Process Mineralogy: An essential booster of the Circular Economy

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Abstract

In order to develop efficient processes for the recovery of metals from both our primary mines and our urban mines, we will need to innovate in process mineralogy. This talk will give an overview of the role of predictive and diagnostic tools in mineralogy to achieve a more circular economy. It will go from complex polymetallic ores to the intimacy of our e-waste.

1. Dealing with minerals.

In 1735 only seven metals were known to mankind and the world appeared to many as the result of a perfect equilibrium that only divine forces could have inspired: seven days, seven planets and seven metals. So, when the expedition sent to Peru to precisely locate the Equator and measure a meridian angle came back with nuggets of a corrosion resistant silvery metal (platinum) it triggered a lot of curiosity and a search for a better understanding of our environment that culminated in 1925 with the discovery of the last chemical element stable on our Earth, namely Rhenium.

The quest for a systematic understanding of the composition of rocks and minerals laid the foundations of modern chemistry and turned mineralogy into one of the most popular sciences of the XVIIIth and XIXth centuries.

Still today the reference book for mineralogy is the regularly revised book first edited by Dana et al. in 1848 and the most widely accepted definition of a mineral is still very much the same. The most flexible definition being probably the one proposed by Nickel (1995): "*A mineral is an element or chemical compound that is normally crystalline and that has been formed as a result of geological processes*".

Most researchers dealing with process mineralogy would agree that this definition is the one of a geologist and that it is not properly suited to address the analysis of all materials that are being processed today to recover metals or other valuable elements and molecules. Mining primary ores will remain an essential activity for centuries, but the importance of secondary materials generated by mankind during the XIXth century has widened the scope of metal extraction to landfill mining and urban mining. In order to properly describe the materials being processed in this context a broader definition of mineral should be adopted, probably leading to a definition very close to the one usually adopted in material sciences for a phase: "*a phase is a region of space, throughout which all physical properties of a material are essentially uniform*". The intention is to properly describe the specificities of any material that will impact its (re)processing by mechanical, thermal or chemical processes.

Lessons of humility are to be learned from pioneers such as the self-taught geologist Henry Sorby or the metallurgist Fritz Wüst who, among others, worked indifferently on natural and man-made materials and clearly understood that similar tools and techniques had to be adopted.

2. Choosing the right perspective

Even if we can agree on a broader definition of a mineral, there is still a striking difference between a mineralogist and a process mineralogist. Both may be looking at the same material under the microscope, but they are not looking in the same direction. A classical mineralogist will describe the material under scrutiny with the aim to pose a diagnostic. His interest is to be able to understand where the material comes from and how it was formed. Typical examples include metallogeny (making hypotheses on source, transport and deposition mechanisms of metals in the environment) but also archeometallurgy (rebuilding metallurgical processes from ores, scraps, artefacts and slags found around ancient workshops). In the perspective of diagnostic mineralogy, it is essential to identify all mineral species even the less abundant ones. It is also important to understand mineral equilibria and estimate under which P, T conditions they may have been formed.

A process mineralogist on the other hand will adopt a prognostic perspective. His aim is to recommend the best possible processing route for beneficiation or to predict how the material will behave in a given unit process (e.g. ball mill, smelter, etc.). A process mineralogist must have a good understanding of the complexity of materials and ores but he must also be educated as a process engineer. Sampling and quantification are critical questions that he needs to address instead of spending his energy in trying to identify insignificant minerals (the "do more less well" paradigm). He should track valuable as well as penalty elements and anticipate any possible impact on the economic efficiency of the process.

Considering the diversity of raw materials and processes we have to deal with in 2017, adopting a prognostic perspective is a daunting task. A prerequisite being certainly to adopt a multidisciplinary approach by which mineralogists, geologists, mineral processing engineers, extractive metallurgists, etc. combine their efforts and establish a fruitful dialogue.

