The drill core tests were carried out at the Verdalskalk drill core magazine at Hylla (Figure 7 F). A total length of roughly 370 meter of drill core was tested along with the visual logging of the core. The methodology for retrieving the information from the drill cores was by creating variograms showing the spatial dependencies of the sampling points. A variogram is commonly used to quantify the spatial continuity of a regionalized variable (Chiles and Delfiner, 2009). The details are provided in the paper III manuscript.

3.4 IDEF0 and conceptual work

For the geometallurgical flowsheet design in paper II, an IDEF0 methodology was used. IDEF0 (Integration Definition for Function Modelling) is used to represent functions, activities or processes within the modeled system in a structured way (NIST, 1993). It serves as a modelling technique for the analysis, development, and integration of systems, business processes or software engineering analysis (DAU, 2001). A basic IDEF0 diagram consists of a central function, encircled by four elements: an input, output, control and mechanism (Figure 6). Attempts to use the IDEF0 technique in mine planning and management are known from previous studies (Heather et al., 2005). In the research presented here, the IDEF0 methodology modified by Lund et al. (2001) was used for the geometallurgical flowsheet development. Further details are provided in Lang et al. (2018a).

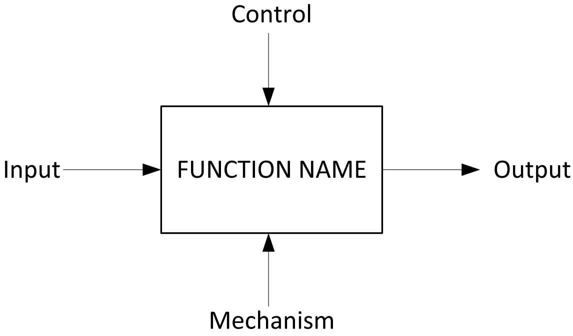


Figure 6. A basic IDEF0 diagram. A function (a process), an input that is transformed to output, a control of the function, and a mechanism supporting the function are main components of the IDEF0 language.

3.5 Additional research

Additional research was conducted to explore the possibilities of implementing a geometallurgical approach to Verdalskalk operations and to improve understanding of the deposit. The research comprised the TOC analysis of the chosen types of marble and long-term logging of some of the operation parameters to observe possible trends over time. The results were not published; however, they contributed to the geometallurgical flowsheet development.

3.5.1 Total organic carbon content measurements

16 samples from different production blasts and of marble type K2 and K5 (Table 3) were chosen to measure the total organic carbon content (TOC). The inorganic carbon present in $CaCO_3$ molecules was removed by treating samples with dilute hydrochloric acid. Next, the material was burned in a LECO furnace and total carbon content was measured by infrared gas analyzer. The measured parameter is defined as Total Organic Carbon and represents the amount of both organic carbon and graphite. TOC is a good estimate of graphite content in samples where organic carbon is not present.

Table 3: Samples chosen for the total organic carbon content measurement.

Sample signature	Marble type
1.28/3	K2
2.28/3	K2
8.17/2	K5
5.26/3	K2
6.26/3	K2
11.17a/2	K5
11.17b/2	K5
11.17c/2	K5
3.19a/2	K5
3.19b/2	K5
VB33.1/4	K2
VB33.2/4	K2
VB33.3/4	K2
VB35.1/4	K2
VB35.2/4	K2
VB35.3/4	K2

3.5.2 Log data

Part of the study was dedicated to investigation and comparison of existing information obtained from the plant, at different stages of the value chain, in order to find variables that can be potentially used in the geometallurgical modelling. The research consisted of:

- Logging the PSD of the crushed raw material
- Logging the PSD of the crushed material with regard to the blast direction
- Logging the PSD of the kiln feed
- Logging the measurements of CO_2 residue in quicklime

All the measurements were conducted by the company. The long-term logging, interpretations and comparisons were done by the thesis author. The logging, together with the results presented in paper I set the basis for the case-specific geometallurgical flowsheet development in paper II.

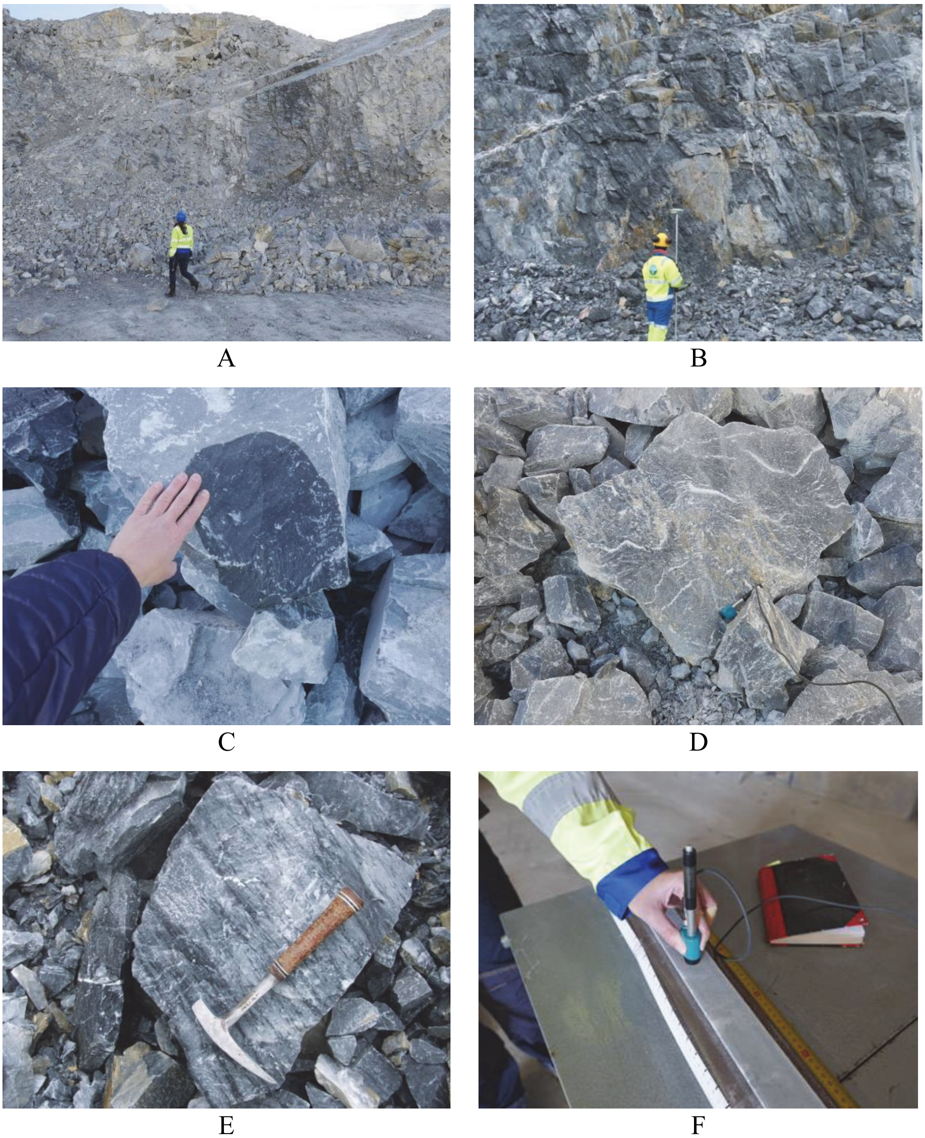


Figure 7. Fieldwork at Verdalskalk AS. A-B: sampling in the pit and geo-localizing the samples; C-D: Equotip in-situ measurements on a clean rock surface; E: macroscopic observations; F: Equotip logging of the drill core.

Chapter 4: Summary of results

4.1 Paper I

Mineral characterization as a tool in the implementation of geometallurgy into industrial mineral mining

Aleksandra M. Lang, Kurt Aasly and Steinar L. Ellefmo

Published in Minerals Engineering 2018; Volume 116. s. 114-122

Authors' contribution:

Aleksandra Lang was a lead author and she contributed with investigation, data acquisition, writing, reviewing and editing of the original draft. Kurt Aasly contributed with conceptualization, editing, supervision and funding acquisition. Steinar Ellefmo contributed with editing, supervision and funding acquisition.

The geometallurgical investigations at Verdalskalk established relationships between different raw material properties through the mining value chain linking them to the processing performance of raw material. One of the main problems reported by the company was an unstable burning process of a specific marble type even though the geochemical characteristics were satisfactory. The kiln performance may be related not solely to chemistry of the rock, but also to petrological characteristics like texture, porosity or grain size (Boynton, 1966). Therefore, the objectives of the research were to describe and compare the mineralogical and textural characteristics of two chosen marble types (K2 and K5) used for the PCC production to examine whether despite similar bulk chemistry the two types have textural differences. A second objective was to conduct surface hardness in-situ tests for both types of marble and to define potential links between textural properties and surface hardness values. As part of the research, the appropriateness of the Equotip 3D device as a cost-efficient easily-accessible geometallurgical tool was tested.

For the mineralogical and textural study four production blasts were chosen and 9 samples were taken from each blast. A thin section was prepared from each sample. The thin sections were investigated using light microscopy. Additionally, SEM observations were performed.

Parameters including typical grain size, grain boundary shape, other textural features and accessory minerals were described for every sample. Calcite was reported to be the major constituent of all samples and the typical grain size ranged from 50 to 400µm. Most of the samples showed heteroblastic texture. Accessory minerals present in the samples were pyrite, graphite, iron hydroxides, quartz and muscovite; these minerals constituted less than 1% of the sample area in thin sections. During SEM imaging, apatite and Titanium oxide were also identified. For marble type K2 the typical grain size was within a range of 50 to 400µm, but grains as large as 3 mm were also noted. For marble type K5 the typical grain size was in the <50 – 200µm size range (Figure 8). Pyrite was present in both types of marble, whereas quartz grains were noted only in type K2. Type K5 contained more graphite. In both types of marble, a texture of microcrystalline calcite on the rims of larger grains was observed.

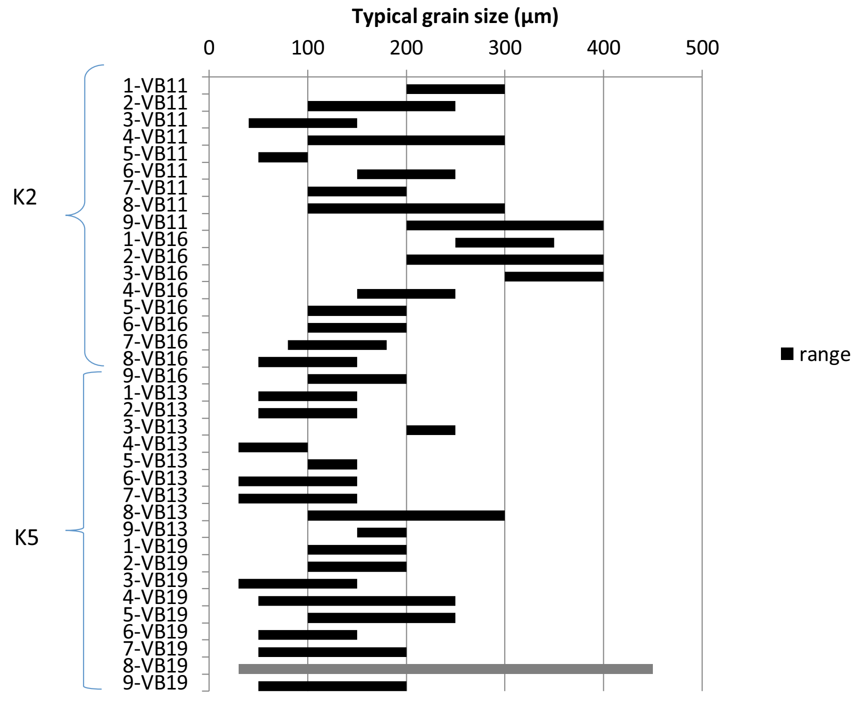


Figure 8. Typical calcite grain size ranges in two types of marble: K2 and K5. Sample 8-VB19 was very heterogenous and no typical grain size was observed.

For the surface hardness study, a total of 110 sample surfaces belonging to 10 production blasts were tested with the Equotip 3D portable device in the pit. The single impact method (SIM) was applied and the L_{max} results (an average of the three highest readings per surface) were reported along with the standard deviation, average standard deviation and measurement uncertainty (based on a standard deviation of the three highest readings).

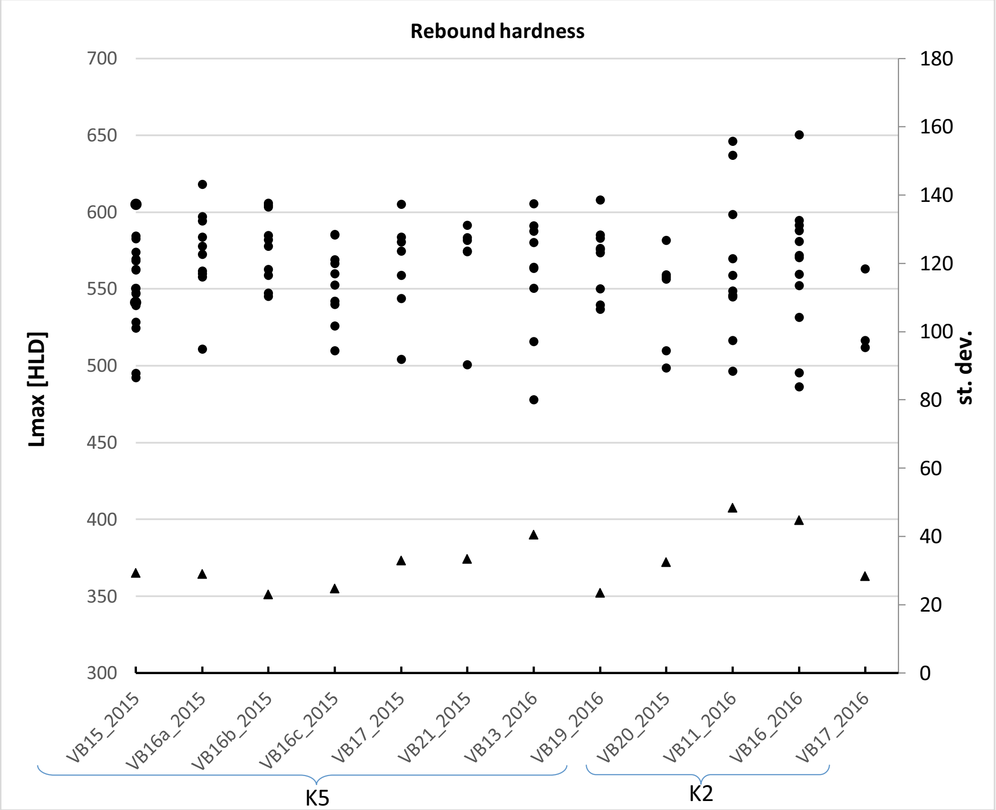


Figure 9. Surface hardness tests results. Dots refer to the left-hand axis and present L_{max} values for each blast. Triangles refer to the right-hand axis and represent the standard deviation of results for each blast.

The surface hardness study revealed that the average values of the surface hardness of the two marble types were comparable; however, highest L_{max} values were obtained for type K2 (Figure 9) It was interpreted as related to coarser grain size and higher silica content in type K2 comparing to K5. Differences within the standard deviations for the two types were observed, with the K2 marble showing more variable results. The results were interpreted as dependent on the changing K2 mineralogy and presence of fractures filled with iron oxides that are related to lower L_{max} values. In case of type K5 relationship between mineralogy and L_{max} values was more difficult to establish. It was recommended that more Equotip tests are made to establish better links between internal structure of the marble and surface hardness values.

4.2 Paper II

Geometallurgical flowsheet as a tool for designing and communicating geometallurgical programs

Aleksandra M. Lang, Steinar L. Ellefmo and Kurt Aasly

Published in Minerals 2018, 8*,* 372.

Authors' contribution:

Aleksandra Lang was a lead author and she contributed with investigation, data acquisition, writing, reviewing and editing of the original draft. Steinar Ellefmo contributed with conceptualization, editing, supervision and funding acquisition. Kurt Aasly contributed with conceptualization, editing, supervision and funding acquisition.

The research presented in paper I along with literature study and geometallurgical investigations at the mine site led to the creation of the geometallurgical flowsheet, which was the main result of paper II. The main objectives of paper II were the definition of the geometallurgical flowsheet concept, clarification of the geometallurgical model definition, clarifications of the relationships between the geometallurgical program, geometallurgical flowsheet and geometallurgical model and the mining value chain, and assessment of the use of the IDEF0 business modeling technique in geometallurgical flowsheet design.

The IDEF0 technique is designed to model actions and decisions within a system using a combination of graphic and text. The two primary components are functions (processes) and objects belonging to four categories: inputs, controls, mechanisms and outputs.

The flowsheet was defined as a tool for designing and communicating a geometallurgical program in order to establish a geometallurgical predictive model. It was proposed to be used on site, for enhanced communication between specialists and between operators and management.

In addition, a literature study allowed for setting up a theoretical background for the flowsheet creation. The geometallurgical model definition was specified as a function that links georeferenced in-situ geological characteristics and georeferenced measure of performance in a processing plant, emphasizing the positioning of the geoscientific data. The dependency can be qualitative or, preferably, quantitative and takes the form of an equation:

Performance measure = f(x,y,z, var1, var2, var_n), where *x*, *y*, and *z* are the spatial coordinates in the mine.

The literature study led to the conclusion that there are inconsistencies in the terminology especially in terms of the relationship between geometallurgical model and the geometallurgical program. The authors clarified this by stating that a geometallurgical model is the outcome of the implementation of a geometallurgical program that consists of a number of working processes. To overcome literature inconsistencies, the term *a priori model* was introduced in the paper to describe a primary ideal model that is checked and validated during the execution of a geometallurgical program.

A general geometallurgical flowsheet using the IDEF0 methodology was proposed as a central process of geometallurgical model development with an *a priori* model as the main control. In the next step of the theoretical flowsheet the central function was broken down to "Build geometallurgical model, validation decision and reconcile model function". In a next step, the build geometallurgical model function was broken down to three functions of sampling, testing and analyzing and developing equations.

In the case-specific geometallurgical flowsheet the *a priori* model for Verdalskalk AS was proposed as:

- *Raw material textural and mineralogical characteristics = f(x,y,z, surface hardness)*
- *Quicklime activity and* CO_2 *residue = f(x,y,z, raw material textural and mineralogical characteristics, kiln feed PSD, burning parameters)*

The sample function was proposed to be broken down to three functions of sampling in the pit, sampling at crushing plant and sampling at the kiln site.

The test and analyze function was proposed to comprise five main child processes that gather data from 5 processes, namely: 1. Thin section analysis, 2. Surface hardness measurements, 3. Screening and weighing for the kiln feed PSD estimation, 4. Milling and laboratory testing for the main product characteristics, 5. Logging the burning parameters (Figure 10). The main output of this part of the flowsheet was all the data collected during testing and analyzing process.

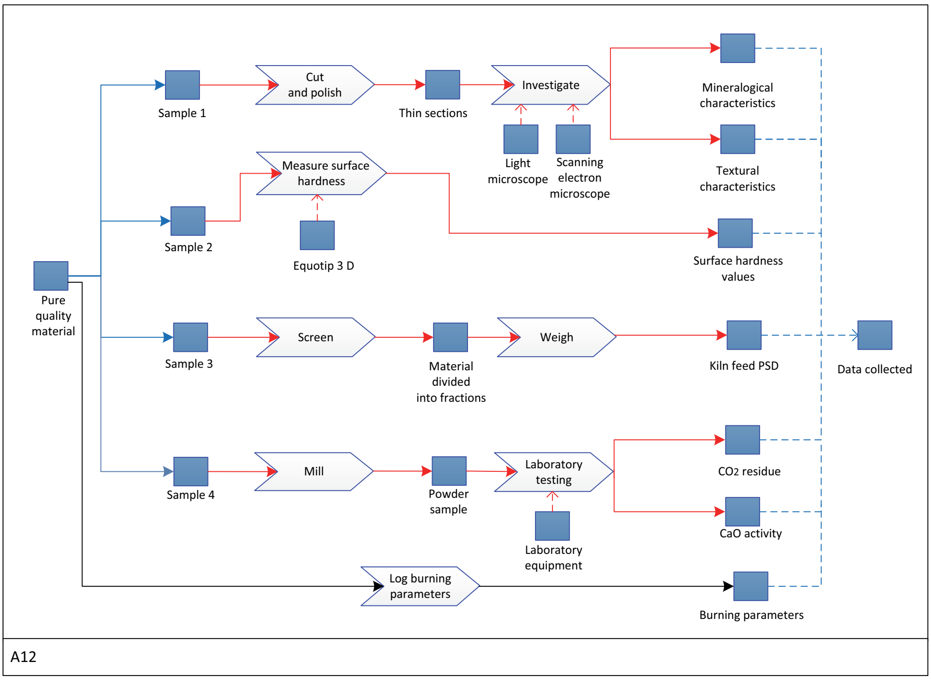


Figure 10. An example of the IDEF0 diagram that shows the "test and analyse" function broken down to a more detailed diagram. The functions are depicted as chevron-shapes. The four samples are taken at different stages of the mining operation.

