ResearchGate

See discussions, stats, and author profiles for this publication at: https://www.researchgate.net/publication/319631578

AN EVALUATION OF THE APPLICATION OF X-RAY MICROSCOPY IN UNDERSTANDING GOLD LOSSES IN TAILINGS

Conference Paper · August 2017

CITATIONS
0

READS
10

2 authors:

Shaun Graham
Carl Zeiss Microscopy
13 PUBLICATIONS **6** CITATIONS

SEE PROFILE

Christopher. P. Brough
Petrolab Limited
18 PUBLICATIONS **145** CITATIONS

SEE PROFILE

Some of the authors of this publication are also working on these related projects:

Project Operational Mineralogy View project

Project X-ray Microscopy View project

All content following this page was uploaded by Shaun Graham on 11 September 2017.

The user has requested enhancement of the downloaded file.

AN EVALUATION OF THE APPLICATION OF X-RAY MICROSCOPY IN UNDERSTANDING GOLD LOSSES IN TAILINGS

S. D. Graham[1] and C. Brough[2]

[1]Carl Zeiss Microscopy
509 Coldhams Lane
Cambridge, Cambridgeshire, United Kingdom, CB1 3JS

[2]Petrolab Limited
C Edwards Offices
Redruth, Cornwall, United Kingdom, TR15 3AE

ABSTRACT

The extractive metallurgy of gold is largely controlled by mineralogical factors such as the presence of refractory gold, particle size, gangue mineral associations, presence of preg-robbers, oxygen and cyanide consumers, and locking characteristics in base metal sulphides.

Light microscopy and automated mineralogy techniques are regularly used to characterise the effect of these variables on gold recovery. However, despite their widespread application there are a range of limitations when grades are low. Typically, the analysis of low-grade samples requires the preparation and analysis of numerous polished blocks. This is often costly and time consuming, with complexities regarding analysing statistically representative particle quantities and problems overcoming stereological bias. This is compounded by the “nugget” effect and high tenor nature of gold mineralisation.

X-ray Microscopy techniques have the potential to overcome many of these problems, in particular the statistical representivity of analysis, removing stereological bias and effectively locating phases that are present in ultra-trace proportions. In this paper we outline the potential benefits of employing X-ray Microscopy (XRM) in characterising gold losses from a typical Cu-Au porphyry project, which were illusive in 2D based analysis. The talk will also outline additional application areas of XRM within the extractive value chain.

KEYWORDS

Automated Mineralogy, Process Mineralogy, Tailings, X-ray Microscopy

INTRODUCTION

Gold losses during mineral processing can be assigned to a variety of mineralogical, textural and processing controls. Variation in the gold mineralogy, association, textural setting, grain size, gangue mineralogy and also the mineralogical reactions that occur during processing can all impact recoverability. Characterization of such features is of increased importance for ore types that contain refractory gold. Gold can be largely split into two distinct types; “refractory” and “free milling”. “Free Milling” is largely described where cyanidation can be used to extract >90% of the contained gold, whereas “refractory” is used to describe more difficult to extract through conventional cyanidation. In addition, deposits can exhibit more complex populations where there are multiple populations of gold exhibiting a spectrum of refractoriness.

Characterization of complex and variable ore is becoming more important than ever (Baum, 2014; Gu *et al.* 2014; Hoal, 2008). It is widely reported that the current and future deposits are extracting lower grade material, with greater mineralogical complexity and variability (Baum, 2014; McKeith *et al.* 2013; Mudd *et al*. 2013). Between 1950 and 2008, average gold grade discoveries have fallen from 8 g/t to 1 g/t (McKeith *et al*. 2013). While some of this can be attributed to a falling cut-off grade with the development of heap leaching methods of extraction, discovery costs have risen from USD$ 3 to USD$ 80 in the same time period (McKeith *et al.* 2013). As the data outlines, discoveries, specifically of world class gold deposits are becoming rarer and with a greater discovery cost. Such trends can be used to outline how a greater level of resource base knowledge is required to increase the life time of the mine and also to ensure recovery is optimized and OPEX is kept to a minimum.

