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History and growth of modern process mineralogy

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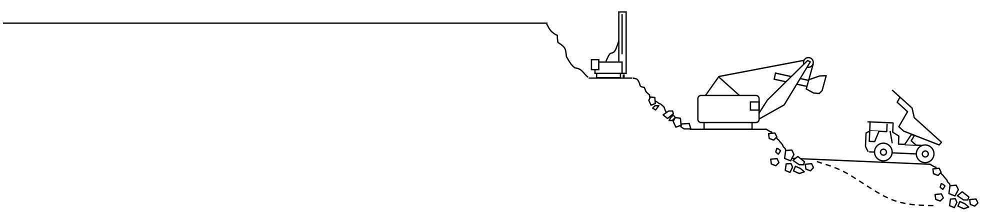
ABSTRACT

Process mineralogy is defined as an interdisciplinary science connecting basic and applied mineralogy to geometallurgy without strict scientific or technological borders separating the disciplines. The history of process mineralogy is divided in four periods of time. The Pre process mineralogy period of time prior 1965, the Birth and the early growth of process mineralogy 1965 – 1980, the Golden age of classic process mineralogy 1985 - 2000, and the Automated mineralogy period of time after 2000. Each period is described with regards to people with significant influence on the development on process mineralogy, important developments in technologies as well as important events. At the end it is given a brief status of modern process mineralogy and some possible trends for the future.



1. INTRODUCTION

Process mineralogy has during the last two decades developed to a more and more important discipline within modern mineral production. Based on my own experiences in a discipline I have devoted most of my research and professional life, I will try to disseminate some knowledge considered important in respect to history, events, people and technologies. Another researcher from another part of the world, with another experience, most probably would emphasize differently, and thus presented a paper with a different content. Especially the impact and influence of people concerned will be judged differently depending on their own experiences and contacts. None of these researchers are more right or wrong than others. It is their own background, history and field of interest which of course is the background for different views.

It will be paid tribute to people I consider important for the development of process mineralogy. The ability of these people to build relations and expert teams are important. A few research institutions and universities will also be mentioned, as well as important events and activities which have shaped process mineralogy to the discipline we face today.

The very early history and birth of process mineralogy will be emphasized. This is the time before process mineralogy was used as a terminology at all, and the people paid tribute to did not even know they had significant contributions to the discipline. These people, however, formed some of the basic principles or methodologies being relevant even today - although in a different wrapping.

A paper describing the growth of a discipline must also include important developments in methodologies and instrumental innovations. A complete list has not been the aim of the paper, rather the developments and the use of what I consider the most significant breakthroughs in techniques, and why these techniques have become important. In this connection I have emphasized on the development of quantitative analysis of minerals, mineral texture and liberation, as the key technology to describe the developments in instrumentation and methods.

Process mineralogy is becoming a more and more important tool in mining and mineral processing. The major reasons for this development are trends in ore qualities such as gradually less metal content, more complicated textures and demand for higher recoveries, as well as environmental aspects and the increasing world demand for products from the mining industry. Consequently, more and more knowledge concerning mineral occurrence in the raw materials, their behavior in milled products and in the process is needed.

2. WHAT IS PROCESS MINERALOGY?

A number of definitions of process mineralogy have been launched. A challenge which may confuse many is that definitions of applied mineralogy, geometallurgy and industrial mineralogy overlap process mineralogy. I will demonstrate this with a few examples and conclude.

The definition I have used is: "Process mineralogy relates the physical, chemical, mineralogical and textural properties of the mineral raw materials to their behavior in the process, to product quality and the utilization of the mineral products".

It implies that available and relevant techniques are used for investigations on all kind of materials connected to the mineral and mining industry including industrial minerals, natural stone as well as the use of minerals in cement, concrete, ceramic materials, metallurgical and recyclable products, paper, paints and other materials.

Another definition is given by Centre of Mineral Research, University of Cape Town (Homepage CMR 2014) saying: “Process mineralogy is the application of mineralogical information to understanding and solving problems encountered during the processing of ores, concentrate, smelter products and related materials”. It seems quite clear this definition is limited to investigations of metallic ores. Certainly it is not including investigations during exploration of ores.

Other definitions of process mineralogy, mostly variations of the given ones, might be mentioned, but I consider of more interest to look at the relations between process mineralogy and definitions of related disciplines such as applied mineralogy and geometallurgy.

