QEMSCAN MINERAL ANALYSIS FOR ORE CHARACTERIZATION AND PLANT SUPPORT AT CERRO VERDE

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1 ABSTRACT/SUMMARY:

In recent years there has been significant progress in the application of process mineralogy to metallurgical challenges in the minerals industry mainly because of the increased availability and improvement of SEM-based automated systems for acquiring quantitative mineralogical data. This progress combined with advances in analysis, data visualization, and linkages between geological and metallurgical information has led to a new level of understanding of the significance of mineralogical parameters and their impact on metallurgical performance.

The present paper describes the operation and application of the QEMSCAN™ automated applied mineralogy technology and how it is being utilized for long-range planning—by characterizing and optimizing the primary-sulfide reserve while providing operational support of the ongoing secondary-sulfide leaching operation at the Cerro Verde Mining Complex in Arequipa, Peru.

The primary-sulfide ore feed material is being characterized in order to optimize flotation recovery by identifying the key mineralogical features such as sulfide deportment, grain size, locking/liberation characteristics, and the presence of hydrophobic gangue minerals.

The information generated by the QEMSCAN™ for the secondary-sulfide leaching process is being used to profile and refine the current leach ore types in order to improve the overall copper recovery by characterizing and quantifying the copper losses in the final residue.

2 INTRODUCTION

The identification and characterization of ores and the minerals that make up those ores is of fundamental importance in the development and operation of mining and mineral-processing operations. Traditionally, such information has been provided by a mineralogist or geologist during DDH logging or using an optical microscope. This conventional approach has been improved by the development of automated mineral analyzers using state-of-the-art SEM microscopes combined with very powerful image-analysis systems (1). The QEMSCAN™ (Quantitative Evaluation of Minerals by Scanning Electron Microscopy) developed and distributed by Intellection Pty Ltd— located in Brisbane, Australia—recently installed and commissioned the first automated mineral analyzer of its kind on a mine-site at Sociedad Minera Cerro Verde S. A. A. near Arequipa, Peru. This technology not only provides quantitative mineralogy but also elemental assays, so that the data can be utilized for material balancing, calculating recoveries, and optimizing metallurgical operations based on particle economics. This sort of in-depth analysis can be utilized on material to be processed both by leaching and by flotation and concentration.

This paper will give a basic overview of the QEMSCAN™ technology and how it is applied at the Phelps Dodge Cerro Verde mining operation. The first example of applied process mineralogy's impact on the Cerro Verde operation is the application of the technology for the chalcopyrite/pyrite primary-sulfide ore.

The QEMSCAN™ is used to refine the current primary-sulfide ore types on the basis of key process mineralogical features. In addition, the technology has been extremely helpful in the design of the metallurgical flow sheet for the newly constructed concentrator.

The second area concerns the ongoing secondary Cu sulfide leaching operation. The QEMSCAN™ is used to profile the geo-metallurgical ore types currently being delivered to the permanent crush leach pad. Then those same ore types are monitored through the leach cycle to refine the leach kinetics and target opportunities for areas of improvement in the metallurgical process on account of the effect that the mineralogy has on recovery.

2.1 QEMSCAN™ OVERVIEW

The QEMSCAN™—as shown in Figure 1—is based upon a modern LEO SEM with four Gresham EDS light-element detectors affixed to the SEM chamber. The first commercial QEMSCAN™ appeared in the mid 1980s and was developed to identify particles' characteristics rapidly by using Backscattered Electron Intensity (BEI) and x-ray images produced by the SEM (2). Particle characteristics such as detailed compositions, particle size, shape, and elemental mapping became the building blocks for the technology that we currently employ to design and develop new ore bodies such as the primary sulfides present in Cerro Verde. QEMSCAN™ is also utilized as a tool to perform detailed mineralogical and metallurgical audits on operating plants so as to identify opportunities and improve efficiency in the daily operation. This work in general is generating a tremendous amount of useful data, information, and basic knowledge, which can be used to improve standard operational practices throughout mineral-process operation.