To help improve the knowledge of the ore body, geometallurgical/process mineralogy studies can be used to understand how the mineralogical variation in different domains will respond in the processing environment. The key aspect to such studies is the techniques available to generate the mineralogical data. The techniques available for the characterization of visible gold ores include light microscopy, automated mineralogy and electron microprobe. However, based on the 2D sample analysis and the sample preparation required, multiple challengers remain. Such 2D techniques impart sampling bias, stereological artefacts and representivity issues. Whilst these 2D limitations are accepted in the analysis, they are compounded with the presence of high tenor precious metal minerals found in low concentration, with a fine grain size. In order to overcome these issues, numerous samples must be taken and prepared to ensure the data collected is statistically valid.

In this case study example we will outline how volumetric XRM analysis can be used to overcome some of the issues associated with 2D analysis techniques to characterize gold texture. We will discuss advantages and limitations of the 2D techniques, mainly automated mineralogy, and outline how automated mineralogy and XRM analysis can be used as a complementary technique to understand gold losses in tailings.

GEOMETALLURGY & PROCESS MINERALOGY – AUTOMATED MINERALOGY FOR GOLD CHARACTERIZATION

Process mineralogy and Geometallurgical studies involve the integration of extractive processing techniques with thorough mineralogical characterization. This is a result of the understanding that rock, mineral and textural relationships impact on recovery. With particular focus on gold, the causes of gold losses can be attributed to the processing of a refractory ore type and insufficient understanding of that ore type and how it reacts in the processing plant. Some of the key causes of refractoriness are highlighted below in table 1.

Cause	Description
Gold Mineralogy	Change in mineralogy/gold mineral composition. Typical examples include gold been present as an alloy (i.e. telluride).
Grain Size	Variation in the grain size adjusts the required grind size to produce liberated or sufficiently exposed gold grains
Host Mineralogy	Mineralogical variation of the gangue can cause a change in the textural setting or the gold in the deposit.
Passivation	In-soluble coatings can form over the surface of the gold grains. This inhibits cyanidation and reduces recovery. Carbonates, sulphides and oxides can have this effect
Decomposition	Increased reagent consumption can be achieved through reactions with copper, zinc, lead, antimony and arsenic bearing minerals. This will decrease the cyanide leaching efficiency.
Preg-robbing	A process where the aurodicyanide complex is removed from solution usually by carbonaceous material.

Table 1. Summary table of the causes of refractoriness in gold ores (Goodall and Scales, 2007).

However, a greater understand and knowledge of the resource base through the development of a geometallurgical or process mineralogy study can help manage and optimize processing circuits to maintain a consistent operation in terms of efficiency and recovery. Independent studies (McKinsey & Company, 2015) have estimated that within the mining industry by 2025, around $250 billion of value can be extracted by improving the management of operations. Operations management includes, having a greater operational management through a deeper understanding of the resource base, optimized equipment and material flow and increased real-time performance *vs* the mine plan. An integral part to this operational management should be seen as the value and importance of mineralogy and understanding ore losses in operations. In recent years, trends have seen a movement towards a greater "Operational Mineralogy" approach through the adoption of on-site solutions for a greater monitoring of real time performance. This has resulted in the development of "Operational Mineralogy", where automated mineralogy is carried out on-site as a routine analysis to optimize and monitor plant performance (Strongman *et al.* 2017). Case study examples, such as Kansanshi in the Zambian copper belt have shown how onsite mineralogy and an operations management approach is been utilized to boost yearly revenues for copper and gold production (Kalichini *et al*. 2017).

However, with the characterization of gold ores, the application of 2D analyses using light microscopy, automated mineralogy and electron microprobe has its limitations. These limitation centre around the sample preparation and representivity. For automated mineralogy analysis, the samples must be sized and cured in resin which is a time consuming process. In addition, with the creation of a 2D sample, there are issues associated with the statistical representivity of the 2D section, sampling bias and also stereological artefacts. One of the solutions is to produce multiples samples to boost the statistical representivity of the 2D area covered in the analysis. This has its draw backs in terms of the number of samples the need to be prepared and the time and cost of this process, combined with the 2D analysis time of the samples. Whilst application specific protocols, such as bright phase searching are possible, the high resolutions required to scan the sample surface to locate the precious metal grains result in long analysis times and thus a delay in producing reliable and actionable data.