In his textbook “Applied Mineralogy in the Mining Industry” William Petruk (Petruk 2000) defines applied mineralogy as follows: “Applied mineralogy in the mining industry is the application of mineralogical information to understanding and solving problems encountered during exploration and mining, and during processing of ores, concentrates, smelter products and related materials”. Except “Exploration and Mining”, the definition by Petruk of applied mineralogy is identical to the definition of process mineralogy given by Centre of Mineral Research. Also the term industrial mineralogy is used. Luke C.H Chang (Chang 2001) defines Industrial mineralogy in his text book “Industrial Mineralogy” as follows: “It is the science of examining and evaluating mineralogical properties, geological occurrence, distribution of deposits, industrial processes, and uses of industrial minerals”. Chang restricts industrial mineralogy to industrial minerals and in this way also restricts the definition of process mineralogy.

Swapna Mukherje (Mukherje 2011) defines industrial mineralogy in the chapter “Industrial Mineralogy” in his text book “Applied Mineralogy” as: “The science of examining and evaluating the mineral properties for industrial applications”. As Chang (Chang 2001) he restricts industrial mineralogy to industrial minerals. On the other hand, it seems to be a tendency by some researchers that process mineralogy is restricted to metallic ores, and/or to the processing of metallic ores. I shall not claim that anyone is more right or wrong than others in this issue. In my view, process mineralogy comprises a wide range of scientific disciplines. Depending on the objectives for the investigations it includes topics from both basic as well as applied mineralogy. Process mineralogy is used at different levels in mining from exploration to the investigations of environmental aspects. In this way the interdisciplinary character of process mineralogy requires engineers and scientists with diverse backgrounds, expertise and interests. Certainly, a skilled process mineralogist, in my view, must also be skilled in process technology or at least understand the physical background for beneficiation processes of any geological raw material. It will enable him to understand the need for collecting the right knowledge and to include this knowledge into the downstream beneficiation technologies.

Also geometallurgy is defined in different ways. Two definitions are quoted here to demonstrate the diversity. More definitions are given by Butcher (Butcher 2012a) verifying the diversity in the understanding of what is included in geometallurgy.

“Geometallurgy (Homepage SGS 2014) is the integration of geological, mining, metallurgical, environmental and economic information to maximize the Net Present Value (NPV) of an orebody while minimizing technical and operational risk”. “Geometallurgy (Homepage weekly Magazine 2010) aims to determine the cause of recovery problems at an existing mine and also to predict and remedy potential problems before a treatment plant is established when a new mine is being developed. It is a rapidly developing field that is facilitated by new instrumental developments related to automated mineralogy that is performed on a scanning electron microscope and that has come to the fore in the past ten years”.

The variety of definitions indicate that geometallurgy by some researcher are considered synonymous, ore near synonymous, to process mineralogy, while other consider geometallurgy to be a much wider concept (Homepage SGS 2014). In this much wider definition geometallurgy is about maximizing the overall yield by understanding and managing data about geology, mineralogy, plant performance data, market etc.

To conclude, I consider mineralogy, basic and applied, to be an important tool in process mineralogy, while process mineralogy is a tool of major importance to be used in geometallurgy. There are no strict scientific or technological borders separating the disciplines. Overlapping use of knowledge is in fact a premise to perform best practice in all three disciplines. The variety of definitions and terms used demonstrates the distinctive interdisciplinary character of process mineralogy.

3. THE HISTORY OF PROCESS MINERALOGY

The history and growth of process mineralogy may be divided in several phases with gradually transitional periods. The Pre process mineralogy phase prior 1965, the Birth and the early growth of modern process mineralogy phase 1965-1980, the Golden age of classic process mineralogy period 1980-2000, and the Automated mineralogy time period after 2000. In each period there have been peoples with significant influence on process mineralogy, important developments in methodologies or technology, or important events.

3.1 The Pre Process Mineralogy History, prior 1965

This period is first of all characterized of the work of a few pioneers in mineralogy and in ore dressing who realized the importance of gathering quantitative information of minerals, mainly to classify rocks, and later the need of mineral knowledge for the processing of ores. The research and publications in mineralogy were related to basic topics, but has been important because it has formed the basis for later developments in methodologies in process mineralogy.