Figure 1 Sociedad Minera Cerro Verde S. A. A. QEMSCAN™

The goal and objective of these systems is to provide quantitative information on ore feeds and/or process streams, which can then be directly linked to metallurgical performance. As mentioned earlier, this type of information was previously produced visually and/or manually and was therefore qualitative in nature (3). The advantages of automated systems like the QEMSCAN^{TM} are their statically robustness, reliable mineral identifications, round-the-clock operations, high throughput, multiple applications with high degree of flexibility, multiple measurements modes, built-in quality-control programs, and data/information that can be utilized by geologists, metallurgists, mining engineers, chemists, material scientists, and accountants. The bottom line is that quantitative mineralogy can now be used just as well as a total Cu assay in a mining operation—but, more importantly, it can provide a detailed understanding of how such Cu assay is distributed in the material.

The QEMSCAN^{TM} can perform several types of measurements to produce modal abundances, particle images, particle and grain size information, mineral associations, and liberation/locking data. These data and information is then interpreted using image-analysis software to generate reports that highlight the key process mineralogical and metallurgical features. This information can then be applied in the grinding circuit, the flotation cell, or leach pad.

2.2 CV PRIMARY-SULFIDE ORE CHARACTERIZATION:

In 2002, a complete mineralogical profile was completed on the Cerro Verde primary-sulfide ore at the Phelps Dodge PTC (Process Technology Center – Safford AZ), including conventional mineralogical and chemical analyses as well as QEMSCAN^{TM} automated mineralogy and chemistry of 135 drill-hole composites (4). These samples represented a selection of drill-hole interval samples taken from about 19,700 m of a diamond-drill program conducted by Cerro Verde in their primary-sulfide ore body. The major conclusion was that the Cerro Verde sulfide ores could be classified into four geo-metallurgical ore types according to the relative abundance of chalcopyrite and pyrite quantified in the QEMSCAN^{TM} bulk modal-analysis measurements (5). These ore types were described as Figure 2 and Table 1 show.

QS Ore Type 1 – Pyrite-dominated, with chalcopyrite and low K-feldspar.
QS Ore Type 2 – Pyrite-dominated with increasing chalcopyrite: moderate recovery potential.
QS Ore Type 3 – Chalcopyrite-pyrite ore with increasing K-feldspar, chlorite, and biotite: good recovery potential.
QS Ore Type 4 – Chalcopyrite-dominated, high chlorite/biotite, K-feldspar, lowest quartz: best recovery potential.
QS Ore Types 1 and 2 exhibited the highest levels of pyrite and muscovite/sericite and may require blending in order to minimize the detrimental effects of these minerals in the flotation circuit and increase flotation selectivity, since they have the potential to dilute the final concentrate. There is also an increase in the amount of pyrophyllite—a hydrophobic mineral—in both QS 1 and QS 2 that can add, too, to the dilution of the concentrate products. Ore types 1 and 2 contain the coarsest grained pyrite (90 to 70

microns) but, at the same time, the finest grained chalcopyrite (43 to 46 microns), so the potential for middling losses will increase. Ore types 3 and 4 have the best recovery potential but may exhibit more entrainment of gangue in the concentrate due to the increase in sliming minerals and decrease in quartz. Ore types 3 and 4 contain the finest pyrite (51 to 29 microns) and the coarsest chalcopyrite (55 to 57 microns), so the materials may require longer flotation times.