3. Towards a more circular economy

Circular economy is a term that has been coined only very recently to point out the excesses of our take-make-dispose "linear" economy. It seems quite evident that historians will remember the end of the twentieth century, at least in the wealthiest regions of the world, as a period of consumerism and total unconcern about resources and energy efficiency.

Circular economy, although not new, is an interesting paradigm to stimulate innovation and entrepreneurship towards a more sustainable world. Clearly, it is a kind of utopia ignoring the limits of thermodynamics and the increase of entropy, but it can certainly contribute to define guidelines and build policies towards a more sustainable world with the aim of leaving metallic and non-metallic resources available to future generations for as long as possible.

The best diagram to illustrate the raw materials value chain and position the different actors of a more circular economy is still to be found. It is clear however that the ideal shape should emphasize the role resource engineers and process mineralogists have to play. As evident from the whistle shape illustrated on figure 1, these roles can be grouped under four different actions: feeding the loop; optimizing the loop; slowing down the loop and closing the loop.

Figure 1. Schematic representation of the circular economy of materials and manufactured goods (© European Parliament).

3.1 Feeding the loop

Many of the most vibrant advocators of the circular economy underestimate the importance of a sustained mining production, but anyone who pays a closer attention to the numbers of demography, recycling performance and technological developments will easily admit that primary mining will remain a key activity for decades. A detailed study should be performed by metal and by regions of the world as it is clearly different to analyse the future of copper in Europe or the need for lithium worldwide. To illustrate the need for feeding the loop, we will consider hereafter Germanium, a key metal used dominantly in infrared optics, PET catalysts and fibre optics.

From the compilation of historical production data (USGS, 2014) an estimated 4500 tons of germanium are currently in the anthropogenic stock. Anticipating the need for connecting even a tenth of the world population with efficient internet connections relying on fibre optics it is evident that there is not enough germanium in the loop and that primary mining will have to contribute significantly. Surprisingly enough, germanium is a poorly studied element whose technical applications only started with the electronics age in the sixties. It is not systematically analysed in minerals and ores and therefore no statistics are available on worldwide resources and reserves. A tentative estimation of germanium resources has been compiled by Frenzel et al. (2014). Historically Germanium has been produced as a by-product of zinc metallurgy before relying almost entirely on leaching of Chinese coal ashes as the primary source (Gunn, 2014). A clear mission of process mineralogists and geometallurgists is now to systematically track critical metals, in particular the ones who are essential in advanced electronics such as Indium, Gallium, Germanium, Selenium, etc. Ores, concentrates and tailings (fly ashes, slags,…) should be carefully scrutinized with the modern and accurate techniques such as LA-ICP-MS or with less sensitive but more productive techniques such as Micro-XRF. In Belgium for example, local sourcing of germanium (Fig. 2) from renewed zinc mining could seriously be considered as a more sustainable alternative to importing a metal associated to important CO_2 emissions in China, provided local tax incentives are adopted.

The future of mining is clearly oriented towards multi-elemental beneficiation stimulated by adequate environmental regulations instead of mono-elemental production only driven by metal costs.