A study by Jones and Cheung highlighted that for a sample that contains 1 g/t of gold, with an average grain size of 10 microns, around 200 2D samples would need to be created and analysed in order to produce data that contains a ±50% accuracy (Fig. 1).

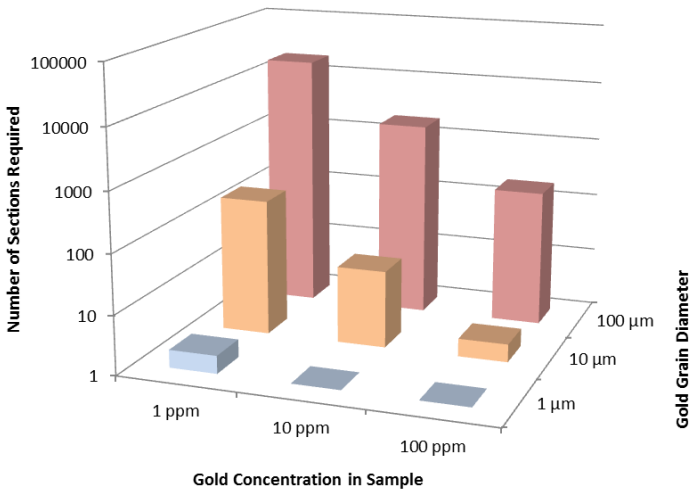

Figure. 1. Modified plot from Jones and Cheung outlining the required number of samples to produce data with at ±50% accuracy range for gold characterization.

As such, a routine operational management approach is not possible for the analysis of gold based on the volume of samples that would need to be analysed to produce reliable data. As a result of this, a single analytical technique is not able to provide robust and reliable data for gold analysis and complimentary techniques are required (Goodall and Scales, 2007).

A proposed solution to the above issues is to use a volumetric 3D analysis through the application of the XRM, which will now be discussed.

X-RAY MICROSCOPY – ARCHITECTURE AND MINERAL DISCRIMINATION

Within the X-ray Tomography world, there are two different types of architecture that are based on a cone beam scanning configuration. In this cone beam configuration, the X-ray source emits X-rays,

which pass through the sample, as the sample rotates and are then collected on the X-ray detector to record the X-ray intensity based on the material it has passed through (Fig. 2.).

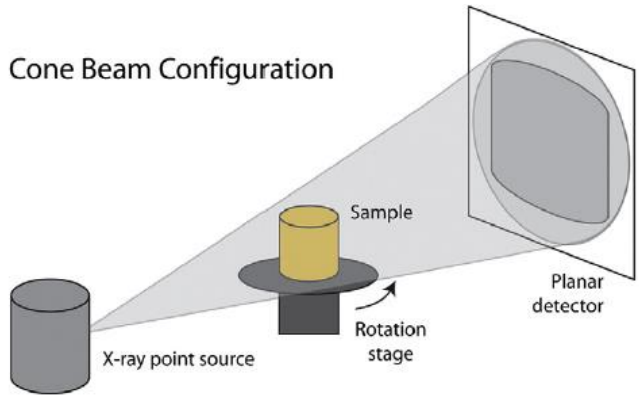

Figure 2. Schematic illustration of a cone beam configuration. Taken from Kyle et al. (2015).

These two main architectural types of the standard cone beam configuration have been developed by different industrial groups for different applications. The conventional geometric magnification approach for the most part has been developed out of the medical science community. In these applications, to achieve the highest resolution possible, the sample must be as close to the X-ray source as possible. As the sample diameter (size) increases the distance from the X-ray source increases and this reduces the achievable resolution.