The process of developing equations was proposed to comprise a set of sub-processes such as calculation of summary statistics, regression analysis and performance of quantitative and qualitative analysis. The output of the sub-processes was proposed to be qualitative and quantitative models that together are the main output of the geometallurgical model.

It was proposed that the geometallurgical model was the main control of the blast specific KPIs estimation, and in this way the relationship of the geometallurgical model to the mine value chain was explained and illustrated.

It was concluded that the IDEF0 methodology is a tool that supports the idea of enhanced interdisciplinary communication, and that the flowsheet built with the used of IDEF0 was an easy to understand, coherent and intuitive tool. The case study of Verdalskalk showed potential in applying the geometallurgical solutions to industrial mineral mining.

4.3 Paper III

Application of rebound hardness testing to assess spatial lithological and textural variations of calcite marble

Aleksandra M. Lang, Steinar L. Ellefmo and Kurt Aasly

Manuscript, unpublished

Authors' contribution:

Aleksandra Lang was a lead author. She contributed with investigation, data acquisition, writing, reviewing and editing of the manuscript. Steinar Ellefmo contributed with conceptualization, editing, supervision and funding acquisition. Kurt Aasly contributed with editing, supervision and funding acquisition.

In Paper III the idea of using the Equotip 3D as the geometallurgical testwork tool was explored. Chosen drill cores from the Verdalskalk archive were logged and surface rebound hardness was measured. The discrimination of rebound hardness classes based on different characteristics of marble types can contribute to geometallurgical domaining of the deposit. The main objectives were:

- To investigate the spatial characteristics and statistical properties of surface hardness for different marble types
- To explain the variations in surface hardness and thereby demonstrate spatial mineralogical and lithological variation
- To discuss the use of surface hardness measurements as a proxy for rock type variations in a geometallurgical perspective
- To assess the usefulness of the Equotip 3 D surface hardness tester applied to different drill core diameters.

A total length of 371.14 m of drill core comprising 3 whole drill cores and 3 core fragments from the Tromsdalen deposit were used in the research. The sample cores and core fragments were first logged and grouped into fourteen types based on observations, previous company logs and the company chemical assays. The rock was classified according to mineral assemblage, color, fabrics and mesotextures, and chemical assays into ten marble types (M), two greenstone types (G) and two phyllite types (P) where the "greenstone" and "phyllite" terms were used for simplicity for greenstone- and phyllite-contaminated marble.

Next, the drill cores were tested with an Equotip 3 D rebound hardness tester, using the single impact method in 2 cm intervals. The raw rebound hardness data, presented as HL unitless values, was then subjected to statistical analysis with the use of Leapfrog Geo software. Three standard deviations of a mean were used as a cut-off value to exclude erroneous records. Then the Leapfrog software was used to calculate summary statistics and to create histograms and downhole sample variograms.

The statistical data showed major differences between marble (M) and non-marble (G and P) groups. The mean HL value was highest for marble and lower for phyllite and greenstone. The standard deviation was highest for greenstone, lower for phyllite and distinctly lower for marble.

Within pure marble types (M) the highest rebound hardness values were obtained for types M10 and M8, both characterized by the presence of dispersed graphite. The lowest values were obtained for types M1 and M2 that are white to greyish impure coarse-grained calcite. This suggests that the grain size and other internal rock characteristics has an influence on the HL values not less than the mineral assemblage. The greenstone (types G1 and G2) was generally softer which was interpreted to be caused by the presence of schistose foliation, pyrite, chlorite and epidote.

The highest standard deviation of the results that is an indication that non-homogenous rock was present in type P1 followed by types G1 and G2. The high type P1 standard deviations were interpreted to be caused by the presence of both very soft material (phyllitic, dark foliated interlayers) as well as very hard calc-silicate veins.

Most of the histograms for the marble types show a normal distribution, with a slight left-skewness. The left skewness was observed even when the left-side outliers were removed. In all marble types except of one, the mean was below the median supporting the skewness observation. The type M7 was an exception, because the histogram showed bimodality, while presenting a very similar mean and median.

The study comprised the comparison of variograms created for each marble type. The highest sill, hence highest variance of the HL values, was observed in P1, G1 and G2 types. Variance is a measure of the spread of the values, indicating a level of homogeneity/heterogeneity of the measured surface. Within marble types (M) the variance was higher for coarser-crystalline marble M1, M2, typical grey marble M3 and M4 and marble with “rice grain” texture (M7). Lower variance, related to less spread HL values and more homogenous characteristics, was noted for the “zebra” texture marble (M8) and dark marble with strong lamination of white marble.

The nugget effect is related either to the variations on a micro scale or the measurement error. The pure nugget effect (relative nugget of 100%) was observed for type G2, meaning that there is no spatial correlation between points in G2. Some of the variograms showed more than one structure, which means reaching more than one sill at more than one range, and this was interpreted as related to textural changes at different scales along the core.

The differences in sill, nugget effect and range allowed for observations of discrete characteristics not accessible when analysing raw numerical data only. It was concluded that the mineralogical or textural domains, with the use of visual logging, rebound hardness data and variable spatial correlation characteristics as proxies, can in future be established and used for texture and mineralogy-based domains. Additionally, the knowledge of methodology of using Equotip 3 D as a geometallurgical tool was expanded. The statistical data were compared for different diameters of the drill core. A positive correlation between core diameter and mean result and between core diameter and standard deviation was found and a need for an appropriate correlation factor was pointed out, as the correction factor mentioned in the literature did not compensate for the differences in the results.

4.4 Additional results

In addition to the published journal papers and results therein, the doctoral work also consisted of additional tests and analyses, not yet published. These results shed more light on the geometallurgical approach to industrial mineral mining. The additional research consisted of: total organic carbon (TOC) measurements for variable graphite content and use of log data of processing parameters such as particle size distribution (PSD) of the kiln feed, variations in kiln feed PSD with relation to blast direction, and CO_2 residue after calcination process, in order to observe possible trends related to marble variations.

4.4.1 Total Organic Carbon measurements

The presence of finely disseminated graphite is one of the characteristic features of Tromsdalen marble (Gautneb, 2012). Fieldwork and microscope observations showed that the graphite content in the samples varies. We followed the hypothesis that the graphite content in marble can be one of the factors affecting the combustion of marble, as combustion of graphite, unlike calcium carbonate, is an exothermic reaction. Therefore, being able to observe the variations in graphite content in the deposit, and quantify the variations, would be a useful addition to current knowledge. The total organic carbon measurement is a good estimation of graphite content in samples where organic carbon is not present.

The results of the study showed that even though the chosen samples had different contents of disseminated graphite, which was possible to distinguish visually, the graphite content was below the detection level of the analysis (Table 4).

Table 4. Total organic carbon results. Even though the samples were visually different in terms of dispersed graphite content and hence color of the samples, the graphite content was below the detection level.

Sample ID	Marble type	TOC[%]
1.28/3	K2	< 0.1
2.28/3	K2	< 0.1
8.17/2	K5	< 0.1
5.26/3	K2	< 0.1
6.26/3	K2	< 0.1
11.17a/2	K5	< 0.1
11.17b/2	K5	< 0.1
11.17c/2	K5	< 0.1
3.19a/2	K5	< 0.1
3.19b/2	K5	< 0.1
VB33.1/4	K2	< 0.1
VB33.2/4	K2	< 0.1
VB33.3/4	K2	< 0.1
VB35.1/4	K2	< 0.1
VB35.2/4	K2	< 0.1
VB35.3/4	K2	< 0.1

4.4.2 Log data

4.4.2.1 The factor of material PSD and percentage of fines

The PSD is measured by the company at two stages of the operation: after the crushing and prior to calcination. In the second case, the material has already been screened to a desired lump size. However, some fines are still created during transport from the crushing plant to the kiln (Storli, A.M., pers.com. 07.03.2015).

The raw material PSD after crushing and after screening was traced during chosen periods of time to observe any fluctuations related to the rock variation. The research was not completed, as during the logging period the company has changed the size requirements for the kiln feed. However, the observations revealed that the PSD curve varied over time and that is a factor possibly affecting the kiln performance.

The crushed raw material was weighed, and PSD was logged over a time of one year (Figure 11). It is possible to observe strong fluctuations of the fines (0-40mm) percentage in the production blasts VB07 and VB09.

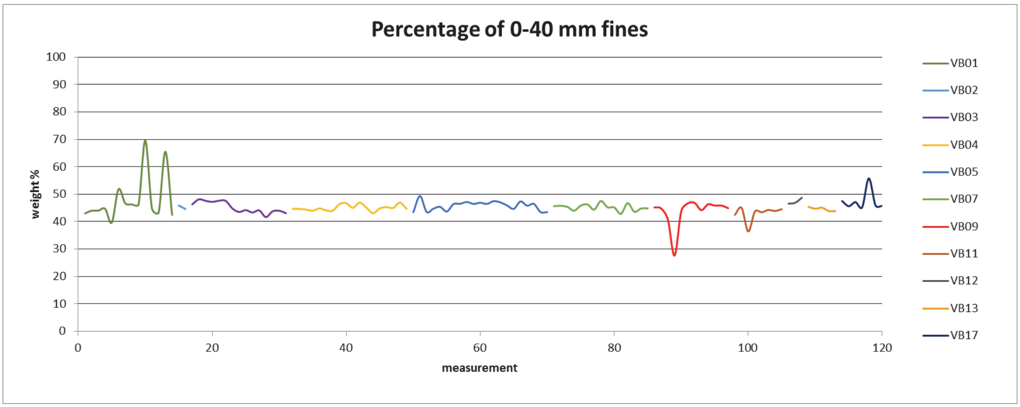


Figure 11. The weight percentage of 0-40 mm fines after crushing, measured over a period of one year. Each colour represents a separate production blast (VB).

Another factor that can be considered when discussing PSD of the raw material is the blast direction (Rojas Ruiz, J., pers.com. 10.03.2015). Depending on the relationship between blast direction and foliation direction or main fracture direction the forces of the blast may create different outcome resulting in overfragmented or underfragmented material.

In this research, some of the production blast material PSD was grouped with respect to the blast direction. In Figure 13 weight percentage of 0-40 mm fines is shown with respect to blast direction in the pit. The logging consists of measurements from 18 consecutive production blasts, taken over a 13-month period. The results showed that raw material of SW directed blasts was characterized by abrupt drops of the fines percentage followed by a long period of very stable percentage. This stability was not observed in blasts of SE and NW direction. The NE blast direction was characterized by higher percentage of the fines. However, this blast direction was logged only on a few occasions. Since the PSD measurements were not done regularly and there were issues with the weighing system, the results were not published, but contributed to the development of the case-specific geometallurgical flowsheet.

Next, kiln feed PSD measurements were logged. Figure 12 shows the 5 consecutive measurements of kiln feed PSD (crushed and screened material) taken in a period of 7 months. It was observed that the finest fraction as well as the coarsest fraction weight percentage fluctuates significantly, whereas the most stable fraction is that of 40 – 63.9 mm.

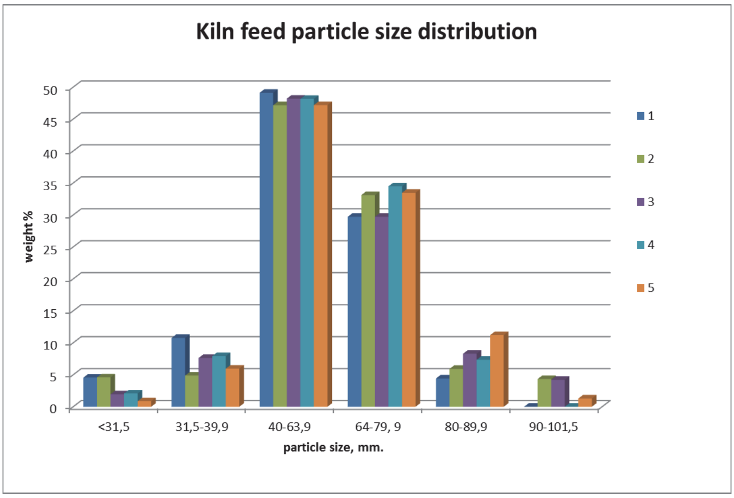


Figure 12. Kiln feed particle size distribution, five measurements taken over a period of seven months.

4.4.2.2 CO_2 residue measurements in quicklime

Long-term logging of the CO_2 residue in the quicklime showed variations with some distinctive peaks. However, no direct relationship between marble types and CO_2 residue was established. Instead, it was observed that kiln settings play a big role in the obtained results. The CO_2 residue values varied a lot when the kiln settings were not stable – for example after switching off the kiln for maintenance. Those variations are visible in Figure 14 as the highest peaks. Therefore, logging of the kiln settings on a longer time scale is suggested as one of the geometallurgical operations in paper II.

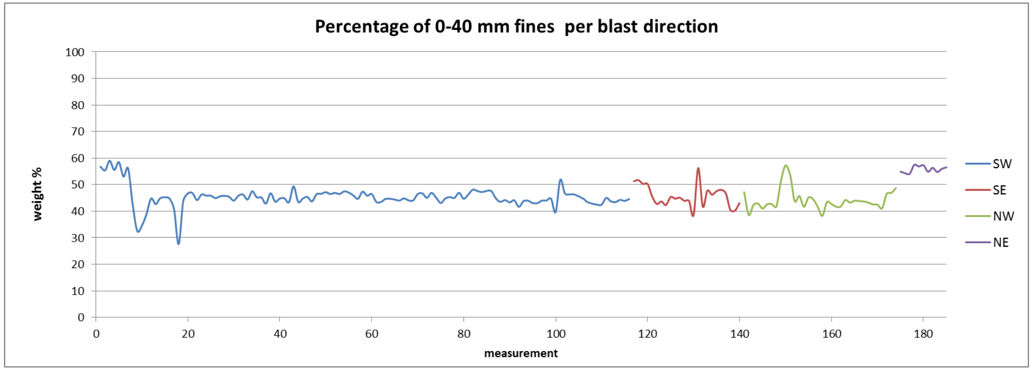


Figure 13. Log of the fines percentage pre blast direction, combined from 18 production blasts over a period of 13 months.

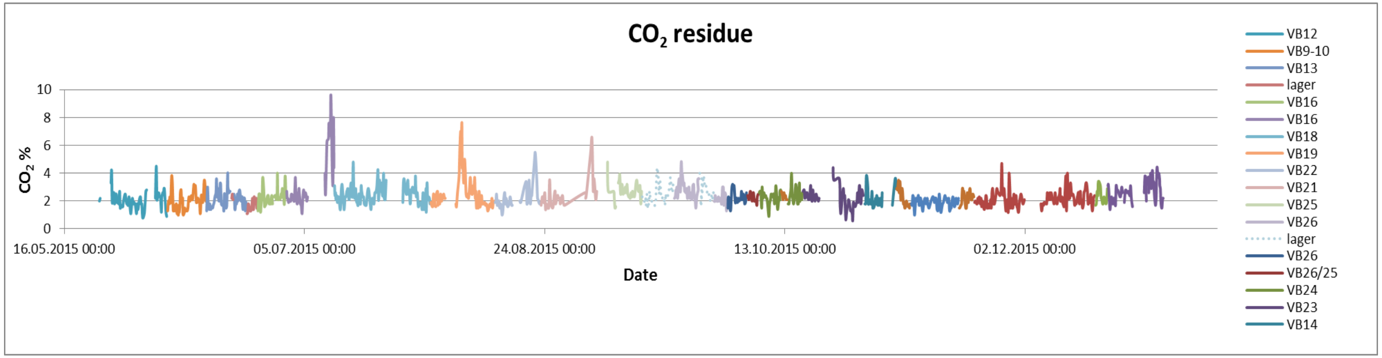


Figure 14. Long-term logging of the quick lime CO_2 residue. Each colour represents a different production blast. Note that the value can rise significantly after a stop in the production.

Chapter 5: Discussion, future work and conclusions

5.1 Discussion

The initial main objective of the current research was the development of a geometallurgical flowsheet. Even though the geometallurgical flowsheet was created during the study, the research focus evolved gradually into the broader aim of finding specific solutions for the implementation of a geometallurgical approach in industrial mineral mining.

The term geometallurgy is, at present, used mostly in relation to metal mining. Usual focuses of geometallurgy are strongly linked with minerals processing. The key performance parameters addressed by the geometallurgical modeling include liberation rate, net recovery, acid consumption (Boisvert et al., 2013). A typical objective is e.g. to link the lithological and mineralogical variations of the ore with the grinding response, using Bond Work index (BWI) tests, and Point load tests (Alruiz et al., 2009, Deutsch et al., 2016), as it is important to quantify mill throughput. Another focus is to link mineralogical data with indices for flotation and leachability (Leichliter et al., 2011).

The PhD research presented here investigates applying geometallurgy to industrial mineral mining, specifically marble mining. In the research presented in this thesis, the challenge was to redefine the geometallurgical aims, as in the case of Verdalskalk AS the raw material is not milled nor leached, and no specific minerals must be liberated from the host rock. The only beneficiation step is calcination, and the process is performed on lumps of 30-110 mm size.

Therefore, one of the research objectives was to extend the knowledge of the relationships between in-situ raw material and processing performance. The objective was addressed by the observations of the mine value chain: sampling and quality check procedures, and investigating the information flow between the raw material knowledge and final product outcomes (Figure 15). It was assumed that full understanding of the relationships and dependencies between rock in-situ and processing parameters is the key to the geometallurgical approach.

During the study, it was observed that the pure quality marble calcination is not always a stable and fully predictable process and some types of raw material are more challenging to calcine, even though they are approved for burning as "pure quality". The issues may include over-burnt material, cores of uncalcined $CaCO_3$ in the quicklime lumps caused by underburning, or quick lime lumps agglomerating. Hedin (1954) and Boynton (1966) pointed out that the raw material textural characteristics as well as the furnace process settings may create variable process outcomes. Hence it was concluded that relying only on bulk chemical analysis conducted by the company to split rock types into production qualities is not informative enough and does not fully predict the process behavior. Hence, the mineralogical research on two chosen types of marble was conducted to check for factors other than bulk chemistry that may affect the kiln performance.

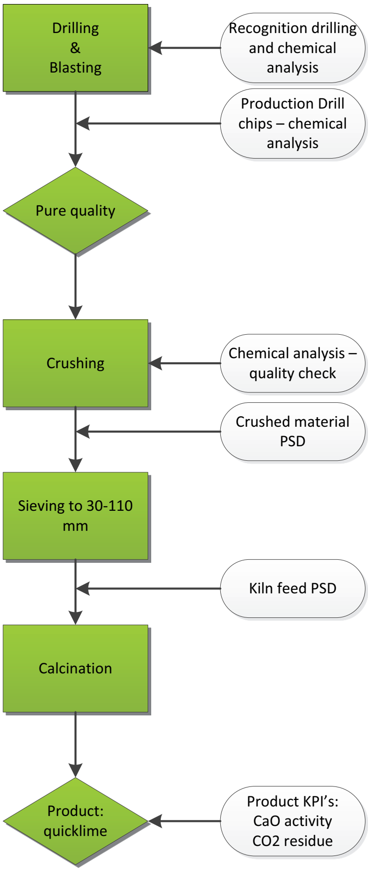


Figure 15. Sampling and quality control along the mining value chain in Verdalskalk. The bulk chemistry is analysed after drilling and after crushing. The PSD is checked ocassionally after crushing and after sieving. The final product quality control is done by CaO reactivity and CO_2 residue tests. Additional tests not presented here are related to furnace process and its environmental control.