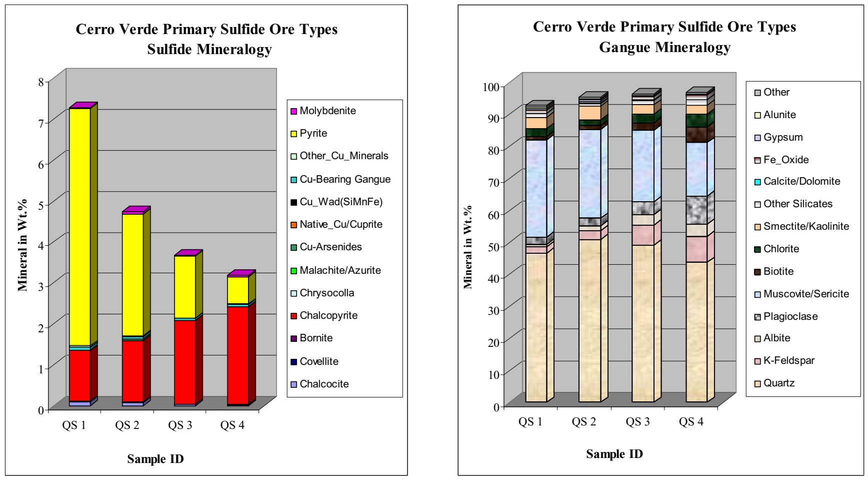


Figure 2 QS Cerro Verde Primary-Sulfide Ore Types

Cerro Verde Primary Sulfide Ore Types				
Sulfide Mineralogy (wt%)	**QS 1**	**QS 2**	**QS 3**	**QS 4**
Chalcocite	0.10	0.08	0.03	0.02
Covellite	0.01	0.01	0.00	0.00
Bornite	0.01	0.02	0.01	0.01
Chalcopyrite	**1.23**	**1.49**	**2.04**	**2.39**
Chrysocolla	0.00	0.00	0.00	0.00
Malachite/Azurite	0.00	0.00	0.00	0.00
Cu-Arsenides	0.01	0.03	0.01	0.00
Native_Cu/Cuprite	0.00	0.00	0.00	0.00
Cu_Wad(SiMnFe)	0.00	0.00	0.00	0.00
Cu-Bearing Gangue	0.07	0.07	0.05	0.06
Other_Cu_Minerals	0.04	0.02	0.01	0.01
Pyrite	**5.79**	**2.97**	**1.50**	**0.65**
Molybdenite	0.02	0.05	0.02	0.05
Gangue Mineralogy (wt%)	**QS 1**	**QS 2**	**QS 3**	**QS 4**
Quartz	**46.53**	**50.92**	**49.08**	**43.72**
K-Feldspar	**1.99**	**2.82**	**6.34**	**8.08**
Albite	0.78	1.49	3.33	3.93
Plagioclase	**2.43**	**2.32**	**3.93**	**8.66**
Muscovite/Sericite	**30.29**	**27.78**	**22.33**	**16.79**
Biotite	1.07	1.15	2.23	4.93
Chlorite	2.36	1.86	2.80	3.92
Clays/Pyrophyllite	**3.60**	**4.16**	**2.95**	**2.72**
Other Silicates	1.18	0.93	1.31	1.78
Calcite/Dolomite	0.07	0.05	0.20	0.11
Fe_Oxide	1.01	0.68	1.05	1.42
Gypsum	0.47	0.34	0.17	0.29
Alunite	0.50	0.36	0.18	0.02
Other	0.43	0.40	0.44	0.44
Total	**100.0**	**100.0**	**100.0**	**100.0**
Grain Size (microns)				
Chalcocite	20.29	17.63	14.65	12.01
Covellite	9.36	8.46	1.66	2.93
Bornite	18.57	16.04	13.85	17.65
Chalcopyrite	**42.99**	**46.12**	**54.95**	**57.15**
Molybdenite	19.19	41.07	33.50	54.92
Pyrite	**89.51**	**71.40**	**51.25**	**28.89**

Table 1 QS Cerro Verde Primary-Sulfide Ore Types

In addition to the above described ore characterization project, a master composite of Cerro Verde ore was prepared and sent for metallurgical test work based on the four described ore types (6). Products from the rougher flotation kinetic tests performed on this composite were submitted for QEMSCAN™ analysis. The aim of this study was to obtain a statistically reliable benchmark on the flotation kinetics of the individual minerals under standard bench-scale flotation conditions (5). This QEMSCAN™ information would then provide the process mineralogy model linking ore and mineral characteristics with the observed metallurgical behavior in order to identify opportunities to enhance design and development of the new Cerro Verde concentrator.