To know the composition of an ore is crucial information always needed when it comes to processing of the ore, and thus is an important part of any modern process mineralogical investigation. But also in rock classification gathering of quantitative mineralogical information to establish the modal composition has been of great importance. It is therefore naturally that a petrograph, the Frenchman A. Delesse (Delesse 1848) developed the first quantitative approach to determine the composition of a rock. Delesse showed mathematically that in a random section though a uniform aggregate of minerals the areas of the different components are equal to the volumes of the components in the sample. His work was pursued in a classic work by A. Rosiwal (Rosiwal 1898) "Über Geometerische Gesteinanalysen" who showed that the volume percent of a mineral is equal to the lengths of the intercepts through a mineral in percent of total line length in a section. The next milestone paper in the development of quantitative methods was by Ellys Thomson (Thompson 1930). He studied the accuracy of the existing techniques and also introduced for the first time point counting using a grid as a practical tool in determining modal composition. Modal analysis was lifted to a higher level when F. Chayes (Chayes 1956) published his book, "Petrographic Modal Analysis – An elementary statistical appraisal". His presentation and discussions of errors and reproducibility are still valid.

All this work mentioned so far was made in order to establish methods for determining the mode of rocks to be able to make relevant rock classification. The first to realize the need for mineralogical competence in the processing of ores was A.M. Gaudin (Gaudin 1939). He introduced in his classical book "Principles of Ore Dressing" both a liberation model and a methodology to sample and to classify particles in a milled product. He also realized that collecting particle information on sections introduced systematic errors because locked particles may appear liberated on a cut through the particles. He even quantified this error through a simplified model. Although his model is too simple to be used in accurate calculations his work is still valid in order to understand and interpret data collected from particles.

Also the German professor Paul Ramdohr must be mentioned from this period because of his excellent contributions in ore microscopy. He was a pioneer in using the microscope as a tool in ore microscopy, ore dressing and metallurgy. His first important work in this field was “Die Ertzmineralien und ihre Verwachsungen” (Ramdohr 1950). Later improved, and with a considerable amount of outstanding and important qualitative information about ore minerals relevant for the processing of ores in his work; “The Ore Minerals and their Intergrowhts” (Ramdohr 1980).

3.2 The Birth and the Early Growth of Process Mineralogy 1965 - 1980

During the sixties and the years to come, developments and improvements of new instruments, particularly the microprobe, but also optical image analyzers appeared enabling researchers to characterize minerals and collect mineralogical data much more accurately than previously possible. This was of major importance as regards both qualitative and quantitative information significant for the processing of ores. Scientists in ore geology and mineralogy realized that these new developments could be possible important tools in the investigation of ores, not only in the study of ore genesis or more basic ore studies, but also to be used in the processing of ores in order to improve liberation, recoveries and processes. This time period represents the real start of using applied mineralogy related to ore processing.

At Royal School of Mines (RSM), Imperial College, London, Meurig P. Jones realized that the microprobe could be used for quantitative mineralogical analysis. In his first publication in this issue (Jones and Gavrilovic 1968) Jones describes an automatic set up for the microprobe enabling it to quantitative location of rare phases. But already in 1965 Jones together with Fleming published a textbook “Identification of Mineral Grains”, (Jones and Fleming 1965). This book was to be used by mineral processing engineers and geologists having access only to simple means such as the stereological microscope and chemicals.

Jones had a vision (Jones 1970) that in the future the microprobe would be the basis of a complete automatic system for quantitative measurement of mineral particles. Special designed microprobes would be used in such a system. Jones used the microprobe to carry out linear analysis on sections of milled material to identify the minerals and to measure the random intercepts trough the different phases. He was convinced that this was the best method to gather large amounts of data to compare batches of metallurgical products. Especially he was concerned about how he could use the data measured on plane surfaces to calculate the features that these quantities represent in the three-dimensional space, -stereological transformations. During the decade to come Jones further developed his system and published his work (Jones 1982) at XIV IMPC 1982, a congress which is commented later. He finished his work and his considerable contributions to applied mineralogy, or process mineralogy, by publishing a text book in “Applied Mineralogy, A Quantitative Approach”, in 1987 (Jones 1987).