The XRM utilizes the "dual magnification" approach which controls the resolution of the scan (Fig. 3). In this dual magnification architecture, X-rays pass through the sample and interact with a scintillator that is attached to an objective. The x-rays are thus converted into light where they are then able to be focused to maintain a small pixel size and thus a high resolution.

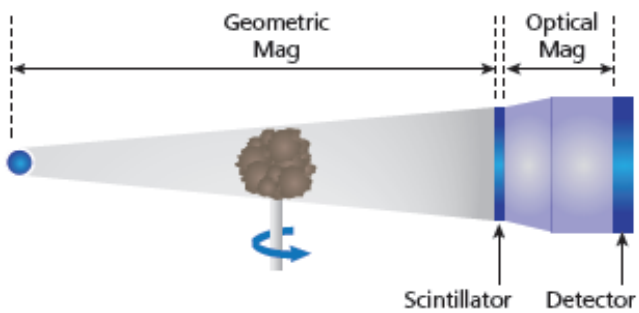

Figure 3. Geometric magnification architecture that does not rely solely on the geometric magnification and the position of the sample relative to the x-ray source. In this architecture, unique to the XRM, the x-ray interact with the scintillator and the objective where they are converted to light.

The advantages of the two stage magnification architecture enable a higher spatial resolution to be maintained despite an increase in the working distance or an increase size in the sample diameter. This is attributed to the two stage magnification architecture that doesn't rely solely on geometric magnification. This technology and architecture was harbored within the synchrotron community and thus provides a true spatial resolution of 0.7 µm. As such, the principle operation is very similar to that of a light microscope, where higher resolutions are achieved by adjusting to a higher powered objective to zoom into the sample. This workflow is known as interior tomography and is unique to the XRM architecture.

Mineral groups within the XRM are classified and grouped based on their x-ray attenuation coefficients. This attenuation of the minerals is a function of the average atomic number, the density of the sample and the spectral characteristics of the x-ray source as described in Beer-Lamberts Law. Theoretical x-ray attenuation coefficients of materials can be calculated using the mass coefficient database (Berger *et al*. 1998) and the mineral density as shown below (Fig. 4).

$$\mu C(\varepsilon) = \rho .\ \mu Tot(\varepsilon),$$

Where ρ is the density (g/cm^3) of the mineral/alloy and the µTot(ε) is the total attenuation with coherent scattering (cm^2/g). Examples of theoretical x-ray attenuation coefficients of minerals typically found in Ni-Cu-PGE ores are shown in Figure 4 (Godel, 2005).

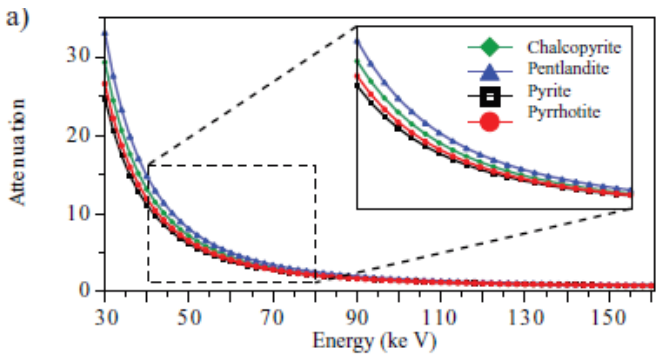

Figure 4. Theoretical linear attenuation coefficients for mineralogy typically found in Ni-Cu-PGE ores. Taken from Godel (2005).

METHOD & RESULTS

Prior to the 3D analysis, an automated mineralogy analysis using Mineralogic Mining was carried out across multiple samples. For the 2D analysis, the tailings samples were upgraded to 18 g/t Au and using Mineralogic Mining a Bright Phase Searching application was carried out. 10 grains were identified, with 9 of these having a maximum feret diameter of < 5 µm. One coarser grained gold grain was identified which had a maximum feret diameter of around 10 µm. All of the gold grains showed near

complete liberation with only two grains forming a binary texture with another phase. The binary grains were associated with chalcopyrite and showed a >50% gold liberation in each case.