Other factors that were linked to raw material quality were the main product KPIs, namely the quicklime reactivity and CO_2 residue. The literature study (Boynton, 1966, Potgieter et al., 2002) and personal communication with the kiln operators revealed that those parameters can be affected by both the rock characteristics and the calcination process. At the same time, the furnace process is adjusted depending on the quality of the quicklime. Hence, a loop of dependence is created, and cause and effect can be confused. Therefore, detailed logging of the parameters and the KPI characteristics with further multivariate analysis was proposed to unwind the loop, at least to some extent.

Crushing is an important step in changing the properties of the raw material. It defines how much material is processed further (the yield), as the fines that are produced during crushing need to be rejected. This factor influences both the efficiency of the production and the energy consumption in the crusher. After screening, particles of the desired size are calcined. The PSD of kiln feed defines the spatial distribution of the material in the furnace, in terms of temperature and CO_2 fluctuations. Therefore, a kiln feed PSD was chosen as one of the parameters important for the geometallurgical approach.

While the research on geometallurgy focuses mainly on geology and mineral processing, mining engineering can and should also be included in the geometallurgical approach, because parameters like blast pattern, blast direction, and transport can also be modelled and viewed in geometallurgical perspective. The blast direction factor, among other mining engineering factors is typically not seen as a parameter related to the geometallurgical model of the mine. However, in the current research it was observed that this factor should be considered. In the Tromsdalen deposit, the marble unit has a dip of 35-55° and a SE dip direction. A main fracture has a NNW – SSE strike. Hence, NE and SW directions of the blast are favorable, as the blast force spreads perpendicularly to the rock fracturing, whereas a SE direction is the least favorable as the force spreads along the foliation and the fracturing, so the rock does not crush properly and big boulders remain in the pit. These big boulders then need additional treatment (iron ball) before transport to the crushing plant which takes longer and generates additional costs. Another example of considering mining engineering in geometallurgical perspective would be multiple loading and transportation of the rock creating too much fines.

Geology is an integral part of geometallurgy. The importance of geological input to geometallurgy was presented e.g. by Hunt and Berry (2017) or Hoal (2008), who emphasized the importance of downstreaming geological information like geophysical study or alteration mapping along the value chain. In the research presented here, the importance of geology was addressed by improving the knowledge of the marble variations in the Tromsdalen deposit. Microscopic studies of the marble variations were performed. The research focused on comparison between K2 and K5 marble types was conducted. The study revealed differences at the micro scale. The most pronounced differences were the typical grain size that was lower for type K5 than for K2. Type K5 contained more graphite, both as very fine and dispersed grains and as bigger flakes in between calcite grains, and fewer quartz impurities. It was concluded that those differences between the types can be responsible for different kiln performance, following the hypothesis formed by Boynton (1966). It is also important to promote the holistic view, e.g. that the understanding of geological processes behind the rock variations is valuable. In case of Tromsdalen deposit, it is variable metamorphic conditions applied to the region that control the marble variations: textures, assemblage, grain size, recrystallization degree and rock foliation.

An attempt was made to test the graphite content in marble as a proxy for different textural type: as visual logging and microscopic studies showed, the graphite occurrence varied among marble types. However, measurements of total carbon content (TOC) revealed that the graphite, even though visible in macro and microscopic observation, is too sparse to be quantified with the use of the XRF analysis method.

The logging of the archived drill cores also expanded the geological knowledge of the deposit and allow the observation of more visually assigned types of marble that those discriminated by company (Table 1), and the observation of different structural styles of contamination of marble by other lithological types of rock.

The next objective was to assess the use of surface hardness as a proxy for quality domains, together with assessment of Equotip 3 D as a geometallurgical tool. Surface hardness tests fit well to geometallurgical “rules of the game”, as they are fast, inexpensive and easy to perform, and the results could potentially be treated as a proxy for the mineralogical and textural characterization. In geometallurgy related to metalliferous mining operations, drill core logging and assessment comprising of, among others, a rebound hardness test, are already used. Research on rebound hardness in a geometallurgical perspective is provided e g. by Montoya (2014) and Tøgersen et al. (2018). The research of relationships between rock mesotextural characteristics and lab-scale mineral processing operation was conducted by Pérez-Barnuevo et al. (2018).

The Proceq Equotip 3D was tested as a potential geometallurgical tool, both on a fresh in-situ rock and on drill cores. The studies on fresh rock surfaces revealed differences between K2 and K5 marble types with type K2 reaching higher rebound hardness values and higher standard deviation of measured values. Also, the uncertainty of results was logged, and the differences were observed and interpreted as related to the micro- or macro scale rock variations. However, a strictly quantitative relationship between surface hardness results and microscopic appearance has not been found so far.

Therefore, the research on half-cores was conducted. Testing the half-cores allowed negative factors like surface roughness and poor accessibility of the fresh and even surfaces to be overcome. The results showed that the surface hardness values had a characteristic that could be determined through more advanced statistics like spatial correlation and variograms. Additionally, cores logging allowed the observation of more variations than previously distinguished by the company and contributed to an increase of the geological knowledge of the deposit. The variogram modelling and observation of variogram structures that are related to actual rock textures, foliation, and fractures is proposed to be used in other types of ores, too, for improved understanding of the rock characteristics.

All the aforementioned objectives led to the last one, which was to generate and define a geometallurgical flowsheet – a set of procedures leading to the creation of a geological model, followed by instructions how to design the procedures conceptually and visually. Here, a geometallurgical flowsheet was described and developed as a tool for mining operations to produce a valid and operational geometallurgical model and to visualize the required operations on different levels of detail.

The flowsheet was defined as the tool that can be used for the design and communication of the geometallurgical program. It shows the steps - geometallurgical operations - that are vital to establish and validate the geometallurgical model. Here, a literature study was also conducted and based on this it was discovered that the literature is inconsistent when it comes to geometallurgical model and program definitions. It was highlighted in the research that the geometallurgical model, as the georeferenced equation, is an outcome of the geometallurgical program, after all the necessary geometallurgical operations (the geometallurgical program) were run. The opposite definition is given by e.g. Lischuk et al. (2015). According to this view, the geometallurgical model is the model that allows the establishment of future geometallurgical operations. This inconsistency was resolved in paper II by the use of the term *a priori model* for a preliminary set of dependencies that allow the design of deposit-specific geometallurgical operations.

The geometallurgical flowsheet created for this study is a combination of a generic flowsheet – a tool that in its basis and on a general level can be used for all geometallurgical operations – and a case-specific flowsheet, where the outcomes of the Tromsdalen deposit study were applied on finer levels. Based on the PhD research it was proposed to include a wide spectrum of parameters into the flowsheet, e.g. mineralogical characteristics, surface hardness proxies, kiln feed PSD, furnace burning parameters, and quicklime KPIs (CO_2 residue and CaO reactivity).

For the design of the geometallurgical flowsheet, the IDEF0 methodology was used and it was concluded in the research that this methodology allows for the clear communication of the working processes, inputs, outputs and controls of the process. Additionally, by using diagrams that can be decomposed into finer units it is possible to obtain a very detailed information flow that is at the same time easy to read.

In the view of Lamberg et al. (2013), the geometallurgical model is created based on two separate approaches: a geometallurgical testing approach with the use of small scale geometallurgical tests, and a mineralogical approach with the use of automated mineralogy. The metallurgical response in the ore must be measured, and hence small-scale geometallurgical tests have been developed. By definition, they should be fast and inexpensive to test a large number of samples to account for ore variability (Lamberg et al., 2013). Examples of such tests are Comminution index, Rotary breakage tester, JK mineral separability Indicator, a Davis tube, to name a few. On the other hand, in the mineralogical approach the geometallurgical model is built as based on mineralogy. In this approach, automated mineralogy plays an important role using SEM-based mineralogical analysis. These are typically MLA or QEMSCAN® software but more recently also e.g. Mineralogic Mining (Zeiss), TIMA (Tescan) or Aztec (Oxford Instruments).

Other authors, e.g. Alruiz et al. (2009), Hunt and Berry (2017), Boisvert et al. (2013),do not provide such a strong definition of modelling approaches and rather name all the above methods as ways to obtain geometallurgical information of the ore, along with the geological data collection. In the PhD research, this view is promoted, as in the designed geometallurgical flowsheet mineralogy (however, not automated) and Equotip geometallurgical tests are combined with other parameters.

In the current PhD research geometallurgy is seen mostly through a perspective of combining factors, that is, functions must be established in order to start creating a geometallurgical model. Hence the "functional" y= f(x) view of the geometallurgical model is here strengthened. When carrying out geometallurgical research or applying geometallurgy to a mine operation one must ask the following questions: what are the KPIs, what factors influence the KPIs and how are they possibly related. This is done through establishing an *a priori* model, and later checked and validated by the selection of accurate methodology and running the geometallurgical program.

Of course, the path from finding out the dependencies to establishing the actual model can be long and tricky. In this PhD research the sampling and testing of the deposit was combined with finding possible dependencies basing on literature study and observing the mine value chain. Creating an actual model that is out of the scope of presented doctoral work would be a next important step combining current and future knowledge. Geometallurgical modelling is a step widely addressed in literature (Alruiz et al., 2009, Keeney and Walters, 2011, Montoya et al., 2011, Boisvert et al., 2013). Multivariate statistics including principal component analysis, clustering, linear regressions are widely-used approaches (Mena Silva et al., 2018, Vezhapparambu et al., 2018). Multivariate analysis is used develop the relationships between variables and to limit their number. Next, numerical predictive models are established through kriging or more advanced techniques. In case of Verdalskalk operation it is suggested to model quicklime main parameters (activity and CO_2 residue) against textural variables, kiln feed PSD and kiln settings (temperature, oxygen use) as a next step of geometallurgical investigations.

5.2 Future work

For future work of exploring the geometallurgical aspects of the Verdalskalk it is recommended to study the kiln performance on a micro scale, particularly to test the different types of marble in high-temperature micro thermometry to observe the potential differences or specific marble behavior during combustion. The combustion would simulate the kiln process, and it is therefore important to choose the temperature and atmosphere parameters with care. The studies on calcination mentioned by Boynton (1966) and Rodriguez-Navarro et al. (2009) revealed differences in dilation and contraction of lime after calcination in different types of limestone. The differences in dilation and contraction were reported to be grain-size dependent. Boynton also reported that coarse grained limestone is prone to crack formation during heating. It is recommended that the different types of Tromsdalen marble are analyzed and tested with respect to these parameters in order to see potential differences.

Another recommended study is to expand the Equotip surface hardness studies on drill cores to obtain more data and test more variable types of the marble. Due to time and equipment constraints only a limited number of drill cores was tested. The results showed variations, but by testing more drill cores the unwanted influence of changing core diameter, equipment drift or low number of results within a marble type will be limited. Also, it is recommended to combine the rebound hardness tests with mineralogical investigation to find direct relationships between the Leeb hardness number values and the internal structure of the rock on the micro scale.

Long-term and often-repeated logging of the kiln feed PSD is also recommended to find potential patterns between the PSD and the kiln performance. It is important to note that the measurements are non-comparable if the company changes the required size of the raw material for the kiln feed.

A further challenge would be block modelling including the results from the current PhD research and future developments of the flowsheet based on incorporating the geometallurgical flowsheet to Verdalskalk routines.

5.3 Conclusions

The thesis presents the application of a geometallurgical approach to the industrial minerals mining sector including a case study of Verdalskalk AS calcite open-pit operation.

The main objectives of the thesis followed the rules of geometallurgy and included: improving the knowledge of the geology and mineralogy of the deposit, unlocking relationships between ore properties, processing parameters and final product, testing rock surface rebound hardness as a geometallurgical proxy for mineralogical variations and building a geometallurgical flowsheet as a tool for designing and communicating a geometallurgical program that leads to development of predictive geometallurgical model.

Improving the knowledge of the deposit was realized through microscopic textural and mineralogical studies of the two main types of marble used to produce quicklime, types K2 and K5. It was concluded that the two types differ in terms of grain size and mineral assemblage. For marble type K2 the typical grain size was larger than for type K5. Pyrite was present in both types of marble, whereas quartz grains were noted only in type K2. Type K5 contained more graphite. In both types of marble, a texture of microcrystalline calcite on the rims of larger grains was reported. Additional TOC research conducted on the two marble types showed that despite the varying graphite content in the two types, the actual amount of graphite is too small to be accurately detected and hence cannot be used as one of the rock qualifying factors.

Assessing rebound hardness as a proxy for mineralogical characteristics was conducted by the in-situ studies in the open pit on K2 and K5 marble types and by a study of archived drill cores. For the two types of marble tested in-situ the average hardness values were comparable. However, the highest L_{max} values were obtained for type K2. This result was interpreted as being related to a coarser grain size and higher silica content compared to K5. Differences in standard deviations for the two types were noted, with more variable values in type K2. This observation was interpreted as related to the variable K2 mineralogy and presence of fractures filled with iron oxides that are related to lower L_{max} values.

The drill core surface hardness studies included characterization of the different types of marble along the drill core which improves the geological knowledge of the deposit. The rock was assembled into ten marble groups of different visual characteristics (colour, mesotexture) and impurity levels, and four groups of marble strongly contaminated by different rock types: phyllite and greenstone. The rebound hardness values (HL) were obtained with the use of Equotip 3D and statistical approach was implemented by creating histograms and downhole variograms for each marble type. The studies revealed that within pure marble types (M) the highest rebound hardness values were obtained for types M10 and M8, both characterized by the presence of dispersed graphite. The lowest values were obtained for types M1 and M2 that are white to greyish impure coarse-grained calcite. The resulting variograms allowed spatial correlation of the rebound hardness values within discriminated marble types and textural characteristics. The variograms of marble contaminated with greenstone and phyllite had distinctly higher sill hence higher HL variance. Within marble types (M) the variance was higher for coarser-crystalline marble M1, M2, typical grey marble M3 and M4 and marble with “rice grain” texture (M7). Lower variance was observed for the “zebra” texture marble (M8) and dark marble with strong lamination of white marble. The differences in nugget effect and range allowed for observations of distinct characteristics not accessible when analysing raw numerical data only. It was concluded that the mineralogical or textural domains, with the use of visual logging, rebound hardness data and variable spatial correlation characteristics as proxies, can be established in future work. Additionally, the knowledge of methodology of using Equotip 3 D as a geometallurgical tool was expanded. The problem of varying core diameter and a lack of established correction factor for marble were observed. Conducting the rebound hardness measurements on different drill core diameters revealed that the correction factors advised for the metallic ore drill cores are not applicable in marble.

Regarding understanding the relationships between in-situ marble variations, processing performance and final product quality, it was concluded that marble grain size and textures can be responsible for the varying heat distribution and hence varying response during calcination process. While marble types K2 and K5 have similar chemical composition and are treated in the kiln as the same quality of material, it is proposed that a better control of the kiln performance and product quality can be obtained by prior knowledge of variations in marble texture and trace mineral assemblage. Kiln feed PSD is also important for the heat distribution, therefore it is vital to have constant control over this parameter. It was also proposed that control over crushed material PSD can be indirectly improved by logging it against production blast direction to unlock possible dependencies. Different heating patterns are related to changes in CO_2 residue and CaO activity that are main product KPI's, and to changes in the kiln parameters. Therefore, it was suggested that after a long-term extensive logging of aforementioned parameters and combining them with Equotip data as mineralogical proxies, it would be possible to reach for numerical models that can predict the kiln performance and product quality.

The objective to propose and to define a generic and a case-specific geometallurgical flowsheet was addressed by the design of a flowsheet using IDEF0 methodology. A geometallurgical flowsheet was defined as a tool visualizing and communicating steps of the geometallurgical program allowing the creation of a geometallurgical model. The term *a priori model* was introduced and defined as a list of dependencies between in-situ parameters and metallurgic response that must be predicted and is based on experience, literature and preliminary testing. The definition of the geometallurgical model as a set of georeferenced functions was strengthened. The case-specific geometallurgical flowsheet was designed in such a way that it encompassed main findings of the thesis, including the mineralogical and rebound hardness studies, company's parameters logging and literature study. Using the case-specific flowsheet on site would allow communication of the georeferenced information in a more effective way and would allow for better understanding of the drivers of process performance. Using the general geometallurgical flowsheet is possible in any other mining operation and it would structure the information flow, promote detailed planning of sampling and tests and allow for clear communication between specialists of different mine facilities.

References

AASLY, K. & ELLEFMO, S. L. 2014. Geometallurgy applied to industrial mineral operations. *Mineralproduksjon,* 5**,** A21-A34.

ALRUIZ, O. M., MORRELL, S., SUAZO, C. J. & NARANJO, A. 2009. A novel approach to the geometallurgical modelling of the Collahuasi grinding circuit. *Minerals Engineering,* 22**,** 1060-1067.

AOKI, H. & MATSUKURA, Y. 2007. A new technique for non-destructive field measurement of rock-surface strength: an application of the Equotip hardness tester to weathering studies. *Earth Surface Processes and Landforms,* 32**,** 1759-1769.

BOISVERT, J. B., ROSSI, M. E., EHRIG, K. & DEUTSCH, C. V. 2013. Geometallurgical Modeling at Olympic Dam Mine, South Australia. *Mathematical Geosciences,* 45**,** 901-925.

BOWELL, R., GROGAN, J., HUTTON-ASHKENNY, M., BROUGH, C., PENMAN, K. & SAPSFORD, D. J. 2011. Geometallurgy of uranium deposits. *Minerals Engineering,* 24**,** 1305-1313.

BOYNTON, R. S. 1966. *Chemistry and technology of lime and limestone,* New York, Interscience.

BUNKHOLT, I. O. 2015. *The implications of sulphides in GCC feed and the potential for their removal during alkaline amine flotation.* Doctoral thesis, Norwegian University of Technology and Science.

CARR, F. P. & FREDERICK, D. K. 2014. Calcium Carbonate. *Kirk-Othmer Encyclopedia of Chemical Technology.* John Wiley & Sons, Inc

CHILES, J.-P. & DELFINER, P. 2009. *Geostatistics: modeling spatial uncertainty*, John Wiley & Sons.

CROPP, A. G., WILL; BRADSHAW, DEE; HUNT, JULIE; BERRY, RON 2014. Communicating and integrating geometallurgical data along the mining value chain. *XXVII International Mineral Processing Congress, Santiago, Chile*.

DAU 2001. *Systems Engineering Fundamentals,* Fort Belvoir, Virginia, Defense Acquisition University Press.

DEUTSCH, J. L., PALMER, K., DEUTSCH, C. V., SZYMANSKI, J. & ETSELL, T. H. 2016. Spatial Modeling of Geometallurgical Properties: Techniques and a Case Study. *Natural Resources Research,* 25**,** 161-181.

DIRMIN 2019. Harde fakta om mineralnæringen. Mineralstatistikk 2018. Trondheim: Direktoratet for mineralforvaltning.

DOMINY, S. & O'CONNOR, L. 2016. *Geometallurgy - beyond conception.*

DOMINY, S., O'CONNOR, L., PARBHAKAR-FOX, A., GLASS, H. & PUREVGEREL, S. 2018. Geometallurgy—A Route to More Resilient Mine Operations. *Minerals,* 8**,** 560.

DUNHAM, S., VANN, J. & COWARD, S. Beyond geometallurgy—gaining competitive advantage by exploiting the broad view of geometallurgy. Proceedings of the first AusIMM international geometallurgy conference, Brisbane, QLD, Australia, 2011. 5-7.

ELLEFMO, S. L., AASLY, K., LANG, A., VEZHAPPARAMBU, V. S. & SILVA, C. A. 2019. Geometallurgical Concepts Used in Industrial Mineral Production. *Economic Geology,* 114**,** 1543-1554.

GAUTNEB, H. 2012. Kommunedelplan Tromsdalen, Verdal. Oversikt over geologiske forhold, marked og produksjon av kalkstein.