At the mineral processing technology team at RSM we also find the name of Gilles Barbery, an outstanding researcher and scientist who has given significant contributions in the field of mineral liberation and separation. He was also an excellent mathematician and was as Jones particularly concerned with the sterological aspects of quantitative mineral analysis typically shown in the publications “Theoretical study and computer simulation” (Barbery 1977) and “Mineral liberation analysis using stereological methods” (Barbery 1984). He became professor at Laval University, Quebec in 1982. Before he died too early in 1989 he authored a very impressive and comprehensive book, published after his death (Barbery 1991), entitled “Mineral Liberation: Measurement, Simulation and Practical Use in Mineral Processing”. The “Volume IX, Process Mineralogy”, (Petruk et al. 1990), was published in memory of Gilles Barbery

Another outstanding scientist who undoubtedly has influenced the development of Process Mineralogy is William Petruk who has dedicated his career at CANMET, Department of Natural Resources, Canada. He started his career in the mid sixties at a time where processing engineers at Mines Branch, Department of Mines and Technical Surveys (former CANMET) performed laboratory test work on a wide variety of ores. His interest was within applied mineralogy and characterization of the ores and process products being tested. According to Petruk (Petruk 2000) it was a dynamic desire among the scientists working with mineral processing and mineralogy at Mines Branch at that time to improve techniques of performing mineralogical analyses. One of the senior Mineral Processing engineers, Dan Picked, really came forth with a gem of wisdom valid also today: “complete mineral characterization solves most mineral processing problems” (Petruk 2000). Having this type of philosophy it was natural that CANMET under the leadership of Petruk developed its own system for the quantitative characterization of ores and process products in the beginning of the seventies where he combined the best of an image analyzer and the microprobe. He developed the MP-SEM-IPS system where he integrated a microprobe (JEOUL 733), energy dispersive X-Ray analysers (TRACOR NORTHERN 2000) and image analyser (KONTRON SE;-IPS) using special software (Petruk 1989a).

During the seventies the QEM*SEM image analyser was designed and developed by the Commonweath Scientific and Industrial Research Organization (CSIRO) in Australia (Miller et al.1982). This system represents together with MP-SEM-IPS the most important instrument and methodology developments in process mineralogy during this period. The framework for the development of QEM*SEM was the same as for MP-SEM-IPS, - a need for much better characterization of process products, especially the liberation of minerals, in order to obtain improved recoveries in the mineral industry. QEM*SEM was based on a Scanning electron microscope and the analyzer used the signals obtained from an EDS and a backscatter electron detector to map the particular mineral present and to give the basic data needed for the calculations of mineral distribution, liberation etc. The QEM*SEM is later developed to the commercial system today known as QEMSCAN.

Although it was developed systems in the seventies for quantitative characterization of ores and process products, none of these systems were commercial available at that time. Most of the mineral characterization work at different laboratories therefore was done using manual, optical methods, such as point counting or grain counting. Skilled mineralogists undoubtedly provide excellent mineral discrimination capacities but compared to automatic optical or X-Ray based methods are slow and with less ability to perform quantitative analyses. To improve the quantification of locked particles Amstutz and Giger (Amstutz and Giger 1972) published a scheme for classification of locked particles based on different types of intergrowths between the minerals.

During the sixties prof. F.M Vokes at NTH (The Norwegian Technology University), later NTNU (Norwegian University of Science and Technology) more and more frequently was asked to carry out mineralogical analysis of ores, and grain counting on process products. He experienced exactly the same need for improved techniques and mineralogists devoted for this work having competence both in mineralogy and in the processing technologies as in Canada, England and Australia. In Norway, at time, several sulphide mines were operating showing large variations in texture and mineralogy giving different challenges in the processing of the ores. Vokes managed to get funding from the National Research Council, in close cooperation with the mining industry, for a research project and a scholarship in “Mineralogy Applied to Ore dressing”. I got the scholarship and started my work in this field in 1972. Fortunately, I was allowed to stay for a semester at RSM in London at the team of M.P.Jones. Under his supervision and pedagogic skill I learned a lot about the different methods and challenges as regards use of mineralogy applied to ore dressing, and during the seventies I visited RSM several times. At NTH we did not have economics and resources to develop our own automatic system. We had to relay the investigations on manually techniques as was the situation for most mineralogists in this field at that time. For instance, when I visited Warren Spring Laboratory in 1973, at that time a laboratory performing ore beneficiations testing for mines all over the world, I was introduced to mineralogist using manual grain counting as recommended by Amstutz and Giger.