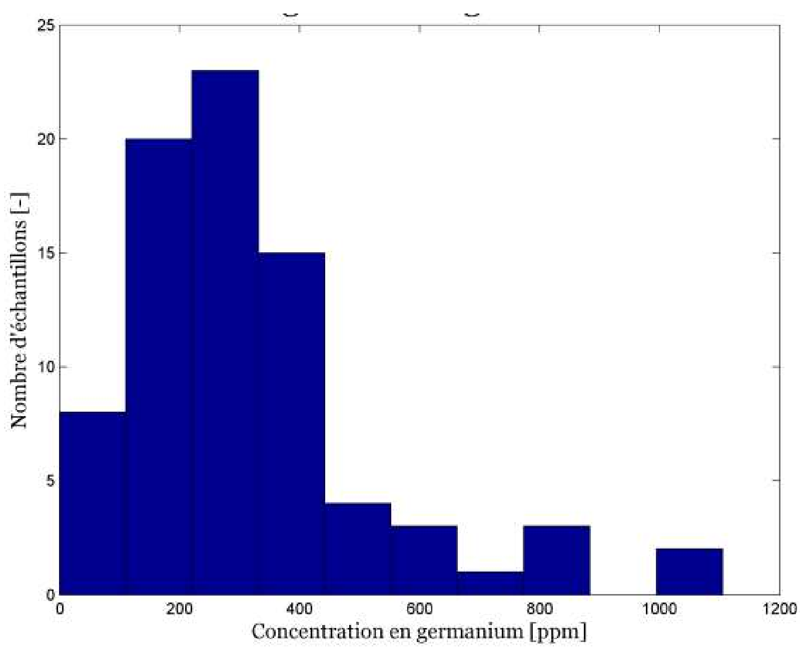

Figure 2 Distribution of germanium in selected Belgian sphalerites Ge analyses (N=82) (Goffin et al., 2014)

3.2 Optimizing the loop

Environmental regulations and the systematic use of lifecycle analysis in many industries has clearly put the pressure on process engineers to optimize their operations. The emergence of process mineralogy as a discipline in the recent decades is clearly linked to this need for better understanding the behaviour of particles in unit processes and trying to optimize the recovery of the valuable ones.

Among others, the systematic study of precious metal deportment in mineral processing operations is an interesting ones as it involves the use of advanced characterization techniques (image analysis, electron microprobe analysis, etc.) but also requires a multidisciplinary approach crossing results from mineralogy, chemistry and material balance to properly understand the trends.

3.3 Slowing down the loop

A more sustainable development can only be achieved if we manufacture more sustainable, meaning longer lasting goods. The need for slowing down the loop has practical implications on the way we design our products. Historically product designers have been focussing on functionality before starting to integrate security or environmental impacts as design criteria by the end of the XXth century. The next step will be to integrate design for dismantling (repairability) and design for recycling (recyclability) while maintaining product performance. This will only be possible if a close cooperation is established between mineral processing engineers and designers integrating for example material compatibility criteria into the material selection databases.

Of course, it is also the consumer's responsibility to change his behaviour and make sure desirability is not always dominating necessity.

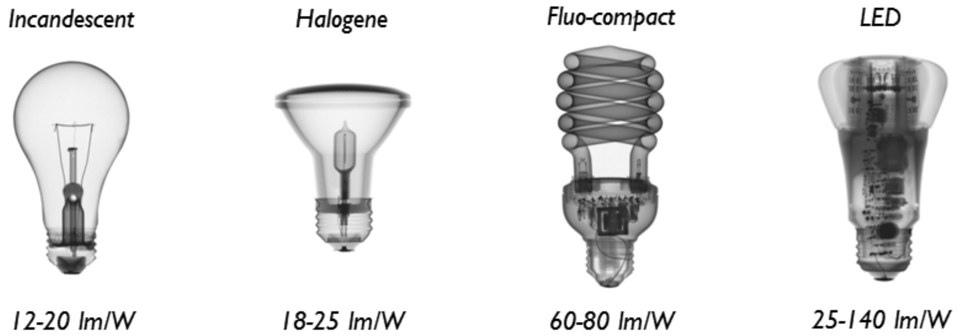

Figure 3. Evolution of light bulb technology showing increased performance (lm/W) but inducing a pressure on critical raw materials and threatening recyclability.

3.1 Closing the loop

The emblematic motto of the circular economy “closing the loop” corresponds to the most challenging step. Closing the loop not only means that we need to optimize material recovery from end-of-life products, but it also means that we need to collect or in other words build the urban mine.