GREGORY, M. J., LANG, J. R., GILBERT, S. & HOAL, K. O. 2013. Geometallurgy of the Pebble porphyry copper-gold-molybdenum deposit, Alaska: Implications for gold distribution and paragenesis. *Economic Geology,* 108**,** 463-482.

HALDAR, S. K. & TIŠLJAR, J. 2014. Sedimentary Rocks. *In:* HALDAR, S. K. & TIŠLJAR, J. (eds.) *Introduction to Mineralogy and Petrology.* Oxford: Elsevier.

HARBEN, P. W. 2002. *The industrial minerals handybook, 4th edition. A guide to Markets, Specifications and Prices*, Industrial Minerals Information.

HARBEN, P. W. & BATES, R. L. 1990. *Industrial minerals: geology and world deposits*, Metal Bulletin.

HEATHER, B., SOUSA, R., LAPWORTH, A. & TOMI, G. D. 2005. Management of Iron Ore Quality Through Effective Technology Implementation Using Software Systems Designed From an IDEF0 Analysis. *Iron Ore Conference.* Fremantle, WA.

HEDIN, R. 1954. Changes Occuring in the Limestone during Heating before Calcination. *Swedish Cement and Concrete Research Institute Bulletin,* 23**,** 34.

HOAL, K. O. 2008. Getting the geo into geomet. *SEG Newsletter, Society of Economic Geologists,* 73**,** 11-15.

HUNT, J. A. & BERRY, R. F. 2017. Geological contributions to geometallurgy: a review. *Geoscience Canada,* 44**,** 103-118.

JACKSON, J., MC FARLANE, A. J. & OLSON HOAL, K. 2011. Geometallurgy - Back to the future: Scoping and communicating Geomet programs. *In:* DOMINY, S. (ed.) *Geomet 2011.* Birsbane, QLD, Australia: Australasian Institute of Mining and Metallurgy.

KEENEY, L. & WALTERS, S. G. 2011. A Methodology for Geometallurgical Mapping and Orebody Modelling. *In:* DOMINY, S. (ed.) *AusIMM International Geometallurgy Conference.* Brisbane, Australia: Australasian Institute of Mining and Metallurgy.

KOGEL, J. E., TRIVEDI, N. C., BARKER, J. M. & KRUKOWSKI, S. T. 2006. *Industrial minerals & rocks: commodities, markets, and uses*, SME.

KORNELIUSSEN, A., RAANESS, A. & GAUTNEB, H. 2014. Chemical and mineralogical characterisation of carbonate deposits in Norway. *NGU Report.*

LAMBERG, P., ROSENKRANZ, J., WANHAINEN, C., LUND, C., MINZ, F., MWANGA, A. & PARIAN, M. Building a geometallurgical model in iron ores using a mineralogical approach with liberation data. The Second AUSIMM International Geometallurgy Conference, Brisbane, Qld, 2013. 317-324.

LANG, A., ELLEFMO, S. & AASLY, K. 2018a. Geometallurgical Flowsheet as a Tool for Designing and Communicating Geometallurgical Programs. *Minerals,* 8**,** 372.

LANG, A. M., AASLY, K. & ELLEFMO, S. L. 2018b. Mineral characterization as a tool in the implementation of geometallurgy into industrial mineral mining. *Minerals Engineering,* 116**,** 114-122.

LEICHLITER, S., HUNT, J., BERRY, R., KEENEY, L., MONTOYA, P., CHAMBERLAIN, V., JAHODA, R. & DREWS, U. Development of a predictive geometallurgical recovery model for the La Colosa, Porphyry Gold Deposit, Colombia. Proceedings from the 1st AusIMM international geometallurgy conference. THE Australasian Institute of Mining and Metallurgy, Melbourne, 2011. 85-92.

LEWIS, P. V. 1987. *Organizational communication: The essence of effective management*, Wiley.

LISCHUK, V., LAMBERG, P. & LUND, C. 2015. Classification of geometallurgical programs based on approach and purpose. *SGA 2015.* Nancy.

LUND, H. 2007. Renewable energy strategies for sustainable development. *Energy,* 32**,** 912-919.

LUND, Ø., BILOV-OLSEN, J., LILLEÅS, J. E. & JOHANSEN, T. E. 2001. Håndbok i Prosessmodellering i Forsvaret.

MENA SILVA, C., SØRENSEN, B., AASLY, K. & ELLEFMO, S. 2018. Geometallurgical Approach to the Element-to-Mineral Conversion for the Nabbaren Nepheline Syenite Deposit. *Minerals,* 8**,** 325.

MINERALSTECH. 2015. *What is PCC - Precipitated Calcium Carbonate?* [Online]. Available: http://www.mineralstech.com/Pages/SMI/Precipitated-Calcium-Carbonate-(PCC).aspx [Accessed 30.07 2015].

MONTOYA, P. A., KEENEY, L., JAHODA, R., HUNT, J., BERRY, R., DREWS, U., CHAMBERLAIN, V. & LEICHLITER, S. Geometallurgical Modelling Techniques Applicable to Prefeasibility Projects–La Colosa Case Study. The First AUSIMM International Geometallurgy Conference, 2011. 103-114.

MONTOYA, P. L. 2014. *Geometallurgical Mapping and Mine Modelling - Comminution Studies: La Colosa Case Study, AMIRA P843A.* Master of Science in Geology, University of Tasmania.

MORAN, C. J., LODHIA, S., KUNZ, N. C. & HUISINGH, D. 2014. Sustainability in mining, minerals and energy: new processes, pathways and human interactions for a cautiously optimistic future. *Journal of Cleaner Production,* 84**,** 1-15.

MUNRO, P. & TILYARD, P. Back to the Future-Why Change Doesn't Necessarily Mean Progress. Conference Proceedings from the Tenth Mill Operators' Conference 2009, 2009.

NGU 2015. Mineral resources in Norway 2014. *Focus.* Geological Survey of Norway.

NGU 2019. Nasjonal berggrunnsdatabase, berggrunn N50. Trondheim, Norway.

NIST 1993. Integration definition for function modelling (IDEF0). Ohio, USA.

NORSK KALKFORENING 2005. Karbonatbergarter og omgivelser.

OATES, J. A. 2008. *Lime and limestone: chemistry and technology, production and uses*, John Wiley & Sons.

PARBHAKAR-FOX, A. 2017. Predicting Waste Properties Using the Geochemistry-Mineralogy-Texture-Geometallurgy Approach. *Environmental Indicators in Metal Mining.* Springer.

PÉREZ-BARNUEVO, L., LÉVESQUE, S. & BAZIN, C. 2018. Drill core texture as geometallurgical indicator for the Mont-Wright iron ore deposit (Quebec, Canada). *Minerals Engineering,* 122**,** 130-141.

POTGIETER, J., POTGIETER, S., MOJA, S. J. & MULABA-BAFUBLANDI, A. 2002. The standard reactivity test as a measure of lime's quality. *Journal of the Southern African Institute of Mining and Metallurgy,* 102**,** 67-69.

PRIOR, T., GIURCO, D., MUDD, G., MASON, L. & BEHRISCH, J. 2012. Resource depletion, peak minerals and the implications for sustainable resource management. *Global environmental change,* 22**,** 577-587.

PROCEQ. 2017. *RE: Equotip Operating Instructions.*

RIEMER, M. J. 2007. Communication skills for the 21st century engineer. *Global J. of Engng. Educ,* 11**,** 89-100.

ROBERTS, D., GRENNE, T. & RYAN, P. D. 1984. Ordovician marginal basin development in the central Norwegian Caledonides. *Geological Society, London, Special Publications,* 16**,** 233-244.

RODRIGUEZ-NAVARRO, C., RUIZ-AGUDO, E., LUQUE, A., RODRIGUEZ-NAVARRO, A. B. & ORTEGA-HUERTAS, M. 2009. Thermal decomposition of calcite:

Mechanisms of formation and textural evolution of CaO nanocrystals. *American Mineralogist,* 94**,** 578-593.

SGS. 2019. *Geometallurgy* [Online]. Available: https://www.sgs.com/en/mining/exploration-services/geometallurgy [Accessed].

SOLA, C. & HARBORT, G. 2012. Geometallurgy - Tricks, Traps and Treasures. *11th AusIMM Mill Operators' Conference.* Hobart, TAS, Australia.

TØGERSEN, M. K., KLEIV, R. A., ELLEFMO, S. & AASLY, K. 2018. Mineralogy and texture of the Storforshei iron formation, and their effect on grindability. *Minerals Engineering,* 125**,** 176-189.

VEZHAPPARAMBU, V., EIDSVIK, J. & ELLEFMO, S. 2018. Rock classification using multivariate analysis of measurement while drilling data: Towards a better sampling strategy. *Minerals,* 8**,** 384.

VŠIANSKÝ, D., DVOŘÁK, K., BUREŠ, J. & SLAVÍČEK, K. 2019. *Relationship between microstructure of carbonate rocks, calcite crystallinity and decarbonisation process during lime burning*.

WILLIAMS, S. A historical perspective of the application and success of geometallurgical methodologies. Proceedings of the International Geometallurgy Conference, Brisbane, Australia, 2013.

Part II: Appended papers

Paper I

Minerals Engineering 116 (2018) 114–122

Contents lists available at ScienceDirect

Minerals Engineering

journal homepage: www.elsevier.com/locate/mineng

Mineral characterization as a tool in the implementation of geometallurgy into industrial mineral mining

Aleksandra Maria Lang*, Kurt Aasly, Steinar Løve Ellefmo

Norwegian University of Science and Technology, Department of Geoscience and Petroleum, Sem Sælands veg 1, 7491 Trondheim, Norway

ARTICLE INFO

Keywords:
Geometallurgy
Industrial minerals
PCC
Marble textures
Surface hardness
Equotip 3 D

ABSTRACT

Industrial minerals play an important role in the Norwegian mining industry. The presented research focuses on defining marble deposit variability in order to evaluate parameters that can potentially be related to downstream process performance. Two types of marble raw material (K2 and K5) from the Verdalskalk open pit, used for precipitated calcium carbonate production (PCC) were tested for possible differences within texture, grain boundaries shape, grain size, accessory mineral assemblage. Additionally, surface hardness was measured using the Proceq Equotip 3 D device. K5 type was found to be finer-grained compared to K2. The presence of quartz was more pronounced in K2 type material, which possessed higher surface hardness values and presented higher variation of those.

1. Introduction

With growing needs for ores and industrial minerals it has become essential to aim at constant improvement in recognition of the deposits and commodities not only in the geological but also mineral processing sense.

Chemical analysis and geological mapping are the main tools used to classify the raw material into different types and qualities. The presented study aims to recognize, describe and quantify mineralogical and textural properties of a calcite marble deposit and define parameters that can be used for qualifying the deposit into different geometallurgical domains.

The specific objectives of this research are:

- to describe and compare the mineralogical and textural properties of two types of marble used for Precipitated Calcium Carbonate (PCC) production
- to present and compare surface hardness test results for both types of marble
- to define potential links between surface hardness values and the mineralogical and textural properties
- to verify the appropriateness of the Equotip 3 D as a portable time- and cost efficient geometallurgical test tool for surface hardness measurement in marble deposits.

2. Background

The Tromsdalen deposit operated by Verdalskalk AS is located in Mid-Norway. The deposit, being low metamorphic grade calcitic marble of the Ordovician period, is estimated to be 7.5 billion tonnes. The marble unit is situated between greenschist and phyllite units (Fig. 1A). Due to folding the units occurs in reverse order, with greenschist situated on top the marble and phyllitic strata laying underneath (Gautneb, 2012).

The Tromsdalen marble is fine to medium grained, greyish with lighter and darker bands (Fig. 1B). The typical marble is relatively pure. Most common impurities for Tromsdalen marble are iron oxides, iron sulfides and silicate minerals. Graphite, pyrite, quartz, pyroxene, muscovite and apatite are typical for carbonate rocks (Korneliussen et al., 2014).

The marble is mined in an open pit operation. Based on chemical data as well as physical appearance (color), the deposit is subdivided into 6 marble types (Table 1). The types are assigned to production qualities based on the CaO, Fe_2O_3, SiO_2 and Al_2O_3 content. XRF analysis control is performed on drill cores, drill chips and along production line.

The A (pure) quality consists of types K1, K2 and K5 and is used as raw material for the burned and slaked lime production. The blasts consisting of blended pure and impure marble (e.g. K2 and K3) are classified as B (standard) quality and used as feed to a kiln operated by a different company with lower purity standards. The lower purity K3 and K4 type raw material is used for cement production (C quality).

---

* Corresponding author.
E-mail address: aleksandra.lang@ntnu.no (A.M. Lang).

https://doi.org/10.1016/j.mineng.2017.10.021
Received 30 April 2017; Received in revised form 6 September 2017; Accepted 31 October 2017

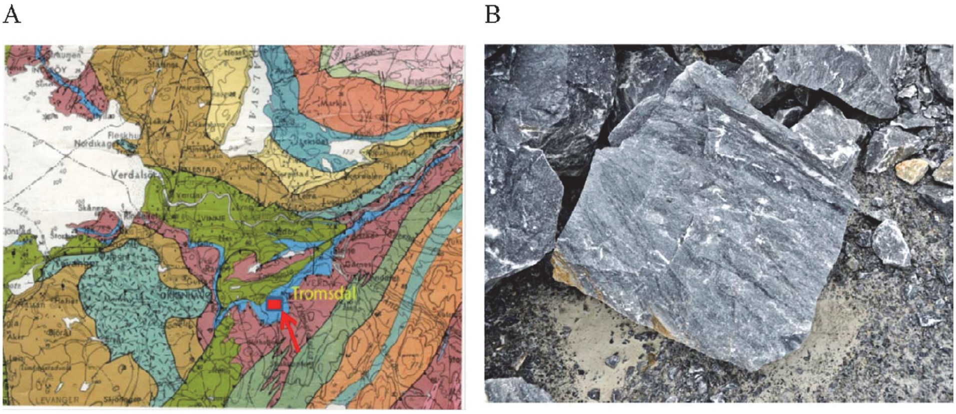


Fig. 1. Geological overview of the Tromsdalen area (A); the marble unit (blue) is located between greenschist to SE (violet) and phyllite to NW (green) (Gautneb, 2012). Typical Tromsdalen marble (B).

Table 1
Quality requirements for marble types in Tromsdalen deposit.

Type No.	Name	Quality requirements		
		CaO (wt%)	Fe_2O_3 (wt%)	SiO_2 (wt%)
K1	Light-grey pure marble	> 54.5	< 0.06	< 0.5
K2	Dark-grey pure marble	> 54.5	< 0.06	< 0.5
K3	Dark-grey impure marble	> 50.0	> 0.12	No requirements, given the purity of the deposit
K4	Light-grey impure marble	> 50.0	> 0.12	
K5	Black marble, pure	> 54.5	< 0.06	< 0.5
K6	White marble, impure	Waste material, no requirements		

Type K6 occurs as a thin strata on a contact with a greenschist unit and is not utilized in production due to high impurity levels (Ruiz J.R., pers.com, 06.03.2015).

The raw material of pure quality is crushed and screened at the mine site before it is transported by truck to the kiln, where it is converted to quicklime (burned lime, CaO), which is the main product from the mine. The CaO is used for PCC production. The crushing plant at the mine site consists of roller crushers with primary and secondary crushing lines. Crushed products are screened to the 30–100 mm fraction, which is then fed to the kiln. At Verdalskalk the calcium oxide is produced in a two-shaft Maerz kiln due to the reaction:

$CaCO_3 + Heat \rightarrow CaO + CO_2\uparrow$, in temperatures reaching 1000–1200 °C in the burning zone (Storli, A.M., pers.com, 07.03.2015).

Currently, marble types K2 and K5 are fed directly to the kiln. They both are of equally high purity but there is an indication, based on operator experience, that marble type K2 has less stable processing performance in the kiln than marble type K5. With similar geochemical data between marble types K2 and K5, there is a need for understanding which mineralogical parameters other than bulk geochemistry influence the kiln performance.

Hence it is reported (Boynton, 1966) that grain size differences can cause changing of the calcite heating pattern in the kiln, as coarse grains tend to crack instead of dissociate, therefore this parameter should be taken into account when classifying raw material into processing types.

The current research is a part of the project aiming at incorporating the aspects of geometallurgy into industrial mineral operations. Typically, geometallurgy is used in metal mining. However, it can be also used for better recognition of process performance and quality needs within industrial minerals.

The main goal of this study is to define new key performance indicators (KPIs) within industrial mineral mining, establishing the links between them and “traditional” indicators such as chemistry, and searching for geometallurgical tests that are suitable for industrial minerals operations. Lischuk et al. (2015) described two main approaches to establish the links utilized in geometallurgy: the mineralogical approach and geometallurgical tests. In the presented research both approaches were applied: mineralogical characterization of the commodity was performed and surface hardness test was examined as potential geometallurgical testing method.

3. Materials and methods

3.1. Materials

3.1.1. Mineralogy

The sampling campaign for the microscopic study was performed in the Tromsdalen calcite marble deposit in the blast piles after production blasting.

Material from four production blasts, VB11-2016, VB13-2016, VB16-2016 and VB19-2016 was tested and 9 samples were collected from each blast (Table 2). In order to test potential variabilities of the marble within mostly homogenous blasts the samples were collected along the pile and the emphasis was laid on collecting samples that showed visual variations. The distribution of the samples along the blasts is illustrated in Fig. 2.

Blasts of two different marble types – K2 and K5, both used as a raw material for the kiln, were selected for the study.

3.1.2. Surface hardness

For the surface hardness measurements, the sampling areas were selected among the largest, stable blast fragments (Fig. 3) and the measuring points were located on the most even surfaces with minor topography and fractures, and with the least trace of weathering and alteration.

A total amount of 110 sample surfaces from 10 separate production

Table 2
Sample numbers with corresponding blast number and marble type.

Sample signature	Production blast	Sample signature	Production blast	Marble type
1-VB11	VB11-2016	1-VB16	VB16-2016	K2
2-VB11		2-VB16		
3-VB11		3-VB16		
4-VB11		4-VB16		
5-VB11		5-VB16		
6-VB11		6-VB16		
7-VB11		7-VB16		
8-VB11		8-VB16		
9-VB11		9-VB16		
1-VB13	VB13-2016	1-VB19	VB19-2016	K5
2-VB13		2-VB19		
3-VB13		3-VB19		
4-VB13		4-VB19		
5-VB13		5-VB19		
6-VB13		6-VB19		
7-VB13		7-VB19		
8-VB13		8-VB19		
9-VB13		9-VB19		

blasts were tested (Table 3).

3.2. Methods

3.2.1. Mineralogy

One polished thin section was prepared from each rock sample. The samples were cut perpendicularly to existing foliation and thin sections were prepared at the Warsaw University (UW).

The petrographic and mineralogical investigations of the thin sections were conducted at the Norwegian University of Science and Technology (NTNU) in Trondheim. A Nikon Eclipse 600 polarized light microscope with a 2 MP digital optical camera was used to record transmitted and reflected light observations. Grain measurements were performed manually using SPOT software. The equivalent circle diameters were measured and the typical grain size within a thin section was estimated based on this. A Scanning electron microscope (Hitachi SU-6600 LV-FE-SEM with Bruker XFlash detector) was applied to chosen thin sections to identify the minerals by backscattered electron imaging (BSE) and energy dispersive X-ray spectroscopy (EDS), with use of Bruker Quantax Esprit software. MinDat website was used to confirm mineral ID and composition.

3.2.2. Surface hardness

The blasted material from the ten blasts was tested for surface hardness using a rebound hardness tester. In the test conducted by a Proceq Equotip 3 D device the impact body is propelled by spring force against the tested specimen. Surface deformation results in energy loss, which is detected by measuring and comparing the velocities of the impact body in both impact and rebound phases. The hardness value is expressed as the Leeb Number (*L*value) or Leeb Hardness (HL), which is the ratio of the rebound velocity to the impact velocity multiplied by 1000 (Viles et al., 2011). Surface hardness tests require that the tested surface is smooth and even, and that the specimen is heavy and stable. The single impact method (Aoki and Matsukura, 2007, Viles et al., 2011) was modified for this research: Each sample surface was tested with 10 measurements in random locations on the surface and for each surface the resulting L_{max} value was calculated as an average from the 3 highest readings.