To determine mineral liberation has always been a major issue as regards mineralogical investigations of ores and ore dressing products. Using manual methods it is time consuming and liberation values are depending on the skill of the mineralogist. However, it was realized by Petruk that different automatic methods gave different liberation values as well. Therefore, to establish reliable liberation models, is an important research topic emerging in this period, although the first attempt was made by Gaudin already in1939 (Gaudin 1939). Wiegel and Li (Wiegel and Li 1969) published an improved Gaudin liberation model in 1969, and later Wiegel (Wiegel 1975) introduced a liberation model to be used in Magnetite Iron formations. None of these models, however, have found much application in practice.

One of the "liberation model schools" was that it would be possible to predict comminution and liberation of minerals based on textural analysis on sections of crude ore. R.P. King (King 1975) was using linear analysis on sections of an ore measuring the intercepts lengths through the mineral grains. The intercepts lengths and distributions could be used as a basis for calculations of liberation models. Ores, however, usually exhibit preferential breakage during comminution. This was verified by myself in my thesis in 1975 (Malvik 1976) and I developed an emperical liberation model based upon manual grain count of milled products. The model was used on a lot of sulphide ores both to map variations in liberation properties through ore being mined and on the exploration stage. Later preferential breakage is confirmed by several authors, latest by Cecila Lund (Lund et al. 2013).

At the end of the period, in 1979, the Process Mineralogy Committee (Petruk 2008) was founded, which brings us over to the next time period of Process Mineralogy.

3.3 The Golden Age of Classic Process Mineralogy 1980 - 2000

In this time period it was a considerable increased activity in process mineralogy. It started with the foundation of the Process Mineralogy Committee in 1979 (Petruk 2008) as a committee of TMS-AIME (The Minerals, Metals and Material Society-The Metallurgical Society of the American Institute of Mining, Metallurgical and Petroleum Engineers). The committee organized continuously annual meetings in Process Mineralogy for the next twenty years. The first one being in New Orleans 1979, followed by a number of meeting or sessions, mainly as part of ICAM congresses. A series of books, totally 17, on the proceedings from these sessions were published thanks to editing work being done by the committee. Papers from symposia in sessions at ICAM conferences outside USA are also included in the books. Three persons must particularly be mentioned due to their contributions in the committee and in editing the books: William Petruk, CANMET. Prof. Richard D. Hagni, Missouri University of Science and Technology, and dr. Donald M.Hausen (died in 2006) who Petruk gave credit in a special speech at ICAM in Australia 2008 (Petruk 2008). The committee lasted to 2004 when it was renamed to “Characterization of Minerals, Metals and Materials within TMS”. The committee continued to be active in conducting sessions within the TMS annual meetings.

To emphasize the considerable growth in Process Mineralogy during this period some ofthe topics included in process mineralogy from these books can be given. They cover a wide range of different fields in applied mineralogy. For instance we find in Process Mineralogy XIII (Hagni 1995), application to Beneficiation problems, Pyrometallurgical Products, Advanced Mineralogical Techniques, Precious Metals, Environmental Concerns, Ceramic Material, Hydrometallurgy and Mineral Exploration. Other topics covered in the books were applications to energy resources, oil shales, Uranium and geothermal systems. A special issue in 1990 (Hausen et al. 1990) is focused on gold, and Process Mineralogy vol. XI (Hausen et al. 1991) is on the Characterization of Metallurgical and Recyclable Products.

To further emphasize the variety of topics included and the widespread use of process mineralogy Baumgart, Dunham and Amstutz authored a textbook in 1984 (Baumgart et al. 1984) “Process Mineralogy of Ceramic Materials”. This book covers topics such as glass, inorganic binders, refractories, oxide ceramics, semiconductors, etc.