Given this textural setting, it was expected that these particles should readably float and the gold content not sufficient enough to explain the wider losses, suggesting an alternative textural setting for the gold.

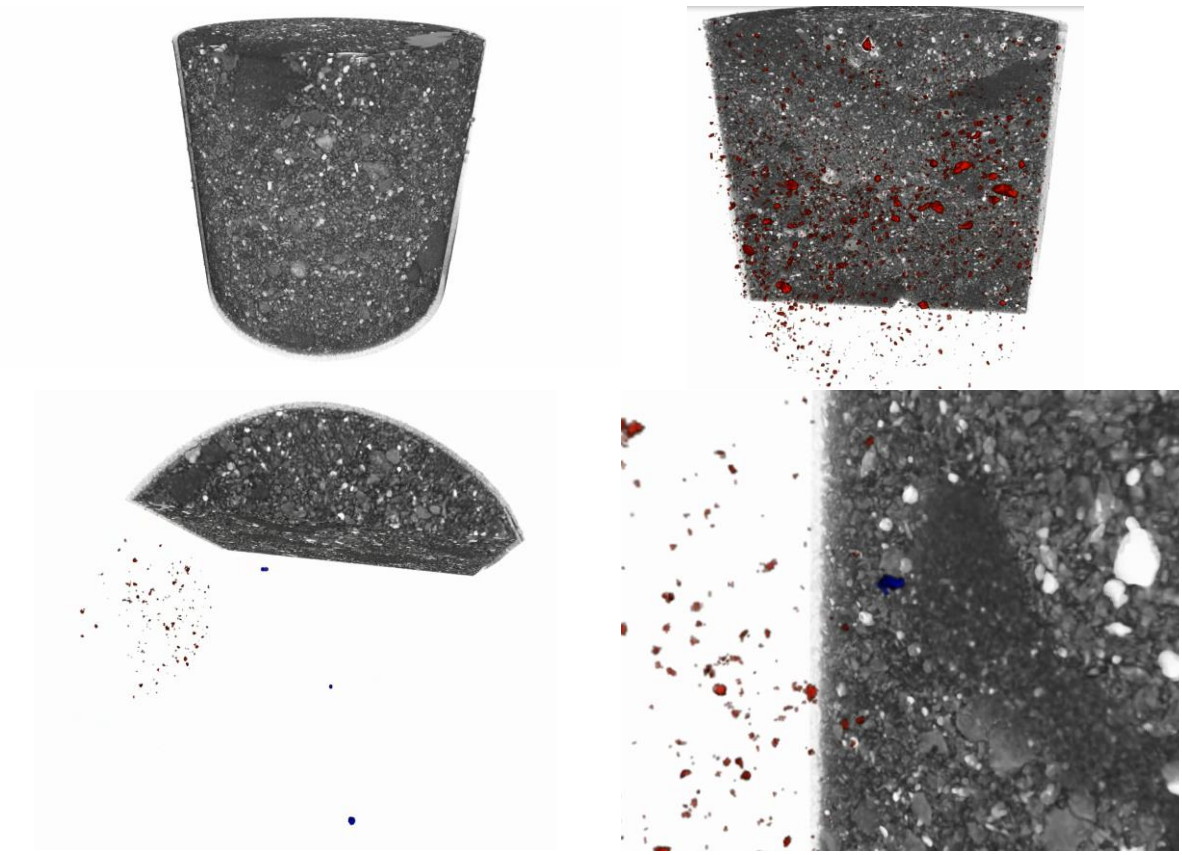

Figure 5. Volumetric reconstruction of the upgraded tailings sample. (a) Full view volumetric sample; (b) Partially segmented view outlining the sulphide particles displayed in red; (c) Segmented view whereby the sulphides are removed (red) leaving behind purely the gold (blue) phases; (d) View of partially remove sulphide mineralogy displaying in the centre the gold grain which is around 20 µm in length and fully liberated.