The original method by Aoki and Matsukura proposes a set of 20 readings per surface. However, the present research was conducted under field conditions and the even and smooth surfaces were not always large enough to conduct 20 measurements. For the same reason, there was a high chance of error readings, and therefore the authors decided to reduce the amount of readings from 20 to 10, and reduce the amount of valid readings to the three highest, assuming that an Equotip reading cannot be too high, but can be lowered due to the surface not being perpendicular to the force vector. Hence, the only possible mistakes are lower values rather than higher values.

For the blasts VB11-2016, VB13-2016, VB16-2016 and VB19-2016 the sampling areas were following the mineralogical sampling pattern (Fig. 2).

4. Results

4.1. Mineralogy

Calcite was the major mineral in all samples. The typical grain size of all samples was within a range of 50–400 µm (Fig. 4A, B, Fig. 5). In most of the samples porphyroblasts (recrystallized calcite grains) were surrounded by a rim of micro- and cryptocrystalline calcite less than 10 µm in size.

Almost all samples presented heteroblastic (recrystallized calcite grains were of different size within a thin section) texture (Fig. 4C). Heteroblasticity was a summary of two factors: microcrystalline calcite grains and coarse veins/layers.

The microcrystalline fraction was usually pronounced as rims between porphyrooblasts boundaries but the amount of this, as well as the size range of this fraction varied from sample to sample and could vary considerably within a sample.

Grain boundary shape was similar for all samples and was typically a combination of curved, slightly sutured, embayed and straight grain boundaries, in different proportions. The straight triple junction grain boundaries characteristic for fully recrystallized calcite were not abundant in any sample.

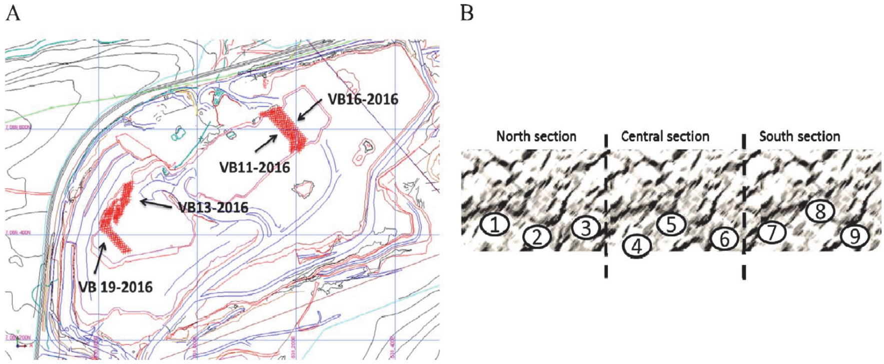


Fig. 2. The sampled blasts' location within the mine (A) and an illustration of the sampling pattern- the production blasts was divided into three parts and three samples were taken from each part (B).

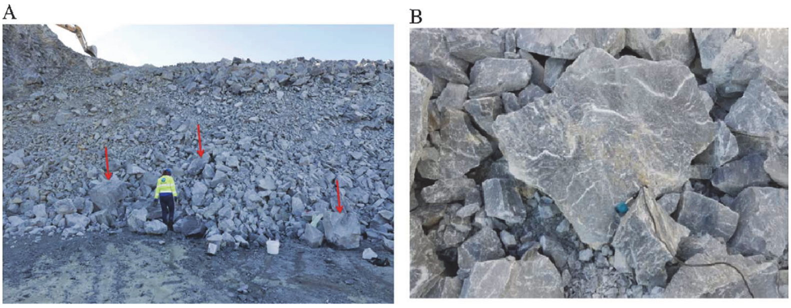


Fig. 3. Typical boulder size (A) and typical surface (B) for Equotip tests.

Table 3
Surface hardness measurements: chosen production blasts and number of surfaces tested. Note that blast VB16-2015 is split into three parts due to the large dataset.

Blast number	Type	Amount of results (tested surfaces)
VB15-2015	K5	18
VB16a-2015		10
VB16b-2015		10
VB16c-2015		10
VB17-2015		7
VB21-2015		6
VB13-2016		9
VB19-2016		9
VB20-2015	K2	6
VB11-2016		10
VB16-2016		12
VB17-2016		3

Accessory minerals found in thin sections were typically pyrite, graphite, iron hydroxides and quartz. It is important to note that within all thin sections total impurities constituted less than 1% of the mineralogy.

Pyrite was the most common impurity mineral and occurred typically as sparse euhedral inclusions within calcite porphyroblasts – in most of the samples (Fig. 4D), or as framboidal aggregates associated with graphitic layers- mostly in samples related to the blast VB19-2016 (Fig. 4F). In most of the samples pyrite crystals were less than 20 µm across.

Mineral iron oxide was present mostly as a pseudomorph after pyrite, of typical pyrite shape (Fig. 4D) but irregular elongated grains were also observed.

Silica minerals observed in the samples were quartz and muscovite. The typical size of quartz grains ranged between 50 and 100 µm (Fig. 4E).

Four of the samples were additionally observed under SEM, and EDS analysis was conducted.

Additionally to minerals mentioned above, micro grains of apatite and TiO_2 were detected.

For compiled mineralogical and petrographic results see Appendix A.

4.1.1. K2 marble type

Within production blast VB11-2016 typical porphyroblast size varied between 50 and 400 µm in total. Porphyroblasts of less than 100 µm were typical for two thin sections, and porphyroblasts larger than 250 µm were typical for four thin sections. In sample 9-VB11 grains bigger than 400 µm were present. Thin sections from production blast VB16-2016 showed similarities to those of blast VB11 and were generally coarse grained. In four out of nine thin sections the typical size range exceeded 200 µm, and in two of the thin sections was lower than 100 µm.

Almost all samples presented heteroblastic texture, and the texture was locally homeoblastic for samples 6-VB16 and 8-VB16.

Microcrystalline and cryptocrystalline grains were mostly pronounced in samples 1-VB11, 9-VB11, 1-VB16, 2-VB16, 3-VB16. In sample 3-VB11 and sample 5-VB11 porphyroblasts were surrounded by a matrix of microcrystalline calcite that was the main constituent of the sample.

Pyrite was found in almost all samples of K2 type. In most of the samples pyrite crystals were less than 20 µm across. In sample 2-VB11, 6-VB11, 2-VB16 pyrite was very sparse and in sample 9-VB11 and 7-VB11 was absent.

Iron oxide mineral was found in five samples within blast VB11-2016, six samples of blast VB16-2016. In sample 9-VB11 Fe-ox was most abundant and the grains were up to 100 µm.

Graphite elongated aggregates and layers were observed in one sample of VB11-2016.

Quartz grains were observed in five samples of the blast VB-11-2016 and two samples of the blast VB16-2016. The typical size of quartz grains ranged between 50 and 100 µm (Fig. 4E) . Muscovite was observed in sample 7-VB11.

4.1.2. K5 marble type

Within blast VB13-2016 typical grain size varied from < 50 to 200 µm. For three of the thin sections the typical size was less than 100 µm, and for one thin section typical grain size was larger than 250 µm.

Thin sections obtained from the VB19-2016 blast were generally fine-grained, for five out of nine sections the range of typical grain size comprised value lower than 100 µm, but contrary to other blasts, in this set of samples the veins of coarse to very coarse material were present. In sample 7-VB19 only one coarse grained vein was visible, with calcite porphyroblasts of sizes up to 3 mm. In thin slip 9-VB19 there were several veins of coarse calcite, whereas in thin slip 2-VB19 there were several transitions from the coarser grained areas to finer grained areas. Thin section 8-VB19 presented extremely heteroblastic texture with extensive microcrystalline occurrence as well as many areas of coarse material.

Microcrystalline and cryptocrystalline grains were mostly pronounced in thin sections from samples 6-VB13, 7-VB13, and most of the thin sections from blast VB19-2016.

Pyrite was the found in all K5 type sections. Pyrite occurrence as framboidal aggregates associated with graphitic layers was visible in thin slips related to the blast VB19-2016.

Iron oxide was noted in four thin sections within blast VB13-2016 and five sections of blast VB19-2016.

Graphite elongated aggregates and layers were observed in one thin section of VB13-2016 blast, and most extensively, in thin slips representing the blast VB19-2016.

Quartz grains were observed in one thin section of the blast VB-13-2016 and none of the blast VB19-2016. For comparison of accessory minerals between marble types see Fig. 7.

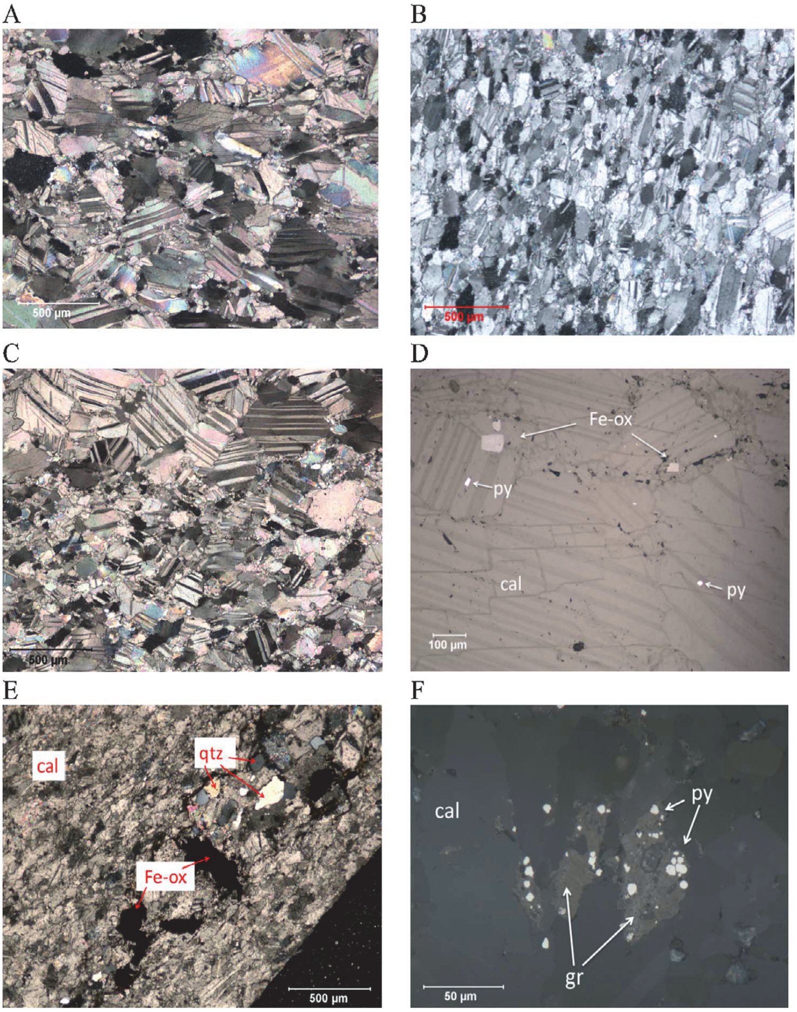


Fig. 4. A: Microphotograph in cross-polarized light, sample 2-VB16, coarse grained with micro- and cryptocrystalline calcite located on boundaries. B: sample 2-VB13. Porphyroblasts much smaller, microcrystalline calcite present, but less pronounced. C: sample 8-VB13, example of extremely heteroblastic calcite, typical grain size impossible to estimate. D: sample 9-VB11, reflected light. Pyrite grains and Fe-ox pseudomorphs after pyrite. E Sample 5-VB11, cross polarized light. Quartz and Fe-ox grains surrounded by microcrystalline calcite matrix. F: sample 9-VB13, reflected light. Framboidal pyrite inclusions in graphite. The mineral abbreviations: cal- calcite, py – pyrite, qtz – quartz, gr – graphite.

4.2. *Surface hardness*

The calculated L_{max} values of the surface measured oscillated between 480 and 650.3 HLD (Fig. 9).

The average L_{max} values of blasts were relatively similar for each of the production blasts and oscillated between 530.4 HLD and 577 HLD (Table 4).

The standard deviation of each blast's measurements oscillated between 23.0 and 48.3 (Table 4, Fig. 8).

The measurement uncertainty of each L_{max} value, that is standard deviation of the 3 readings that constitute the value, was also calculated. The results were shown in Fig. 9 as error bars attached to each L_{max} value point. The average measurement uncertainty per blast was also calculated (Table 4 and Fig. 9) and they ranged between 14.2 and 25.7.

4.2.1. *K5 marble type*

The majority of the surfaces tested belonged to the K5 type due to better accessibility in the pit during sampling campaigns. The calculated L_{max} values were between 478 and 618 HLD.

The standard deviation of L_{max} measurements per blast oscillated between 23.0 and 40.4. The most homogenous measurements were noted for the central part of VB16-2015 (VB16b-2015). The average measurement uncertainty of production blasts oscillated between 15.1 and 25.7. The highest average measurement uncertainty obtained (25.7) was noted for the blast VB13-2016.

4.2.2. *K2 marble type*

For the type K2 the L_{max} value oscillated between 486.3 and 650.3. The three highest L_{max} values of entire campaign were noted for blasts VB11-2016 and VB16-2016.

The blasts standard deviation oscillated between 28.3 and 48.3 which was the highest value obtained.

The average measurement uncertainty was within a range of 14.2 and 23.4 and the lowest uncertainty obtained in the results (14.2) was noted for the blast VB20-2015.

5. Discussion

5.1. *Mineralogy*

It was observed that the type K2 thin sections were in general coarser grained than those of type K5 and for K5 type the fine grained calcite of less than 100 µm was more typical (Fig. 5 and 6). However both types had variations in grain size. While for the K2 type the variation was mostly between coarse and very coarse grains, the K5 type

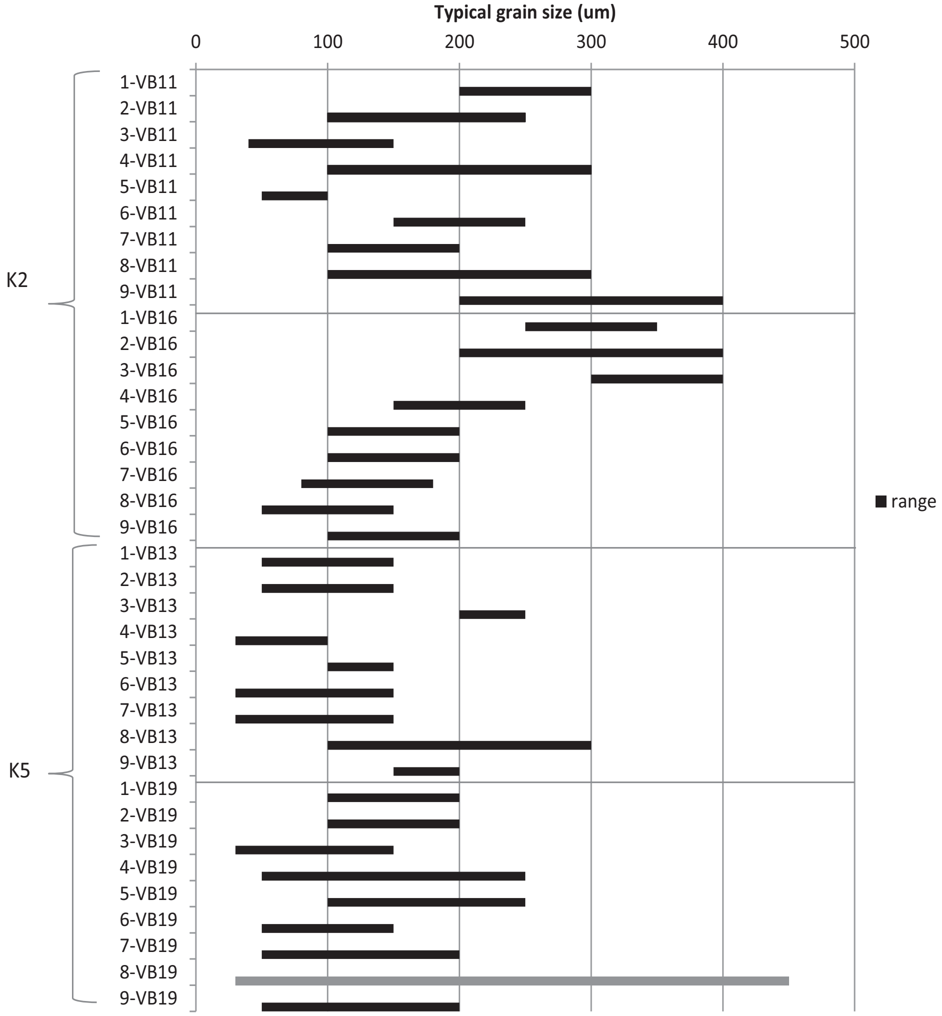


Fig. 5. Typical grain size (equivalent circle diameter, μm) of each thin section. Note that for the thin section 8-VB19 it was not possible to estimate the typical grain size, as the range was too broad.

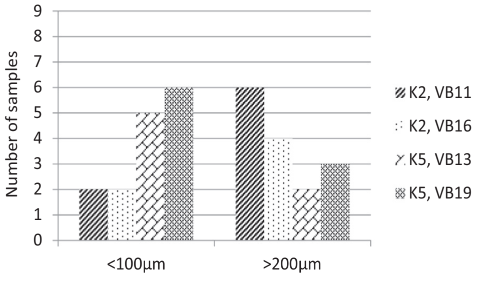


Fig. 6. Comparison of grain sizes observed in thin sections. The figure shows the number of thin sections per blast in which typical grain size is within a range of less than 100 and more than 200 μm respectively.

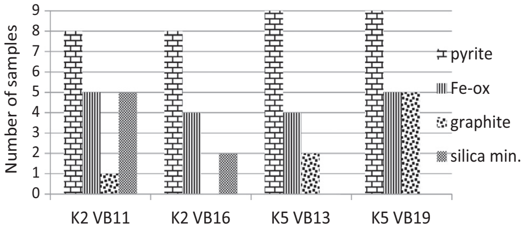


Fig. 7. Comparison of accessory minerals observed in thin sections from each blast. Note that silica was only observed in type K2 marble, while most graphite was observed in K5 type.

presented both very fine and very coarse grain size, especially in the blast VB19-2016.

Microcrystalline calcite located in-between porphyroblast boundaries was generally pronounced in both types of marble, but blast VB19-2016 contained the most abundant micro- to cryptocrystalline fraction.

As stated by Boynton (1966), the grain size has a major impact on the heating pattern in the kiln, and this raises a need for redefining the marble types at Verdalskalk in order to take into consideration the differences in calcite grain size and divide the current K5 type into subtypes.

Pyrite was present in both types of marble. It was observed in different forms (euhedral, anhedral, disseminated and aggregated) but no trends were observed in terms of changing abundance between marble types.

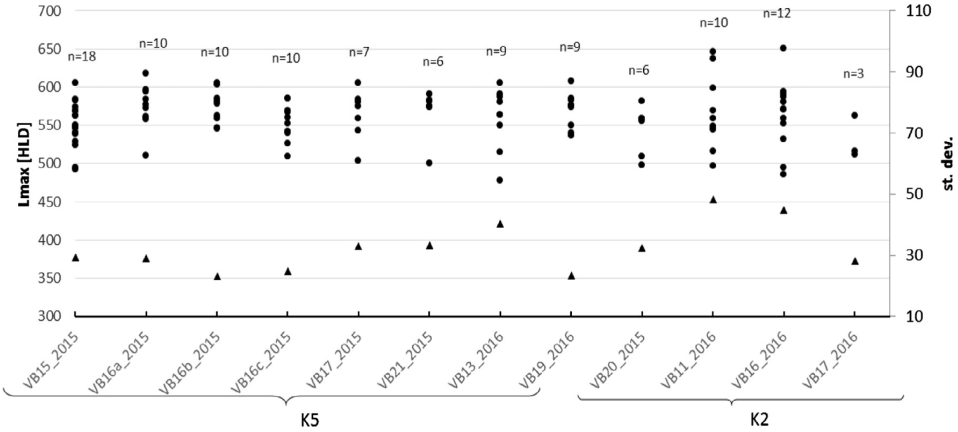


Fig. 8. Equotip tests results. Dots refer to the left hand axis and present L_{max} values for each blast. Triangles refer to the right hand axis and represent the standard deviation of results for each blast.