Process Mineralogy became accepted as an important discipline and tool in all kinds of mineral processing. A breakthrough for this was already in 1982 at the IMPC congress in Toronto in 1982 (Petruk and Park 1982) were the committee conducted one plenary session in Mineralogy Applied to ore Dressing with participants from USA, Canada, Europe, Australia and Africa. In this conference the different technologies for quantitative analyses of minerals developed in the seventies were presented. This included presentation of optical image analyzer, a microprobe based system, and for the first time the QEM*SEM was introduced for an international audience (Miller et al. 1982)). I remember very well that during the plenary discussion after the presentations it was discussed whether linear measurements or area measurements was the future to go for automatic determinations of mineral textures or liberation values. Today it is well accepted that area measurements are giving most significant data from polished sections.

As regards developments and improvements in the technologies capable for quantitative measurements of minerals, we can state that although considerable effort was made already in the 1970s to introduce modern technology in process mineralogy, the real development started in the early 1980s. One of the main reasons to this development was that electron microscopes and microprobes became equipped with simple image analysis programs which enabled the users to quantify mineral amounts, particle size, particle shape etc. The image analysis programs were elementary and could not carry out significant analyses, but introduced users to image analyzing and showed the range of mineralogical problems that could be solved by the technique (Petruk 1989b). In the years to come different laboratories used different analytical techniques due to different capabilities of commercial image analyzers and it was a growing belief in automatic techniques as the ultimate method to measure mineral liberation and other important parameters for the processing of ores.

Although a lot of varieties, principally, three different system or methods were competing:

1) Plain optical based image analyzers, gradually color based, which improved the discrimination capabilities, but still much less able to classify different minerals due to overlap in optical properties than electron based systems. Classification of minerals must also totally rely on the skill of the mineralogist. The greatest advantage was that optical based image analyzers were cheap compared to X-ray based systems. The most advanced systems were able to discriminate quite well common sulphides and oxides in reflected light.

2) The MP-SEM-IPS Image Analysis System (Petruk 1989a). This system was developed at CANMET, Department of Energy, Mines and resources, Canada, and consisted of a Jeoul 733 microprobe, a TRACOR Northern 2000 energy dispersive X-ray analyzer and a KONTRON SEM-IPS image analyzer interfaced in such a manner that communication was possible in both directions between the units. The images were segmented on basis of grey levels corresponding to different minerals in the backscattered electron image. Then the individual grains were scanned with the electron beam to get an X-Ray signal for each mineral and to get element X-Ray maps. In this way the system aimed at combining the best from electron based and optical systems.

3) The QEM*SEM image analyzing system Quantitative Evaluation of Minerals by Scanning Electron Microscopy, developed by CSIRO, Australia late 1970s beginning of 1980s (Miller et al. 1982, Pignolet-Brandon and Reid 1989) This system was entirely electron based and contained an automated controlled image analyzer based on a scanning electron microscope. Both X-ray pattern to identify

the minerals and backscattered images were used to grey level discrimination of the different minerals. The system was installed at the Mineral resources Research center at the University of Minnesota in 1985 for service to the North American mining industry (Pignolet-Brandon and Reid 1989), and in 1987 a system was installed at Anglo American Platinum (Rule et al. 2011).

Although electron based, both systems had limitations in mineral identifications and the methods were mostly used in reflected light to discriminate the major ore minerals. Silicates and gangue were normally grouped in one class. At that time it was generally assumed that liberation data obtained from one image analysis technique system would be the same as data obtained by other systems. The different systems, however, were set up with different algorithms during the image analysis and to perform the calculations of mineral liberation. In addition, the measurements were carried out by linear or area measurements giving different results, as well as different ways to define the liberation of minerals. In addition to research on the stereological challenges on transforming two-dimensional parameters to the three dimensional equivalents it was also growing concern that different techniques would give different results. In a paper from 1997 (Petruk and Lastra 1997) discussed these problems in an excellent way, and even today this is a problem to be addressed.

QEM*SEM and the MP-SEM-IPS image analyzer laid through their practical applications and use by experienced mineralogists in the 1980s and 90s the foundation for the further advanced developments of automatic techniques to carry out mineralogical analysis at the end of the former century and beginning of the next century. A large drawback was that none of these systems were easily commercial available at that time. Only large research institutions with significant resources as regards both expertise and founding were able to purchase and use these most advanced systems.

Then, at the end of the previous century, and at the beginning of the next, the QEM*SEM was further developed in to a commercial system, QEMSCAN (Quantitative evaluation of Mineralogy using Scanning Electron Microscope) by CSIRO, and the Mineral Liberation Analyser (MLA) was developed and manufactured by the Julius Krutschnitt Research Centre (KJ) Australia in cooperation with FEI. The developments of these highly automated and advanced systems for quantitative measurements of micro textures introduce the latest time period in the history and development of process mineralogy, - the Automated Mineralogy Period of Time.