A major part of the technical literature in the recycling sector focusses on grades and especially on precious metal content in end-of-life consumer goods such as WEEE (Waste Electric and Electronic Equipments) (Hagelüken, 2013; Chancerel, 2013). Indeed, the average gold grade of some selected WEEEs (PCB, cellphones,…) is several orders of magnitude higher than the average of operating gold mines (1 g/t in 2016). But, as for any deposit, the grade must be considered as a function of the available tonnage. In the case of urban mines, the grade must be considered as a function of the end-of-life goods reasonably available for collection. Table 1 shows the average composition of a typical cellphone due for recycling in 2015 (Lambert, pers. comm.). Based on these numbers, the residual value of a cellphone is close to 1€ and a minimum of one billion specimens have to be collected to rival with the annual production of an average gold mine (15 t Au /yr). In practice, cellphones are not collected and processed separately, they are often blended with other small electronic devices into an obscure “other” category whereas CRT screens, batteries and home appliances have their own collection strategies. Table 1 also indicates that design for dismantling has an immediate technical and economic impact on the recovery of cobalt contained in the Li-ion batteries.

	Upper Conti.Crust http://earthref.org/ GERMRD/11/ (1)	Cellphone *WITH Battery* (2)	Cellphone *NO Battery* (2)	Enrichment in WEEE	Enrichment in ORE
Polymers		19,2 %	31,2 %	-	-
Si (ox)	65 %	19,4 % (glass)	31 %	-	-
Al	8 %	11 %	9,6 %	x 1	x 3
Fe	4,5 %	2,7 %	4,3 %	x 1	x 10
Cu	26 ppm	10,7 %	13,4 %	x 5000	x 200
Co	17 ppm	8,4 %	0 %	x 4000	x 200
Ni	44 ppm	1,2 %	1,7 %	x 300	x 300
Zn	60 ppm	0,7 %	1,2 %	x 200	x 1000
Li	22 ppm	0,8 %	0 %	x 360	x 1000
Pb	15 ppm	7 ppm	6 ppm	x 0,5	x 2000
Sn	5,5 ppm		1 %		
Nd	27 ppm	1935 ppm	2147 ppm	x 100	x 500
Ta	0,9 ppm		500 ppm		
Ag	50 ppb	868 ppm	1366 ppm	x 30	x 500
Au	1,8 ppb	95 ppm	151 ppm	x 100	x 500
Pd	0,5 ppb	4 ppm	6 ppm		
Ga	17 ppm	17 ppm	27 ppm	x 1,5	x 3
In	0,06 ppm	10 ppm	16 ppm	x 250	

Table 1. Composition of a typical cellphone with and without battery. Indicative enrichment factors for WEEE and ore deposits relative to earth crust geochemistry.

Last but not least, an appropriate characterisation of the urban mine is a prerequisite for designing the optimal processing route and, as illustrated by figure 3, if nothing is done in terms of product design and durability this might very quickly become a nightmare and a close to impossible challenge. As an example, an optimal processing route to recover rare earth from fluocompact lamps has been patented by Solvay in 2011 (Coleop'Terre project), but the economic viability of the process has quickly been hampered by lower prices and the fact that the next generation of lamps (LEDs) was to require a completely different process route (Industrie.com, 2016). This challenge is clearly bigger than the one of moving from a supergene oxide zone into a mixed and a primary sulphide mineralisation in many base-metal deposits.

4. Future developments in process mineralogy

The importance of process mineralogy as a prognostic tool to optimize and conduct a process is nowadays well established, but considering the growing importance of alternative resources (landfill mining, urban mining) and the permanent innovation in digital tracking technologies (internet of things, RFID,…) a series of future developments can be expected. The following paragraphs illustrate a series of ongoing developments.

4.1 Identify metal carrier

The first step in a systematic process mineralogy study is to identify the metal carriers. They are the essential building blocks of our material: metal-bearing minerals in primary ores or metal-bearing phases in anthropogenic materials. Despite the use of “automated mineralogy” to designate advanced SEM-based instruments fitted with BEI (backscattered electron imaging) and EDX (energy dispersive X-ray microanalysis), there is still a long way to go to identify minerals automatically. Current practice is to collect spectra or chemical composition and to look into an extensive mineral database with over 4000 species (e.g. webmineral, mindat, …) for best fits. The result is a SIP file whose quality will be highly dependent on the availability of a skilled operator. With artificial phases coming into play the database will become almost unmanageable for a human operator. The need for a fully automatic identification will become an absolute necessity. Modern SEM-based microscopes eventually complemented with correlative microscopy to integrate VNIR multispectral images (Pirard et al., 2008) are ideal platforms to develop non-supervised classification algorithms (e.g. cluster analysis). The result is a series of unnamed phases (or domains) which can then be compared to a hierarchical and intelligent mineralogical or material database. By hierarchical we mean a database wherein probabilities of mineral associations are used to increase the precise identification of a given species/phase. By intelligent we mean that these databases contain valuable information regarding the physical properties of each mineral/phase (hardness, stiffness, thermal conductivity, electric susceptibility, etc.).