The type K5 marble has been reported by the company to have higher a graphite content, hence the color and name of the type (Table 1). The graphite grains were reported to be very fine grained and disseminated (Gautneb, 2012). In the present research however, visible graphite grains were most pronounced in the VB19-2016 samples. It is suggested that higher graphite content may cause different heating patterns locally as the graphite burns prior to the calcium dissociation because of the differences in the combustion enthalpies (−3935 kJ/mol for graphite, vs 1778 kJ/mol for calcite (Rodriguez-Navarro et al., 2009).

The presence of silica minerals was more noticeable in type K2 material as there were seven samples containing quartz and one containing muscovite, compared with only one sample containing quartz within type K5. It is highly possible that silicate minerals which were more abundant in type K2 can make the raw material behave slightly differently in the kiln by forming dicalcium silicate layers (Hökfors, 2014). Therefore even if the overall amount of silicate minerals in the kiln is below the cut-off value, the need for redefining the cut-off value in the future or the need for examining the raw material more locally before processing in the kiln may arise.

5.2. Surface hardness

The Equotip D device was tested as a potential tool for easily-accessible, portable, low-cost geometallurgical testing. The method of testing blocks of raw material instead of drill cores was applied. Overall results were similar for both types of marble and did not vary from type to type in terms of average L_{max} value of production blast. Single measurements however, showed variations and it is important to note that the 3 highest L_{max} values were obtained for the K2 type.

Table 4
Average L_{max} values and standard deviation (st dev) presented per blast.

Blast number	Type	Average L_{max}	St. dev.	Average measurement uncertainty
VB15-2015	K5	551.4	29.3	24.3
VB16a-2015		573.4	29	18.8
VB16b-2015		577.3	23	15.1
VB16c-2015		553.7	24.7	18.4
VB17-2015		564.5	32.9	23.9
VB21-2015		567.7	33.4	20.6
VB13-2016		559.6	40.4	25.7
VB19-2016		569.8	23.4	19.5
VB20-2015	K2	543.9	32.4	14.2
VB11-2016		566.4	48.3	19.5
VB16-2016		564.4	44.8	23.4
VB17-2016		530.4	28.3	22.3

All the results showed differences in terms of standard deviation – within a blast as well as within a single L_{max} value (measurement uncertainty).

Varying standard deviation is an indicator that some parts of the deposit have less homogenous internal structure. In terms of a blast

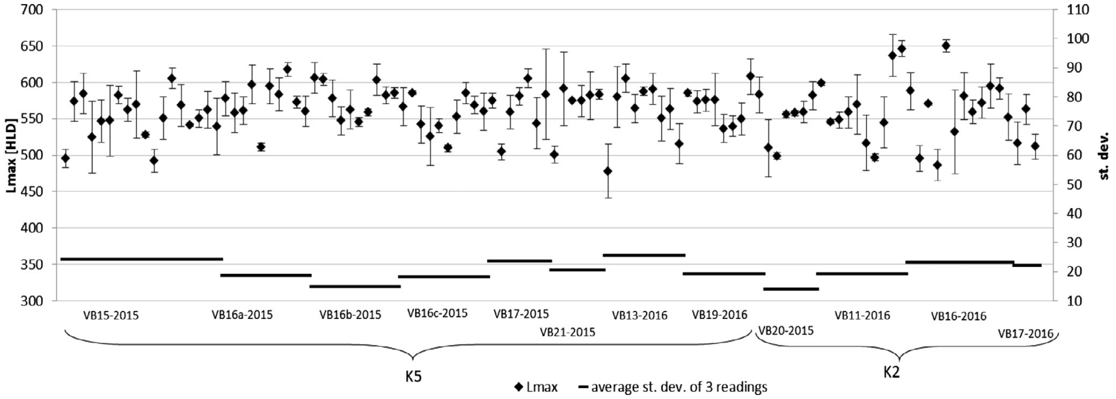


Fig. 9. Equotip tests results. The left hand axis refers to the L_{max} values for each blast. Error bars attached show the measurement uncertainty (based on standard deviation of the 3 Equotip readings included in the final L_{max} value). The right hand axis refers to the average measurement uncertainty of each blast and is shown as thick lines.

standard deviation, the highest value was noted for K2 type and lowest for K5 type, but in terms of a single surface average standard deviation the highest value was noted for K5 type and the lowest for K2 type. It can be an indication of the different scale of internal variability of the raw material: while high standard deviation of a blast shows that measurements differed from surface to surface (in different parts of a blast), the high values within a surface represent the variability within a single surface, that is, on a smaller scale.

5.3. Relation between mineralogy and surface hardness values

Two process implications of raw material parameters can potentially be interpreted from the Equotip measurements: (1) L_{max} values represent the internal textures of the calcite and hence, can be used as proxy for mineralogical textures; (2) L_{max} values may be used as a proxy for crushing hardness and the final particle size distribution from the crusher (Montoya, 2014). Both parameters are known to have influence on furnace performance as stated by Boynton (1966).

The collected data allowed for comparison between mineralogy and the Equotip testing results for blasts VB11-2016, VB13-2016, VB16-2016 and VB19-2016. It is important to note that the link between the results is not direct, as the samples used for thin sections were located in similar places within a blast, but were not the same as the surfaces used for the Equotip testing.

For K2 type it appears that the high L_{max} values obtained in blasts VB11-2016 and VB16-2016 are related to the coarser grain size and possibly higher silica content. The blast VB11-2016 was observed to have larger variation in terms of grain size which appears to be followed by higher standard deviation of surface measurements in the blast (Fig. 8). However, the blast VB16-2016 reached higher average value of the measurement uncertainty (Fig. 9) and therefore, this might be an indication of a smaller scale variability comparing to blast VB11-2016. An example would be small scale quartz veinlets compared to thick layers of coarser calcite within a blast.

Relation between mineralogy and L_{max} values in K5 type is more difficult to establish. The Equotip measurements show that both on a scale of single surface (Fig. 8) as on a scale of single measurement (Fig. 9), the standard deviation is higher for blast VB13 than VB19, which seems to be contrary to mineralogical observations (Fig. 5) where blast VB13 tended to be more homogenous in terms of grain size. The abundance of accessory minerals is also lower for blast VB13-2016 than for the blast VB19-2016 (Fig. 7). Hence, the reason for more homogenous L_{max} results in VB19-2016 is interpreted to be related to higher content of microcrystalline calcite which is an indication of higher level of metamorphic recrystallization. More Equotip tests are required in order to establish the links between parameters.

6. Conclusion

This study showed significant differences between two marble types that to date have been processed as the same quality. Based on obtained results the following conclusions can be drawn:

- Thin sections of marble type K5 were generally more fine-grained than those of type K2.
- Marble type K5 was however not homogenous in terms of grain size, as very fine and coarse grains coexisted within one blast samples.
- Quartz was observed in thin section more often in type K2 samples than in type K5 samples.
- Graphite was observed mostly in blast VB19-2016 belonging to K5 type.
- The grain size and mineralogical differences within marble types indicate the need for revision of the classifying parameters in order to establish new geometallurgical domains that could improve the process performance.
- The Equotip 3 D measurements showed that K2 type samples reached higher L_{max} values than K5 samples and had more variability within certain blasts.
- The K5 type material was on average more variable locally (within tested surfaces of certain blasts).
- Further Equotip 3 D tests are needed in order to observe possible trends and relations to internal structure of the marble.

Further studies of marble textures via use of image analysis and marble behaviour during dissociation via the use of a heating stage microscope are planned for the next part of the research study.

Acknowledgement

This research is funded by the Research Council of Norway in the User-driven Research based Innovation (BIA) program under the grant agreement 236638/O30, the industry partners and the Norwegian University of Science and Technology.

Appendix A

Sample			Typical grain size (µm)	Grain boundary shape	Other textural features	Accessory minerals	Sample			Typical grain size (µm)	Grain boundary shape	Other textural features	Accessory minerals
K2	VB11-2016	1-VB11	200–300	cu, em, su	m	py, Fe-ox	K5	VB13-2016	1-VB13	50–150	cu, str, su	m	py, Fe-ox
		2-VB11	100–250	cu, em, su		qtz, (py)			2-VB13	50–150	str, cu	m	py
		3-VB11	< 50–150			py, Fe-ox			3-VB13	200–250	su, em, cu		py, Fe-ox*Ti-ox*
		4-VB11	100–300	cu, str		py, Fe-ox			4-VB13	< 100	cu		py, gr
		5-VB11	50–100	cu, em	mcv 100–200 µm	qtz, py, Fe-ox*ap, Ti-ox*			5-VB13	100–150	cu, em, su		py, Fe-ox
		6-VB11	150–250	su, em		qtz, (py)			6-VB13	< 150	cu, su	m	py
		7-VB11	100–200	cu, str, em		qtz, ms, py, gr			7-VB13	< 150	em, su	m	PY
		8-VB11	100–300	su, em, sc		qtz, py			8-VB13	100–300	cu, str		qtz, py, Fe-ox
		9-VB11	200–400	cu, str, su	m	Fe-OX			9-VB13	150–200	cu, str	m	py, gr
	VB16-2016	1-VB16	250–350	cu, su, str	m	py, (Fe-ox)		VB19-2016	1-VB19	100–200	su, cu	m	py, gr, Fe-ox
		2-VB16	200–400	su, em	m	Fe-ox, (py)			2-VB19	100–200	su, em	m	py, gr, Fe-ox
		3-VB16	300–400	cu, su	m	qtz, py			3-VB19	< 150	su, cu	m, cv 350–600 µm	py, gr, Fe-ox
		4-VB16	150–250	su, str, em		py			4-VB19	50–250	su, em		(py)
		5-VB16	100–200	cu, str, su		py			5-VB19	100–250	su, cu		(py)
		6-VB16	100–200	cu, su		PY			6-VB19	50–150	su, cu	m, cv 300–450 µm	(py)
		7-VB16	80–180	cu, str		qtz, (Fe-ox)			7-VB19	50–200	str, cu	cv 3 mm	py, gr, Fe-ox
		8-VB16	50–150	cu, su, str	cv 350–600 µm	py, Fe-ox			8-VB19	0–450	su, cu, em	m	py
		9-VB16	100–200	cu, su, str		py-Fe-ox			9-VB19	50–200	su, cu, em	cv 300 µm	py, gr, Fe-ox

Appendix A: Compilation of information for mineralogical samples. Grain boundary shapes (GBS) noted in samples are: Cu (curved), Em (Embayed), Su (sutured), Str (straight). Accessory minerals are quartz (qtz), pyrite (py), graphite (gr), ferrous oxides and hydroxides (Fe-ox) and muscovite (ms). Minerals shown in brackets are present in extremely small amounts, whereas minerals in big letters are relatively abundant. Minerals mentioned with italics are trace minerals detected with SEM: apatite (ap), titanium dioxide (Ti-ox). Microcrystalline to cryptocrystalline calcite occurrence is marked as (m). Coarse grained veins (cv) show the typical size of vein constituent.

References

Aoki, H., Matsukura, Y., 2007. A new technique for non-destructive field measurement of rock-surface strength: an application of the Equotip hardness tester to weathering studies. Earth Surf. Process. Landforms 32, 1759–1769.

Boynton, R.S., 1966. Chemistry and Technology of Lime and Limestone. Interscience, New York.

Gautneb, H., 2012. Kommunedelplan Tromsdalen. Oversikt over geologiske forhold, marked og produksjon av kalkstein, Verdal.

Hökfors, B., 2014. Phase Chemistry in Process Model for Cement Clinker and Lime Production. Umeå Universitet, PhD.

Korneliussen, A., Raaness, A., Gautneb, H., 2014. Chemical and Mineralogical Characterisation of Carbonate Deposits in Norway. NGU Report.

Lischuk, V., Lamberg, P., Lund, C., 2015. Classification of Geometallurgical Programs Based on Approach and Purpose. SGA 2015. Nancy.

Montoya, P.L., 2014. Geometallurgical Mapping and Mine Modelling - Comminution Studies: La Colosa Case Study, AMIRA P843A. Master of Science in Geology, University of Tasmania.

Rodriguez-Navarro, C., Ruiz-Agudo, E., Luque, A., Rodriguez-Navarro, A.B., Ortega-Huertas, M., 2009. Thermal decomposition of calcite: mechanisms of formation and textural evolution of CaO nanocrystals. Am. Mineralogist 94, 578–593.

Viles, H., Goudie, A., Grab, S., Lalley, J., 2011. The use of the Schmidt Hammer and Equotip for rock hardness assessment in geomorphology and heritage science: a comparative analysis. Earth Surf. Process. Landforms 36, 320–333.

Paper II

minerals

Article

Geometallurgical Flowsheet as a Tool for Designing and Communicating Geometallurgical Programs

Aleksandra Maria Lang *, Steinar Løve Ellefmo and Kurt Aasly

Department of Geoscience and Petroleum, Norwegian University of Science and Technology, 7491 Trondheim, Norway; steinar.ellefmo@ntnu.no (S.L.E.); kurt.aasly@ntnu.no (K.A.)
* Correspondence: aleksandra.lang@ntnu.no

Received: 30 June 2018; Accepted: 22 August 2018; Published: 28 August 2018

Abstract: This paper introduces the concept of using a geometallurgical flowsheet as a tool to design, visualize and communicate a geometallurgical program. The development of the concept is carried out using a case study of an industrial mineral mining operation. A modified Integration Definition for Function Modeling (IDEF0) technique is proposed as a methodology to develop the geometallurgical flowsheet. The geometallurgical program is defined as a summary of the operations necessary to develop and validate the geometallurgical model. The geometallurgical model is defined as the function that links georeferenced in-situ geological characteristics and a georeferenced measure of performance in a processing plant. The geometallurgical flowsheet in this study is developed both as a general concept as well as a case-specific illustration based on the example of the Verdalskalk AS industrial mineral operation.

Keywords: geometallurgical flowsheet; geometallurgical model; geometallurgical program; IDEF0; industrial minerals

1. Introduction

As the complexity of newly discovered and developed deposits is increasing, the concept of geometallurgy expands in new directions and faces new challenges, showing more possibilities within a holistic approach to mining. In order to understand and characterize the flow of information and material in the development of the link between in-situ raw material properties and mineral processing parameters, the authors introduce a new concept of geometallurgical flowsheets. Hence, this study presents and discusses the definition, design and development of geometallurgical flowsheets. Further, the use of the modified Integration Definition for Function Modeling (IDEF0) language is introduced as the choice of the modeling technique.

The main objectives of the present study are: (1) To define the concept of geometallurgical flowsheet as a tool to design, visualize, and communicate a geometallurgical program; (2) to clarify the geometallurgical model definition; (3) to show the relationships between the geometallurgical program, the geometallurgical flowsheet, the geometallurgical model and the mining value chain; and (4) to assess the usefulness of the IDEF0 technique in geometallurgical flowsheet design.

To illustrate the creation of a specific geometallurgical flowsheet, the authors present a case study from the Verdalskalk AS industrial mineral operation in mid-Norway. While the main contributions to the geometallurgical approach come from the metal ore mining industry [1–3], it is important to ask the question about whether the geometallurgical approach can be broadened and therefore applied to industrial mineral operations. The challenge of linking processing performance with geological information, being the cornerstone of the geometallurgical approach, is also highly relevant in industrial mineral mining [4,5].

2. Background

2.1. Geometallurgy and Definitions

The concept of geometallurgy is already well defined and tested. Most sources define geometallurgy as an interdisciplinary view incorporating geology with metallurgy/mineral processing in order to increase mine performance and minimize risk values [6,7]. On a more detailed level, the definitions vary depending on the scope of the geometallurgical approach in the mine operations, as well as the predictability level of the defined geometallurgical models [8].

A geometallurgical model is defined as "organization of geological and metallurgical information into a spatial and predictive tool to be used in production planning and management in the mining industry" [2]. Several studies show the importance of creating a valid and effective geometallurgical model in order to fully benefit from the use of the geometallurgical approach in mining operations [1,9]. A successful geometallurgical model must be based on both geological/geochemical/mineralogical inputs and metallurgical tests [10].

A geometallurgical program is often seen as an industrial application of geometallurgy that improves the understanding of the resource [9]. Processes, such as sampling, data collection, establishing models and model validation, are an inherent part of the geometallurgical program [2,11].

The relationship between the geometallurgical model and the program is unclear in the literature. The model may be seen as a final outcome of the geometallurgical program [2] or as the development taken prior to running the program [9,12].

2.2. Geometallurgy for Industrial Mineral Operations

The industrial mineral sector is mainly based on controlling product or concentrate qualities and specific customer requirements. Product prices are negotiated, often according to specific requirements from different customers. The prices are also typically kept confidential. The price primarily depends on the ability to compete in product quality (typically purity of concentrate), and thus competence and the ability to produce high quality specialized products for the high end market will increase prices, but also significantly increase operational costs. Hence, industrial mineral mining can be highly diverse and a geometallurgical approach is critical for expanding the knowledge of the commodity as well as maximizing the outputs, as reported by Aasly and Ellefmo [4]. The two case studies presented in this paper show that the elements of geometallurgy have already been implemented in industrial minerals operations, but as yet no geometallurgical block model—in the traditional sense—has been established.

2.3. Verdalskalk AS Case Study

The industrial mineral company Verdalskalk AS is located in mid-Norway and mines a calcite marble deposit in an open pit operation. The deposit is a pure, low metamorphic calcite marble ($CaCO_3$) of the Ordovician period (approximately 460 Ma). The deposit is assumed to contain approximately 7.5 billion metric tons, having a length of 6 km and maximum width of about 2.2 km [13]. Other phases present are graphite, iron oxides (limonite, hematite), sulfides (pyrite), and silicate minerals such as quartz, feldspar, and biotite [14]. Verdalskalk AS divides the marble into qualities with respect to the amount of CaO, Fe_2O_3, SiO_2 and Al_2O_3. The qualities that are exploited are divided into: Pure, standard and cement quality (Table 1). X-ray fluorescence (XRF) analysis is performed on drill cores during the pre-operational sampling campaign, as well as on drill chips prior to blasting and during production. The pure quality is used for quicklime and slaked lime production (Personal communication with Ruiz, J.R., 6 March 2015). Processing and geometallurgical development of the standard and cement qualities are beyond the scope of the presented research.

Table 1. Quality demands for Verdalskalk deposit. Values in percentage by weight [15].

Oxide (wt %)	Pure	Standard	Cement
CaO	>54.5	>54.0	>50.4
MgO	<0.6		
SiO_2	<0.5		
Al_2O_3	<0.2		
Fe_2O_3	<0.06	0.06–0.12	>0.12
Na_2O	<0.015		
K_2O	<0.04		
MnO	<0.005		
P_2O_5	<0.04		
TiO_2	<0.01		
SiO_2	<0.5		
SO_3	<0.02		
$CaCO_3$	>97.3	96.4–97.3	>90.0

After blasting, the fragmented marble is loaded onto trucks and transported to the crushing plant. The rock used for the quicklime production is crushed and sized to 30–100 mm.

At the kiln facility, crushed pure quality marble is burnt in a two-shaft Maerz furnace in temperatures reaching 1000–1200 °C in the burning zone (Personal communication with Storli, A.M., 7 March 2015). The quicklime (CaO, burnt lime) is created via the reaction:

$$CaCO_{3\ (s)} + \text{Heat} \rightarrow CaO_{\ (s)} + CO_{2\ (g)}$$

The burnt lime is processed to a variety of products of 0–0.2 mm to 0–40 mm particle size (Personal communication with Mork, H., 22 February 2018).

Lang, et al. [16] proposed a series of proxies that can be used in a geometallurgical flowsheet at the mine site. Conclusions were made based on knowledge gained during fieldwork and laboratory work, as well as on literature study and personal communication:

- The calcite burning response is a function of grain size and textures [17]. As the quicklime key performance indicators (KPIs), which are CO_2 residue and CaO activity, depend on the burning performance, the indirect link between the mineralogical properties and the KPIs can be established.
- Surface hardness rebound tests provide a proxy for the rock crushing and milling performance [18].
- Surface hardness can also be a representation of the mineralogical and textural (grain size) features [19]. As mineralogical characterization under the microscope is time consuming and costly, the surface hardness tests were proposed as a proxy for the textural and mineralogical features of the rock.
- Burning performance is a function of kiln feed particle size distribution [17].