Using the Xradia Versa 520 a <20 µm sample of the gold tailings was taken and scanned. The 3D analysis was carried out with a 1.7 µm voxel with a 60 kV x-ray energy using the 4x objective. The analysis was carried out in 90 minutes and was able to scan and identify 26,000 sulphide particles (mainly pyrite) and also identify 3 distinct bright phases that are deemed to be gold (Fig. 5). These grains were approximately 20 µm in length, elongate and found with visible evidence of their association with fine clays. Such grain morphology and mineralogical associations can be used to explain how these freely liberated gold grains reported to the tailings as a result of their slow floatation response time.

DISCUSSION

2D analysis of the gold bearing tailings provided an interesting study to highlight the advantages of the XRM for precious metal search applications in tailings.

Typically, no single technique is capable of providing a comprehensive characterization of precious metal bearing samples. Goodall and Scales (2007) highlight how the application of automated mineralogy in gold studies is limited by the statistical representivity of the scanned samples to understand the gold mineralogy populations. This was supported with the initial analysis using Mineralogic Mining on the above described sample. Statistical data from Jones and Cheung also highlights how 100's of thin sections are needed to produce reliable data for samples that contain around 1 g/t gold that is around 10 microns in diameter.

Godel (2005) attempted to quantify and understand the value in 3D analysis to produce a more accurate and reliable assessment on the mineralogy, specifically in previous metal studies. In the case study, a 8 mm diameter cylinder containing 10 Platinum Group Minerals (PGM) were analysed and through digitally slicing the volume 990 times, only 3.7% of the slices intercepted a PGM grain (Godel, 2005). In addition, a series of 10 tests were carried out whereby in each test, 10 slices where taken through the volume with the aim to sample the PGM grains (Fig. 6a). Of the 10 tests, only 5 of the tests were successful in locating a PGM. In total, 100 slices were taken with only 6 PGM intersected. Further study showed that from these 2D slices, there is also a 50% underestimation of the grain diameter (Fig. 6b).

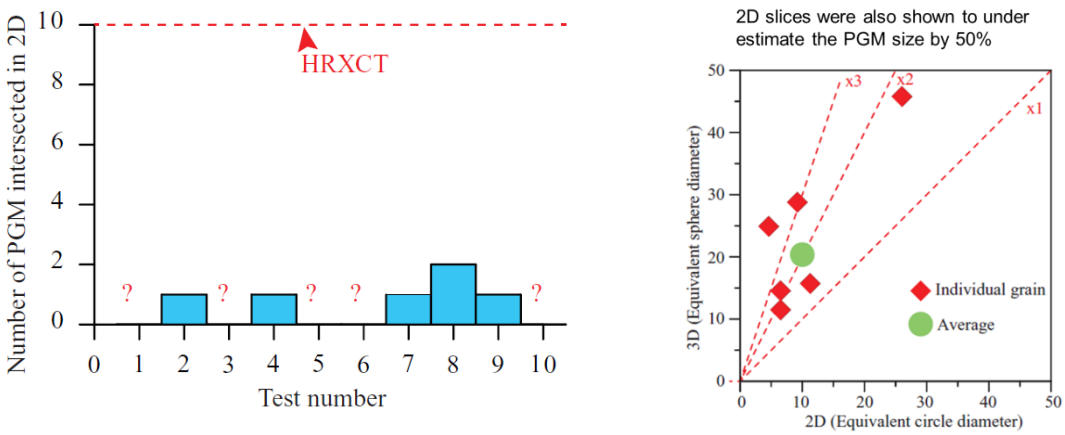

Figure 6. Representation of PGM within a 8 mm diameter cylinder Taken from Godel (2005); (a) a result of running 10 separate tests where each test has 10 slices taken from the cylinder. (b) Representation of the individual grain area represented in the 2D and 3D data.

More recent studies conducted by Brough *et al.* (2017) have begun to highlight additional value of the XRM in reviewing tailings to understand Acid Rock Drainage (ARD). In this study, a comparison on the 2D and 3D statistics outline how 3D data is much more valuable in producing reliable data for liberation studies. This data points towards 2D liberation values providing a overestimation of the actual liberation when compared to 3D data (Brough *et al*. 2017; Miller *et al*. 2009). There also appears to be a greater error in 2D to 3D data when the particle size increases past the +300 µm size range (Brough *et al.* 2017).