4.2 Estimate liberation

Once the metal-bearing phases are correctly identified it is essential to characterize the interfacial properties of our material. How complex are the boundaries separating different phases? Do we need to break these boundaries? If yes, by which mechanism will we best break these boundaries? Which process route is recommended to further separate the phases? What are the size and characteristics of the daughter particles resulting from the dissociation process? How will they behave in the selected process? This question has been approached in many different ways in the literature. Image analysis is the technique of choice here to provide information on intrinsic particle characteristics that can be further fed into mineral processing simulation packages (Lamberg and Vianna, 2007). Simple image analysis currently provides estimators of size, shape, area liberation or perimeter liberation which are often poorly suited to develop predictive models based on sound physical principles. Future developments will have to build on more elaborate textural descriptors such as those suggested recently by Perez-Barnuevo et al. (2013) or Vos (2016). They will also have to move away from geometrical indicators to become physical indicators integrating an intelligent compositing of the physical properties of individual minerals. In other words a particle indicating a 50/50 area ratio between two minerals might have a floatability index which is not a simple average of the hydrophobicity of the two individual minerals.

4.3 Intelligent sorting

What might appear as science fiction in mineral processing is becoming an important field for technical developments in recycling of complex end-of-life products. The development of surfometric imaging, hyperspectral cameras, XRF or XRT sensors and LIBS spectrometers is opening the way to fast online characterization. The information collected by multiple sensors provides an estimate of the size and shape of fragments, their “mineralogy” and their liberation. Even though the indicators that can be computed in real time are still far away from the more advanced indicators accessible through the microscopy of sections, they can be very useful to develop pre-sorting technologies (separate barren from mineralized) or to perform cherry picking of high-valued materials. Moreover modern technologies allow separating into multiple bins whose bulk properties can be optimized in terms of value and volume to satisfy the market demand. As an example, the University of Liège is currently developing an intelligent sorting system to sort a complex mix of non-ferrous alloys and optimize their binning into populations corresponding to marketable alloy compositions (Fig.4).

Figure 4. Prototype of intelligent sorting technology developed by ULg_GeMMe.

5. Conclusions: towards Process Mineralogy 4.0

Process mineralogy or more generically the prognostic analysis of composite mineral assemblages is a field wide open for innovation. In this paper, we have tried to illustrate that the challenge of a more circular economy bears a lot of similarities to the optimization of mineral processing operations in primary mining. The development of multiple sensing techniques combined with powerful 2D and 3D image analysis open the way for the estimation of physically sound indicators. These indicators will not only provide useful information to develop particle tracking in advanced simulation software, but they might also, when available online, provide the indispensable information for intelligent sorting.

A possible evolution in a foreseeable future is that every product (component?) put on the market will have to be labelled with an RFID containing essential information about its composition (hopefully not just elemental contents but valuable "mineralogical" information). To some extent, one can imagine that sorting technologies will capture the information stored in the RFID and sort according to this information. Another foreseeable evolution is that consumer products will have to undergo a *crush test* to estimate the best available technology for the optimal recovery of all materials. Products will be labelled according to this recyclability indicator and collection of end-of-life products will be facilitated (Reuter et al., 2016). There is however still a long way to go before we reach this digital age, if ever, and in the meanwhile the need for advanced characterization techniques operated by well-trained mineralogists remains a priority.

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