2.4. Integration Definition for Function Modeling (IDEF0)

The graphical presentation of either geometallurgical operations or ways to build a geometallurgical model has been presented in the literature before, for example by Keeney and Walters [20], Sola and Harbort [10], and Lund and Lamberg [21]. However, in this study, the authors explored the idea of treating the graphical presentation as a tool to be used on site. A detailed presentation with consistent use of the modeling language IDEF0 is proposed.

IDEF0 is a methodology designed to model the decisions, activities and actions within a system or a process using a combination of graphics and text. The methodology evolved from a well-established graphical language, the Structured Analysis and Design Technique (SADT). Two primary modelling components are functions that are represented on a diagram as boxes, and objects that belong to four main types of relations: inputs, controls, outputs and mechanisms—abbreviated as ICOMs. The ICOMs are linked to functions using arrows (Figure 1). The functions can be processes, activities or actions. The IDEF0 methodology is simple and coherent, and provides a precise visualization of relationships and dependences within a modeled system using a fixed set of symbols. The methodology is applicable to, and recommended for, projects that require a modelling technique for the analysis, development or re-engineering of a system [22].

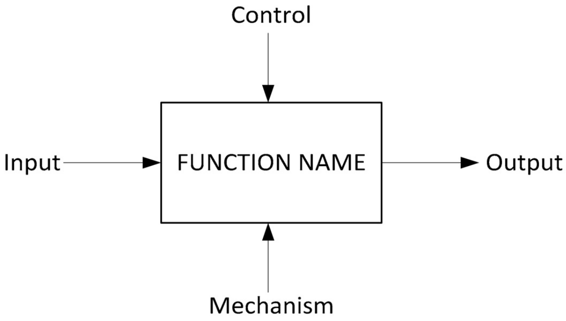


Figure 1. The basic diagram of the Integration Definition for Function Modeling methodology (IDEF0). A function is manufactured with the use of ICOMs: Inputs, Controls, Outputs and Mechanisms [22].

3. Materials and Methods

The IDEF0 method used in this study for the geometallurgical flowsheet visualization is a modified version of the method originally proposed by Lund and Bilov-Olsen [23]. The modifications are related to the appearance of the symbols used in the modeling (Figure 2), and are based on a model developed by Industrial and Financial Systems [24]. The functions are presented by white chevrons with a blue rim, and the ICOMs are shown as blue boxes.

Input boxes are linked to the left side of chevrons. Inputs examples are requirements, information, problems, material or conditions. The input is used, consumed, or altered by the function.

Controls are objects vital to produce an output, as they control the way the function is executed. The control boxes are linked to the top side of chevrons. Examples of controls are standards, regulations, plans, and conditions that have to be fulfilled.

Outputs, such as results, information or products, are created or come out of the function. The output boxes are linked to the right side of the chevron.

Mechanism boxes are placed below the chevron and connect to the bottom side of it. Mechanisms are used but not consumed, and they support the execution of the functions. Examples are human resources, tools, equipment, systems and facilities.

The relationships between functions and ICOMs are presented by lines in different colors and styles. It is therefore possible to distinguish between main flow, secondary flow, specializations and generalizations. The preferred flow direction between inputs and functions, and between functions and outputs, within the modelled system is from left to right. All of the symbols utilized in this study may be visualized in Figure 2.

In the IDEF0 methodology, the functions can be decomposed into more detailed diagrams called child diagrams. In the model proposed for this study, the elements that are detailed are presented with shadows. Each IDEF0 diagram has an A-number. The top-level diagram is called A-0 diagram (A minus zero), and represents the major function of the system. It provides the most general description and scope. The next level diagram is A0. Lower level diagrams are numbered according to the function from which they started (A1, A11, etc.).

The flowsheet development was based on extensive fieldwork and literature study. The fieldwork comprised of data collection, interviews with employees and investigation of the data flow and data management within facilities. The different views on the graphic presentation were tested and developed within numerous meetings and discussions. For the creation of flowsheets, Microsoft Visio 2010 software (Microsoft Corporation, Redmond, WA, USA) was used.

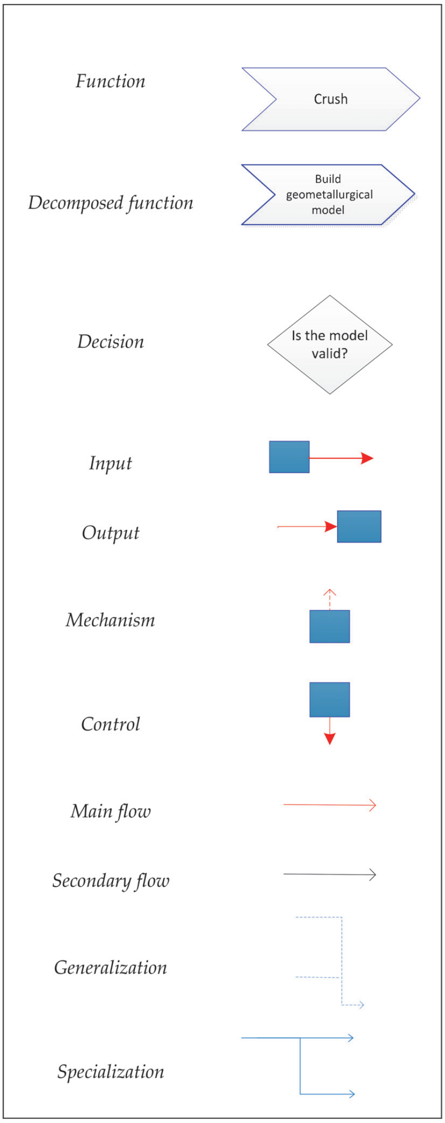


Figure 2. Main symbols used for the modified Integration Definition for Function Modeling (IDEF0) methodology.

The first step of the case specific geometallurgical program and model development is to define the parameters responsible for the mine's KPIs and to outline the initial model. For the case of Verdalskalk AS, the main dependencies were hypothesized based on literature [17,18,25], as well as the mine operators experience (Personal communication with Storli, A.M., 7 March 2015) and laboratory study detailed in Lang, Aasly and Ellefmo [16].

4. Results

In the authors' view, a geometallurgical flowsheet is a tool for designing, visualizing and communicating a geometallurgical program; that is, steps that need to be taken for the geometallurgical model development. According to this perspective, a geometallurgical program is a summary of the geometallurgical operations that, combined in a sequence, lead to the geometallurgical model's establishment and implementation into mine operations.

Based on the available definition in the literature [2], a geometallurgical model is defined as a function that links georeferenced in-situ geological characteristics and a georeferenced measure of performance in a processing plant, emphasizing the positioning of the geoscientific data. The dependency can either be quantitative, semi-quantitative or qualitative. The dependencies can take the following form:

$$Performance\ measure = f\ (x, y, z, var1, var2, \ldots\ var\_n),$$

where examples of performance measure are metal or mineral recovery, breakdown costs or product quality (e.g., purity), and examples of variables that influence the performance include the rock/ore chemistry, mineralogy or hardness. A qualitative dependency is a descriptive understanding of the relation between in-situ properties and the performance.

In the authors' view, a geometallurgical model is the outcome of the implementation of a geometallurgical program that consists of the execution of a number of working processes.

The inconsistencies in the literature regarding the geometallurgical model to program relationship have been resolved using the term *a priori* model for the initial model that had existed as an idea before the geometallurgical program has been started. The *a priori* model can be viewed as a controlling element of the geometallurgical program development. An *a priori* model is seen by the authors as a list of dependencies between in-situ parameters and a metallurgic response that has to be hypothesized, and is based on operational experience, literature review and test-work. Through the execution of the geometallurgical program, geometallurgical test-work and characterization are performed to formulate the equations that describe the nature of the dependencies. Further, the preliminary coefficients used in the equations are determined and validated by iterating the geometallurgical program. The reconciliation of the coefficients by the use of production data is the next logical step and it is only at this point that the geometallurgical model is fully developed.

4.1. General Geometallurgical Flowsheet

Figure 3 shows the A-0 level geometallurgical flowsheet. The *a priori* model serves as the control of the *Develop geometallurgical model* process. The raw material has certain properties (mineral characteristics, processing behavior etc.). These properties are revealed and tested during the *Develop geometallurgical model* process in order to develop the mathematically oriented geometallurgical model.

On a more detailed level, the *Develop geometallurgical model* process is broken down into the process of building the model and reconciliation of the model (A0 level). The model is verified on two levels: First, by possible iterations during *Build a geometallurgical model* process, where the defined coefficients can be adjusted during continuous testing and analyzing, and secondly during the *Reconcile model* process where the coefficients are refined using the data from the regular production (Figure 4). During the reconciliation stage, the model development is a result of adaptations to changes in raw material characteristics and product requirements. Regression analyses are used to update the equations and the coefficients.

The function *Build geometallurgical model* has been decomposed further into more detailed functions on the A1 level (Figure 5). The main functions of this part of the geometallurgical flowsheet are: *Sample*, *Test and analyze*, and *Develop equations*. This concludes the general geometallurgical flowsheet, and these functions will then be decomposed in the development of a case-specific flowsheet. The processes related to data cleaning and quality assurance (QA)/quality control (QC) are within the child diagrams of the *Test and analyze* function in Figure 5. This implies that the data in the *Data collected* box are cleaned and quality assured and controlled.

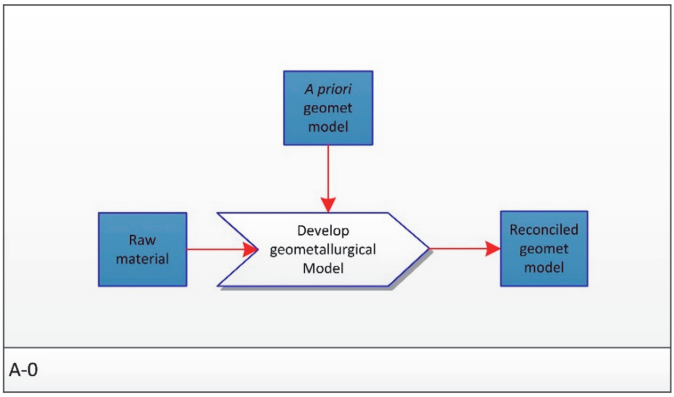


Figure 3. Geometallurgical flowsheet on a most general A-0 level.

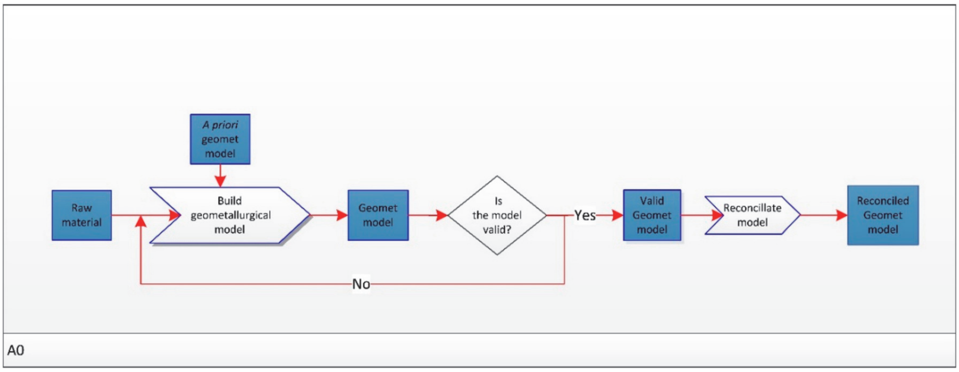


Figure 4. A child diagram of the *Develop geometallurgical model* function.

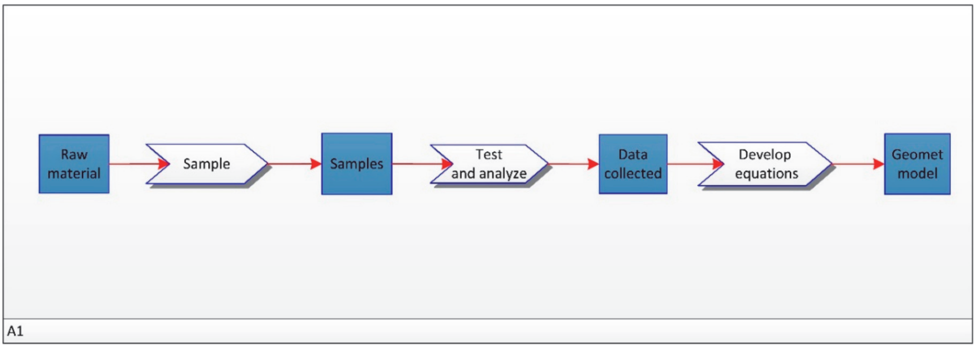


Figure 5. A child diagram of the *Build geometallurgical model* function.

4.2. Case-Specific Geometallurgical Flowsheet—Example from Verdalskalk AS

The geometallurgical flowsheet presented in the following is a combination of the procedures performed during mining operations at Verdalskalk AS and the herein proposed procedures.

4.2.1. The A Priori Model

The *a priori* model for Verdalskalk AS is formulated as follows:

1. Raw material textural and mineralogical characteristics = f(x,y,z, surface hardness).
2. Quicklime CaO activity and CO_2 residue = f(x,y,z, raw material textural and mineralogical characteristics, kiln feed particle size distribution (PSD), burning parameters).

4.2.2. The Sample Function, A11 Level

The detailed *Sample* function, presented in Figure 6, shows the sampling strategy that is needed to follow the *a priori* model.

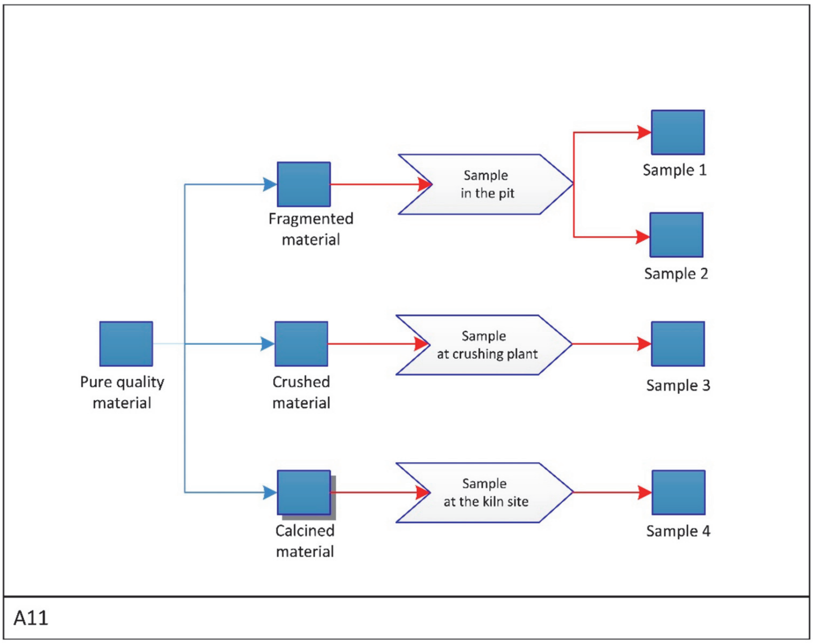


Figure 6. A case-specific geometallurgical flowsheet: A child diagram of the *Sample* function.

In the study, a geometallurgical flowsheet was designed for the pure quality material that had been already qualified based on chemistry. Therefore, geochemical testing of the rock is not shown as a part of the flowsheet in this case.

The flowsheet uses the relation "consists of". The pure quality material used for sampling consists of fragmented, crushed and calcined material. The three types of material are sampled at different stages of the mine operations: After blasting, after crushing and after calcining the raw material.

Every element of such a flowsheet can and should be decomposed further, showing for example the origin of the specified material or details of the sampling procedure. In Figure 6, the box *Calcined material* is presented with a shadow that indicates later decomposition. This example is expanded in Figure 7.

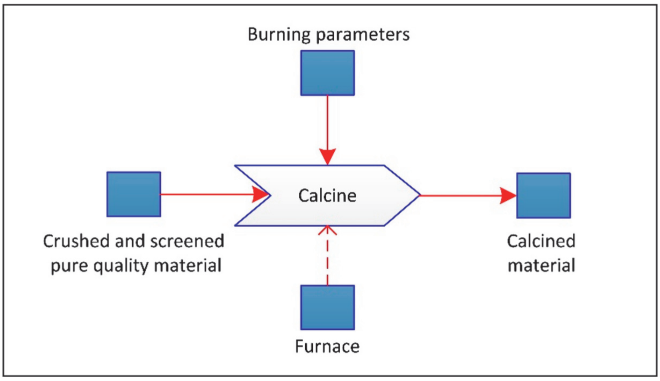


Figure 7. Decomposition of the *Calcined material* box.

Other important factors that can be communicated at this level are, for example, detailed sampling procedure, amount of the material needed, and equipment necessary for sampling.

4.2.3. The Test and Analyze Function, A12 Level

The detailed *Test and analyze* function is shown in Figure 8.

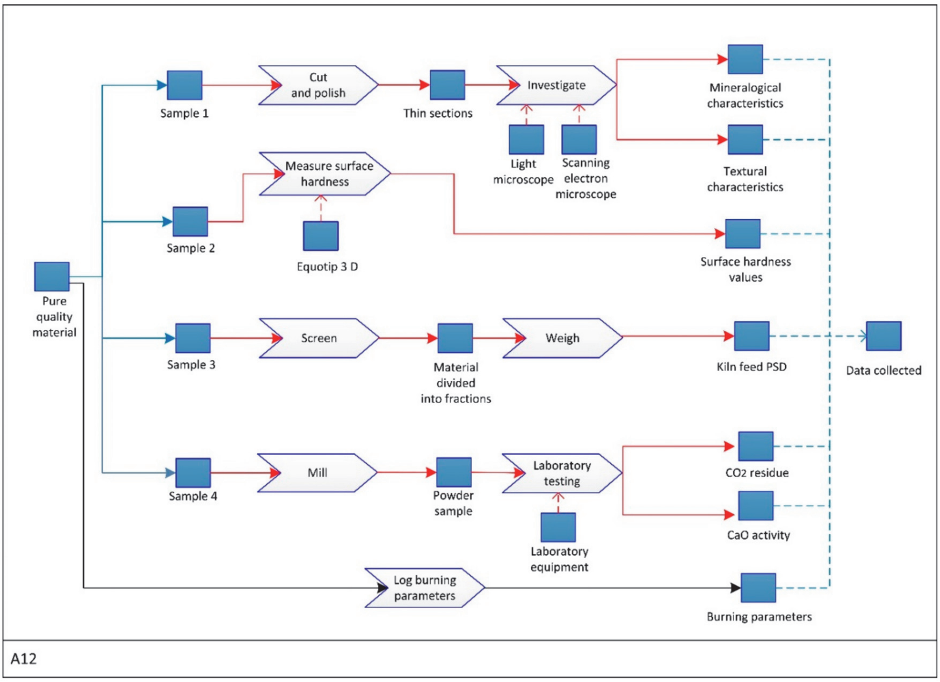


Figure 8. The *Test and analyze* function decomposed into details. Note the use of the "generalization" type of relation (dashed blue lines). PSD—particle size distribution.

The pure quality material is divided into sampling lines and samples are ready to be used based on the previous part of the flowsheet, as shown in Figure 8. At this point, possible decomposition allows for a detailed view of the analyses taken. The fractional collected data is combined as a final *Data collected* output. The analysis proposed for Verdalskalk is based on four sampling lines:

1. The material sampled in the pit after blasting is used to prepare thin sections that undergo the textural and mineralogical analysis with the use of a light and scanning electron microscope.

The textural characteristics that affect the kiln performance are grain size and textural variations [16,17]. In terms of mineralogy, the content of graphite-, quartz- and iron oxides may vary, even if the values are within specifications or below the XRF detection limit [16], hence textural and modal mineralogy tests are proposed.

2. Surface hardness is measured directly in the pit after blasting, with the use of an Equotip 3 D device.

Since the product quality after burning is the function of textural characteristics, which is itself the function of surface hardness, in the ideal situation the surface hardness values could serve as direct proxy for the burnt lime KPIs. However, in our study the direct proxy was not yet possible to establish, hence we propose the program that consists of both surface hardness and textural/mineralogical tests with possible improvements in the future.