The preliminary data from the analysed samples combined with the above studies clearly illustrate some the pitfalls associated with 2D analysis and the utilization of automated mineralogy to study gold bearing samples. This is compounded further when we start to look at trace minerals in low concentrations, such as those that we typically expect to find in tailings. The analysis was successful in quickly scanning the volume to identify, based on the grey level values, the gold grains within the sample. Such gold grains were expected to be present in the sample but were not identified with conventional 2D automated mineralogy analysis.

The speed, lack of required sample preparation and ability to highlight gold grains and their textural settings in tailings samples outlines an exciting new application area for XRM within the mining value chain. It is proposed that on-site and rapid assessment of feed and tailings in gold operations can help provide greater understanding of the resource base in terms of ore variability. Such analytical techniques and the value of the data they provide will be of increased importance in the future as we continue to explore and develop unfavourable projects in terms of the mineralogy and textural setting of the gold.

CONCLUSION

The initial stage of this study highlighted how 2D analysis using automated mineralogy provided challenges in been able to produce statistically reliable and reconcilable data in the tailings sample. XRM analysis was carried out to produce a volumetric 3D analysis to overcome the short comings of the 2D analysis which centre around statically representivity, sampling bias and stereological artefacts. Within the mining value chain there are a growing number of applications where the XRM is now been applied and tested. Such applications as the ones demonstrated in this paper offer clear advantages over the conventional 2D analysis methods, but also show how the two techniques are complimentary and can be used in collaboration to provide a greater operational management approach for gold operations.

REFERENCES

Baum, W. 2014. Ore characterization, process mineralogy and lab automation a roadmap for future mining. *Minerals Engineering*, 60, 69-73.

Berger, M.J., Hubbell, J.H., Seltzer, S.M., Chang, J., Coursey, J.S., Sukumar, R., Zucker, D.S., and Olsen, K., 1998, XCOM: Photon cross sections database: NIST Standard Reference Database 8, v. http://www.nist.gov/pml/ data/xcom/index.cfm.

Brough, C., Strongman, J., Fletcher, J., Graham, S. D., Barnes, A., Bowell, R., Warrender, R and Ward, L. 2017. 2D-3D liberation comparisons in HCT testwork for the Hannukainen IOCG deposit, Finland. *Process Mineralogy*, 2017.

Godel, B. 2005. High-Resolution X-Ray Computed Tomography and Its Application to Ore Deposits: From Data Acquisition to Quantitaive Three-Dimensional Measurements with Case Studies from Ni-Cu-PGE Deposits. *Economic Geology*, 108, 2005-2019.

Goodall, W. R. & Scales, P. J. 2007. An overview of the advantages and disadvantages of the determination of gold mineralogy by automated mineralogy. *Minerals Engineering*, 20, 506 – 517.

Gu, Y., Schouwstra, R. B. & Rule, C. 2014. The value of automated mineralogy. *Minerals Engineering*, 58, 100-103.

Hoal, K. O. 2008. Getting the Geo into Geomet. *Society of Economic Geology Newsletter*, 73, 11-15

Jones, M. P. & Cheung, T. S. 1988. Automatic method for finding gold grain in ores and mill products. Asian Mining, 73-81.

Kyle, J. R. & Ketcham, R. A. 2015. Application of high resolution X-ray computed tomography to mineral deposit origin, evaluation and processing. *Ore Geology Review*, 65, 821-839.

McKeith, T. D., Schodde, R.C. & Baltis, E. J. Gold Discovery Trends. S*ociety of Economic Geology Newsletter*, 81, 19-26.

Mudd, G. M., Weng, Z. & Jowitt, S. M. 2013. A Detailed Assessment of Global Cu Resource Trends and Endowments. *Economic Geology*, 108, 1163-1183.

View publication stats