3.4 The Automated Mineralogy Period of Time, after 2000

First of all this time period is characterized by the development and rapid growth in the use of automatic measurements systems. Two technology platforms have dominated, and still are dominating the marked – the MLA and QEMSCAN. The systems have been described in details in several publications and I refer to Alan Butcher (Butcher 2012b) who gave an automated mineralogy overview in 11th Freiberg short course in economic geology in 2012. Undoubtedly, the development of detectors able to collect large amount of data, and the developments in data and computer technology have been crucial factors enabling this growth, in addition to the ability to bring together people with different competence. SEM-based systems are also superior to optical based systems when it comes to spatial resolution, mineral identification and ability to produce high quality quantitative information included liberation measurements. In the beginning of the century only a few large laboratories and mines used the technology in routine automated mineralogy, but today there are more than 100 units installed all over the world. The world leading research communities in automated mineralogy has been in Australia and annual conferences in automated mineralogy were organized in Brisbane in the period 2006 – 2008.

In the first years it was a competition in the marked between the two systems, but in 2009 FEI, who also market the MLA, purchased the QEMSCAN technology, and we had a monopole situation as regards automated mineralogy.

No one takes advantage of a monopole situation in the long run. Both systems are expensive and a user has to buy the whole package included the hardware. The cost has no doubt prevented smaller laboratories and potential other users to afford buying the system. I will also claim that the monopole situation has delayed the development of other systems to compete MLA/QEMSCAN. But recently we can see that other SEM and detector manufactures have developed similar systems. But although I have been skeptical of the FEI monopole, the success of the MLA and QEMSCAN has been a driving force for the development and use of fully automatic mineralogical methods, and has maybe also been a model for the development of other systems.

At NTNU we started to develop our own system already in the beginning of the century in a project "Advanced characterization of industrial minerals and beneficiated products", founded by the Norwegian Research Council. The project aimed at developing automatic SEM-based quantitative measurements on major and trace elements in rocks and ores and the methodology was denoted PTA, (Particle Texture Analysis). A prototype of the system was presented at IMPC, Istanbul in 2006 (Moen at al. 2006) and is further developed in collaboration with Bruker. The system is based upon the same principles as MLA and QEMSCAN, but with flexible software, and being able to run with SEM instruments from different producers. Today the system is working as a research tool at NTNU giving the quantitative information needed in process mineralogy.

Other recently developed systems are TESCAN Integrated Mineral Analyser (Homepage Tescan 2014), and Oxford Inca Mineral (Homepage Oxford Instruments 2014), which both offers adequate quantitative mineralogical measurements. It is likely that other systems are to be developed in the years to come.

It is important to consider that automatic systems as MLA and others are important and efficient tools, and no solutions. A skilled mineralogist should always be responsible for the measurements. As regards process mineralogy, it is important that the data are both relevant and presented in a logic way for the actual case. It may even be better to present less comprehensive amount of data at many occasions than the systems are available to produce.

It is important to realize that the same parameters measured on different systems may be different. Consequently, calculated values of liberation may be different depending on how the measurements are carried out, or which algorithms are being used, as was the concern by Petruk already in the 1980s. All measurements are still two dimensional measurements on sections. Except for mass proportions, stereological transformation to the third dimension is not particularly well understood. In my opinion, stereological transformations therefore should be avoided as regards liberation, grain sizes etc., until hopefully reliable methods are developed.

It is also important to remember that depending on the goal for any mineralogical investigation the most proper method should be used. Process Mineralogy is applied at different phases in the life cycle of a mine, - from early exploration stage, in the planning and the feasibility stage, and at all stages of test work from simple batch tests to pilot plant test work, in the production stage both for ore investigations and in process control and in trouble shooting as well as used in environmental aspects of mining. To solve a simple problem, - or to give simple and adequate information use of the optical microscope may be sufficient. In other cases a simple XRD analysis may give the answer, or a simple mineral analysis using the microprobe. A skilled process mineralogist must always bear this in mind because the use of advanced technologies always will imply the use of more comprehensive facilities as well as human resources and bring about increased costs in a project.