3. The kiln feed material after crushing (30–100 mm) is screened and weighed in order to measure the particle size distribution.

The burning performance can be affected by too much fines in the kiln. Currently the tests done by Verdalskalk serve in order to check if the feed kiln is within the desired PSD, but it is advisable to run the tests more often in order to notify potential relationships between the PSD and burning performance on a daily basis.

4. Samples of calcined material are milled, split and tested for CO_2 residue and CaO activity.

CaO activity and CO_2 residue are important qualifying parameters of the final product (burnt lime). For measuring the CaO activity a sample of milled burnt lime is added to water. The time that it takes the water temperature to rise from 20 °C to 60 °C (T_{60}) and a total temperature rise (ΔT_{tot}) as a result of the exothermic slaking reaction between the water and the lime, is measured. CO_2 residue in quicklime is measured with the use of hydrochloric acid and the gasometric method.

In addition to the four sampling lines, there is also a need for logging and collecting the burning parameters as furnace temperature, pressure, oil usage. This line is presented in Figure 8 as a secondary flow because it represents the observations and not sampling results.

4.2.4. The Develop Equations Function, A13 Level

The *Develop equations* function is decomposed into details, as shown in Figure 9.

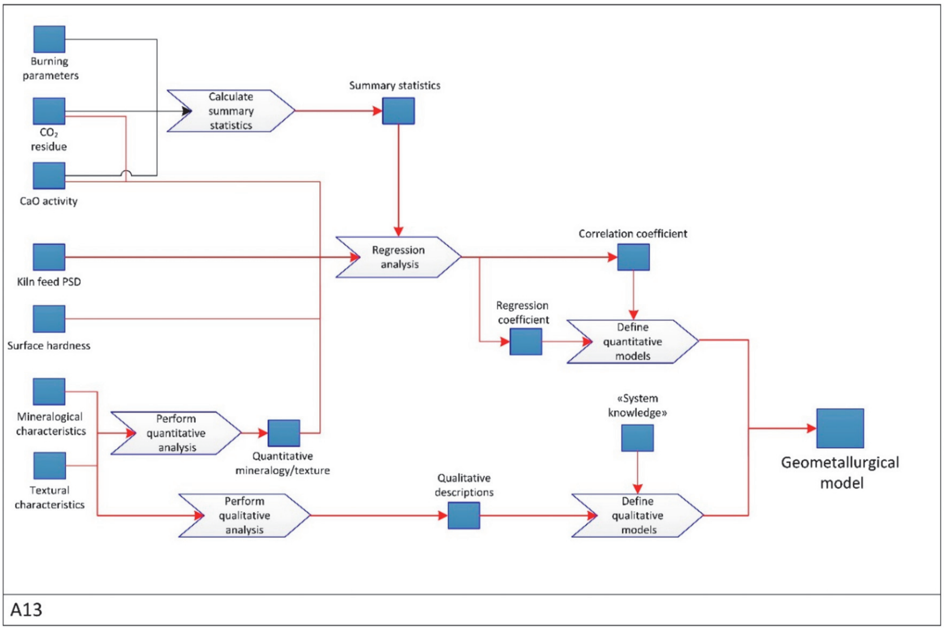


Figure 9. The *Develop equations* function detailed as a child diagram.

On this level, all the quantitative data undergo mathematical analysis and all the qualitative data are also processed in order to find relations between parameters. Burning parameters, CO_2 residue, and CaO activity form a large dataset that undergo the *Calculate summary statistics* process and the output of the process can be used as the control of the *Regression analysis* process. CO_2 residue, CaO activity, and surface hardness results are quantitative data that might be correlated. The final geometallurgical model in Figure 9 is the combination of the quantitative and qualitative models.

Examples of further decomposition of the processes on this level are the details of mathematical operations, the software used for analysis and the detailed qualitative descriptions of the textures and mineralogy.

The example summary statistics from Verdalskalk AS kiln operation are provided in Table 2. The statistics comprise the burning parameters and quicklime KPIs on three random days within a production year. These data can be used as a control for establishing the regression coefficient between KPIs and raw material parameters.

Table 2. Example summary statistics from Verdalskalk kiln facility. St.dev.—standard deviation; T_{60}, ΔT_{tot}—quicklime activity parameters.

		Day 1		**Day 2**		**Day 3**	
Chosen Parameters		**Average**	**St. Dev.**	**Average**	**St. Dev.**	**Average**	**St. Dev.**
Burning parameters	Fuel (l/min)	167.8	2.1	163.2	2.8	149.5	3.0
	Pyrometer (°C)	877.6	7.4	881.6	15.4	890.7	8.7
Quicklime KPIs	T_{60} (s)	96.5	39.9	362.2	110.7	53.0	11.2
	ΔT_{tot} (°C)	53.7	1.0	53.0	0.8	54.9	0.7
	CO_2 (%)	1.9	0.7	1.2	0.4	2.5	0.3

5. Discussion

The geometallurgical flowsheet has been coined and defined in this study as a tool for the design, visualization and communication of a geometallurgical program. It is to be used on site and developed in collaboration with specialists associated with different parts of the mining value chain. This is supported by Lund et al. [23], who proposes that any process flowsheets are created within an organization during meetings and workshops, thereby allowing for collaboration and experience exchange between specialists and between departments.

In this work, the definition of the program, as the summary of operations, needed to establish the final and validated geometallurgical model [2], was followed and expanded by introducing the concept of the *a priori* model as a control of the model development. This clarified the inconsistencies that exist in literature [2,21,26]. It is imperative to identify the potential relations between geological and metallurgical parameters first, but it is only after the program is executed and data are obtained that one can establish the quantitative and qualitative relationships that constitute the geometallurgical model. The geometallurgical model will continuously be developed through the geometallurgical program execution, specifically as a part of the reconciliation process.

After the model creation, the program is still executed further to validate the model and to implement the model as a controlling element of the mining value chain. The ideal situation is to build a model that is fully predictive and therefore the geometallurgical program is non-repetitive. However, it is important to keep in mind that the program and the flowsheet design must remain dynamic and agile, and the need for iterations and fast modifications, controlled by such elements like in-situ raw material variations, technical issues, mine capacity demand and new customer requirements is essential.

The general geometallurgical flowsheet should be treated as the basis when building an operation-specific geometallurgical flowsheet. The following main functions and associated ICOMs, vital for the flowsheet development, must be considered:

- The *a priori* model: A preliminary model based on pre-testing, experience and literature.
- The *sampling* function: Presentation of sampling methods and taking care of representativeness of the samples.
- The *testing and analyzing* function: Presentation of the testing and analyzing technologies and methodologies used to develop the model.
- The *develop equations* function: The presentation of the development of the mathematical relationships included in the final model.

The predictive capabilities of the model cannot be better than the quality of the input used during model development. Having a function for data cleaning and QA/QC is therefore vital. In the proposed flowsheets, these functions were implicit and included within the testing and analyzing function. Therefore, the output from the function should be considered as clean and quality assured/controlled.

A case-specific geometallurgical flowsheet is the natural evolution of the general flowsheet into case-dependent details of the geometallurgical program. The authors chose to present the geometallurgical flowsheet as a series of diagrams presenting sampling, testing and analyzing, and establishing equations needed for model establishment. Most of the presented functions can be decomposed into child diagrams. Decomposing avoids chaos in the graphical representation of processes as it prohibits mixing the details that are important at different levels.

Other proposed elements not stated in the graphical presentations in this paper are, for example, a description of the types of material available for analysis, amount of the material, cost and location of analysis, as well as the detailed flow of the results, including who will be using them and at which step.

It is essential to provide a link between the geometallurgical flowsheet and the actual mining value chain. The final geometallurgical flowsheet is full-fledged only after its relation to the actual mine value chain is fully developed and understood. In the current work, it is proposed that the established geometallurgical model becomes a controlling element of an *Estimate blast specific KPIs* function (Figure 10).

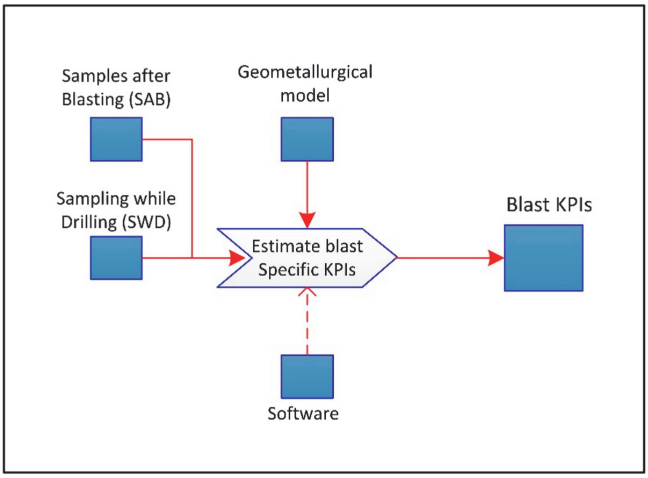


Figure 10. Geometallurgical model used as a controlling element for estimation of blast specific KPIs (key performance indicators).

For Verdalskalk AS, the main goal is to predict the quicklime CaO activity and CO_2 residue for each blast. In other cases, the specific KPIs can be used either in a blending procedure or for selecting the processing route the blast material should follow.

This also leads to possible geometallurgical domaining or re-domaining of the deposit. The Verdalskalk commodity is an example of a relatively homogenous deposit. It has to be mentioned that in more complex deposits the geometallurgical domains of different characteristics are often subdivided. This raises the need for an even more detailed flowsheet with precise descriptions of relations and significant parameters within each domain.

The main advantage in communicating the program through the geometallurgical flowsheet is the increased understanding of what types of processes have to be performed and how the processes are linked. It is also helpful in realizing what types of requirements are needed to be put on processes and what has to be done to assure that the requirements are met.

In the current study, the authors propose a structured and detailed presentation with a consistent use of the well-established modeling language IDEF0. The IDEF0 language is one of many that can be used when presenting the process development. The main strength of the IDEF0 language is that the method serves well for communication as the detailed description of activities can be presented by ICOMs, and that a model can be refined into greater and greater detail when needed. IDEF0 is a good analysis tool as well, as it assists in identifying controls and mechanisms of the functions. The "input versus control" separation rule allows for better determination of the role of data as there is an increased level of understanding about what processes/objects are consumed and what processes/objects are not modified but serve as controlling elements [27]. In the presented study, the communication was enhanced by the modified Lund version [23], where greater variety in terms of colors and shapes of the flowsheet compared to the original standard can help with even more effective use of the created models. The modified IDEF0 used in this study presents details that are not very visible in the original method. The presentation of the ICOMs as boxes (and not only text fields, as in the original IDEF0) causes increased visibility and understanding of the processes.

Additionally, including too much information in a single flowsheet must be avoided. IDEF0 methodology serves well for this challenge as possible decomposition of diagrams can easily lead from more general to more detailed operations. Also different types of flows are clearly marked and easy to distinguish.

The use of colors represents both strengths and weaknesses of the modified method. It allows for greater variability of communicated messages, however it does not follow the “keep it simple” rule and may cause chaotic appearance if the color coding is not properly explained. On the other hand, the color system can, in future developments, be further enhanced and used to distinguish between physical- (samples, equipment, etc.) and non-physical objects (data, analysis, etc.).

The original IDEF0 method encourages the horizontal types of flow, while the advantage of the modified method is that it is possible to amalgamate several processes and visualize them as several lines shown simultaneously (Figures 6, 8 and 9). This provides an enhanced and more holistic view of the processes. It is possible to amalgamate the processes horizontally and compose longer chains of diagrams, especially if a broader view of the geometallurgical program is needed. However, the authors do not recommend creating the diagrams only on a single horizontal level as such design would contradict the holistic view of the geometallurgical program. It is important to note that the IDEF0 technique is not a representation of a timeline, and therefore the processes can be looped and repeated until a better understanding of the model and the program is achieved.

6. Conclusions

- The geometallurgical flowsheet is an illustrative tool used to visualize and communicate the elements of a geometallurgical program. It is proposed to be used on site, for enhanced communication between specialists.
- The execution of geometallurgical program leads to creation of a geometallurgical model, which is the quantitative (as well as qualitative, if quantitative is not possible) and geo-referenced formulation of links between processing parameters and key performance indicators.
- The geometallurgical *a priori* model serves as a controlling element of the geometallurgical program. A validated geometallurgical model is an outcome of the geometallurgical program.
- The general geometallurgical flowsheet is a base for creating the specific geometallurgical flowsheet.
- On a general geometallurgical level, it is important to relate the *a priori* model to the actual geometallurgical program and to relate the flowsheet to the mine value chain.
- The case-specific geometallurgical flowsheet creation needs an understanding of the relations between geology, processing and the final product outcome. On a case-specific level of the geometallurgical flowsheet it is vital to provide detailed information about sampling, testing and analyzing, developing the quantitative as well as qualitative relations, and validating the model against the *a priori* model by iterations.
- The geometallurgical flowsheet, built with the use of IDEF0 technique, is an easy to understand, coherent and intuitive tool. The ability to decompose the diagrams into sub diagrams helps with visualization of both the main process flow as well as the details. The use of colors assists in distinguishing between primary and secondary flows of processes.
- As geometallurgy as a concept leads toward better communication between disciplines, the IDEF0 methodology is a tool that fits well in to the idea of elevated interdisciplinary communication.
- The case study of Verdalskalk shows a potential in applying geometallurgy and geometallurgical flowsheets into industrial mineral operations.

Author Contributions: Conceptualization, S.L.E. and K.A.; Investigation, A.M.L.; Writing-Original Draft Preparation, A.M.L.; Writing-Review & Editing, A.M.L., S.L.E., K.A.; Supervision, K.A. and S.L.E.; Funding Acquisition, K.A. and S.L.E.

Funding: The research is financed by Norwegian Research Council project 236638/030, “Increased Recovery in the Norwegian Mining Industry by Implementing the Geometallurgical Concept”.

Acknowledgments: Julie Hunt (University of British Columbia) is acknowledged for providing ideas and remarks. Rolf Arne Kleiv (Norwegian University of Science and Technology) is acknowledged for his support and fruitful discussions. Maarten Felix (Norwegian University of Science and Technology) is acknowledged for proofreading.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Alruiz, O.M.; Morrell, S.; Suazo, C.J.; Naranjo, A. A novel approach to the geometallurgical modelling of the collahuasi grinding circuit. *Miner. Eng.* **2009**, *22*, 1060–1067. [CrossRef]
2. Lamberg, P.; Rosenkranz, J.; Wanhainen, C.; Lund, C.; Minz, F.; Mwanga, A.; Parian, M. Building a geometallurgical model in iron ores using a mineralogical approach with liberation data. In Proceedings of the Second AusIMM International Geometallurgy Conference, Brisbane, Australia, 30 September–2 October 2013; pp. 317–324.
3. Macfarlane, A.S.; Williams, T.P. Optimizing value on a copper mine by adopting a geometallurgical solution. *J. S. Afr. Inst. Min. Metall.* **2014**, *114*, 929–936.
4. Aasly, K.; Ellefmo, S.L. Geometallurgy applied to industrial mineral operations. *Mineralproduksjon* **2014**, *5*, A21–A34.
5. Bunkholt, I.O. The Implications of Sulphides in Gcc Feed and the Potential for Their Removal during Alkaline Amine Flotation. Ph.D. Thesis, Norwegian University of Technology and Science, Trondheim, Norway, 2015.
6. Dunham, S.; Vann, J.; Coward, S. Beyond geometallurgy—Gaining competitive advantage by exploiting the broad view of geometallurgy. In Proceedings of the First AusIMM International Geometallurgy Conference, Brisbane, Australia, 5–7 September 2011; pp. 5–7.
7. Dominy, S.; O'Connor, L. Geometallurgy-beyond conception. In Proceedings of the Third AusIMM International Geometallurgy Conference, Perth, Australia, 15–17 June 2016.
8. Jackson, J.; Mc Farlane, A.J.; Olson Hoal, K. Geometallurgy-back to the future: Scoping and communicating geomet programs. In Proceedings of the First AusIMM International Geometallurgy Conference, Brisbane, Australia, 5–7 September 2011; Dominy, S., Ed.; Australasian Institute of Mining and Metallurgy: Melbourne, Australia, 2011; pp. 125–131.
9. Lischuk, V.; Lamberg, P.; Lund, C. Classification of geometallurgical programs based on approach and purpose. In Proceedings of the 13th Biennial Meeting of the SGA, Nancy, France, 24–27 August 2015.
10. Sola, C.; Harbort, G. Geometallurgy-tricks, traps and treasures. In Proceedings of the 11th AusIMM Mill Operators' Conference, Hobart, Australia, 29–31 October 2012.
11. Hoal, K.O. Getting the Geo into Geomet. Available online: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.462.2018&rep=rep1&type=pdf (accessed on 30 June 2018).
12. Lishchuk, V. Geometallurgical Programs-Critical Evaluation of Applied Methods and Techniques. Licentiate Thesis, Luleå University of Technology, Luleå, Sweden, 2016.
13. Håvard Gautneb. Kommunedelplan Tromsdalen, Verdal. Oversikt over Geologiske Forhold, Marked og Produksjon av Kalkstein. Available online: https://www.ngu.no/publikasjon/kommunedelplan-tromsdalen-verdal-oversikt-over-geologiske-forhold-marked-og-produksjon (accessed on 30 June 2018). (In Norwegian)
14. Korneliussen, A.; Raaness, A.; Gautneb, H. *Chemical and Mineralogical Characterisation of Carbonate Deposits in Norway*; Technical Report; NGU: Trondheim, Norway, 22 September 2004.
15. Rojas Ruiz, J. Pure, standard, cement kvalitetsgrensene. Unpublished work, 2015.
16. Lang, A.M.; Aasly, K.; Ellefmo, S.L. Mineral characterization as a tool in the implementation of geometallurgy into industrial mineral mining. *Miner. Eng.* **2018**, *116*, 114–122. [CrossRef]
17. Boynton, R.S. *Chemistry and Technology of Lime and Limestone*; Interscience: New York, NY, USA, 1966.
18. Montoya, P.L. Geometallurgical Mapping and Mine Modelling-Comminution Studies: La Colosa Case Study, Amira P843a. Master's Thesis, University of Tasmania, Hobart, Australia, 2014.
19. Verwaal, W.; Mulder, A. Estimating rock strength with the equotip hardness tester. *Int. J. Rock Mech. Min. Sci. Geomech. Abstr.* **1993**, *30*, 659–662. [CrossRef]

20. Keeney, L.; Walters, S.G. A methodology for geometallurgical mapping and orebody modelling. In Proceedings of the First AusIMM International Geometallurgy Conference, Brisbane, Australia, 5–7 September 2011; Dominy, S., Ed.; Australasian Institute of Mining and Metallurgy: Melbourne, Australia, 2011; pp. 217–225.
21. Lund, C.; Lamberg, P. Geometallurgy: A tool for better resource efficiency. *Eur. Geol.* **2014**, *37*, 39–43.
22. National Institute of Standards and Technology (NIST). *Integration Definition for Function Modelling (IDEF0)*; NIST: Gaithersburg, MD, USA, 1993.
23. Lund, Ø.; Bilov-Olsen, J.; Lilleås, J.E.; Johansen, T.E. Håndbok i Prosessmodellering i Forsvaret. Unpublished work, 2001, p. 57.
24. Industrial and Financial Systems, IFS AB. Ifs. Available online: http://www.ifsworld.com (accessed on 30 June 2018).
25. Hökfors, B. Phase Chemistry in Process Model for Cement Clinker and Lime Production. Ph.D. Thesis, Umeå Universitet, Umeå, Sweden, 2014.
26. Cropp, A.G.W.; Bradshaw, D.; Hunt, J.; Berry, R. Communicating and integrating geometallurgical data along the mining value chain. In Proceedings of the XXVII International Mineral Processing Congress, Santiago, Chile, 20–24 October 2014.
27. Knowledge Based Systems Inc. Integrated Definitions Methods (IDEF). Available online: http://www.idef.com/ (accessed on 1 February 2018).

Paper III