4. STATUS OF MODERN PROCESS MINERALOGY

Above all it is, as it always has been, a multidisciplinary science as was described introductorily. However, new possibilities are opened due to the wide variety of advanced technologies and instruments available for uses on a variety of mineralogical problems. In addition to quantitative automated mineralogical tools, process mineralogy routine uses methods as EPMA, LA-ICP-MS, SEM, TEM, XRD-Rietweld, FTIR, Cl, EDSB, DTA, Fluorescense, normative chemistry and others. In advanced research we face the use of X-Ray tomography. Other sophisticated techniques adapted from other sciences most likely will be introduced.

During the last period of time a number of process mineralogical events have taken place including workshops and congresses. Accordingly, the numbers of publications are comprehensive. In 2011 a special issue of Minerals Engineering (Minerals Engineering 2011) was dedicated Process Mineralogy based on the first MEI (Minerals Engineering International) Process Mineralogy Conference in Cape Town in 2010 sponsored by ALS, IMP, Bruker, FEI, AngloAmerican and Panalytica. In 2012, another congress in process mineralogy, “Process Mineralogy 12” was set up in Cape Town, and at last, a new conference, “Process Mineralogy 14” will be arranged by SME, also in Cape Town. “Process Mineralogy ’14” will deal with the following topics: Quantitative mineralogy, including both X-ray and Electron Beam Techniques, Geometallurgy, Ore characterization, Mineral Liberation and Textural Analysis Application of process mineralogy on Site Sampling and Statistics Advanced Process Control. Apparently, The MEI/SME conferences in SA have developed into one of the leading forums for Process Mineralogy.

Additionally, process mineralogy has continuously been an important scientific part of the regular organized ICAM congresses. In the Nordic Countries, process mineralogy has had a significant upturn during the last years thanks to an initiative by prof. Perrti Lamberg, LTU, in establishing ProMinNet in 2011 funded by NordForsk. Lamberg established a network between LTU, NTNU, OU and Bergakademie Freiberg. Hopefully the PROMINET will result in a strong research cluster including several universities and research institutions in Europe in the future, or more exciting, the beginning of a real global network in Process Mineralogy.

With regard to the comprehensive activity in process mineralogy we can face today, it is likely to conclude that process mineralogy still is a healthy and multidisciplinary science which the recent years has increasingly become an even larger part of everyday operation in mines and mineral process plants. In my opinion, process mineralogy can be regarded even more important than before, since it now in addition to the comprehensive use in all stages of mining, also is being closely linked to geometallurgy as it forms one of the main sources of the data and knowledge that is fed in to the geometallurgic predictive models.

5. THE FUTURE OF MODERN PROCESS MINERALOGY

The development in automatic mineralogy we have faced recent years, and the appearance of new and sophisticated mineralogical techniques will proceed. In my opinion it is likely that we in the years to come will face steadily more and more rapid and precise collecting of data in automatic measurements. I am certain that usability and the flexibility of these systems will improve including instruments where the major techniques are integrated in one instrument. More competition between producers and research institutions will lower the prices. This will lead to a wanted development that other research institutions and mines with weaker funding may include these modern technologies in the laboratories. Also the identification of minerals will be more reliable as well as the quantitative determination of the mineralogical composition of rocks and ores.

But there is still one major challenge which today is unsolved and where no standard techniques are available. That is the stereological transformation of data observed in 2D to 3D, as already addressed by Gaudin (Gaudin 1939). The question itself is simple: How does a composite particle, or a mineral texture, look like in the third dimension, and how can it be quantified in a relevant way to be used in predictive models. According to prof. Jan Miller (Miller 2012) X-ray tomography has progressed considerably from the 20th century to the present day, and may be an interesting technique.

Ramdohr published in 1980 his second edition of "The Ore Minerals and their Intergrowth". This classic work of ore textures should still be used by process mineralogists. But I really look forward to the publication: "The Ore Minerals and Their intergrowth in the Third Dimension, a Study based on Modern X-Ray Tomography"

But at last I will emphasize that we never must forget that the most common techniques used in process mineralogy have been, and still is the optical microscope, eventually in combination with XRD and SEM/EPMA. And even more important, the human brain and the skill of the mineralogist will never be outdated.

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