The mineralogy for the master composite and feed characteristics for the rougher flotation kinetics test was identified as QS ore type 2. The gangue and sulfide mineralogy reconciled with the pattern of QS ore type 2, with sulfides contributing little more than 4% of the feed, of which chalcopyrite represented 1.8% and pyrite 2.7%. Figure 3 is a QEMSCAN^{TM} particle image map produced from the (-106/+150 mesh) rougher feed of the master composite rougher kinetics-testing program. This mineral map has been sorted on chalcopyrite and illustrates the complex and multiple particle types being introduced to the rougher flotation circuit.

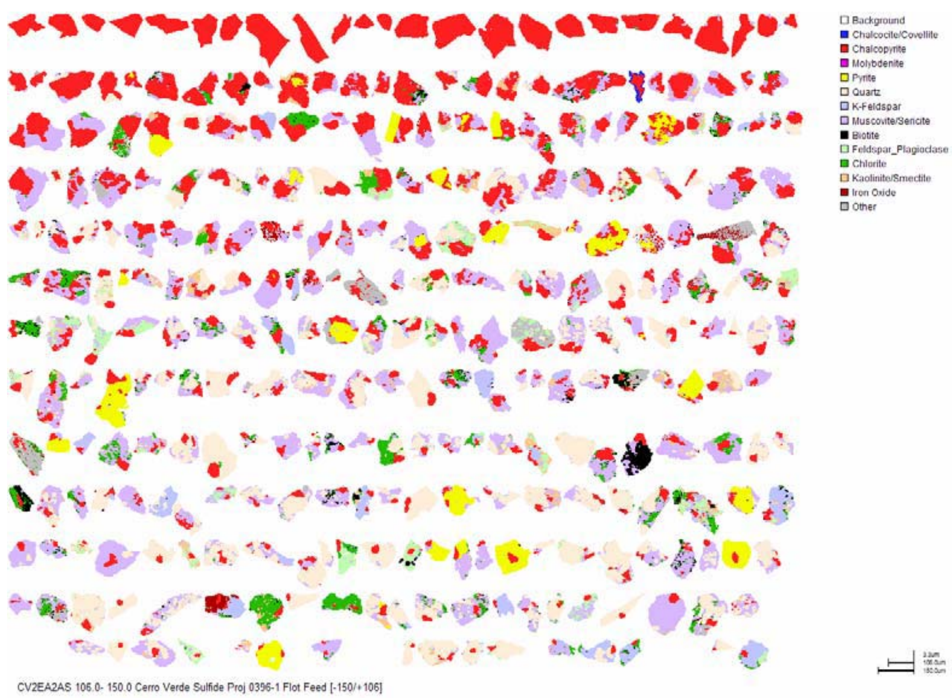


Figure 3 Typical Chalcopyrite Particles of the Cerro Verde Primary-Sulfide Ore

The aim of this section and of this paper was to point out that ore characterization for the Cerro Verde primary sulfides is critical to the success of the project, from development of the ore body to the final concentrate product produced from the new mill. This work will continue at the Cerro Verde material-characterization laboratory and the geo-metallurgical ore types will be refined with additional metallurgical testing and QEMSCAN^{TM} mineralogy. The next step for this project is to introduce the geo-metallurgical ore types to the long-range block model so that the mining planner and the metallurgist in the concentrator can utilize the data and information.

2.3 CV SECONDARY-SULFIDE LEACH OPERATIONAL SUPPORT

In 2003, a joint project was developed between the Phelps Dodge PTC (PD Process Technology Center – Safford AZ) and the Cerro Verde hydro-met leaching department to study the effects of mineralogy on the leaching process in pad 4. This resulted in a very thorough sampling and investigation program with the work being performed at the PTC and the Cerro Verde operation. The samples were collected by Cerro Verde to include the unleached head, agglomerated, 30-day, 60-day, 90-day, 140-day, 190-day, and final residue (of 260 days). This detailed sampling was necessary to obtain information for the complete profile of the leach cycle. The ultimate goal and objective of the study was to improve the understanding of the mineralogical changes through the leaching cycle from head to final residue. From this greater understanding and newly found knowledge, opportunities could be generated for possible further Cu recovery and operational improvements. Listed below were the goals and objectives (7):

- To establish SOP for heap leach surveys (sample collection, preparation, and quality control).
- To establish the key mineralogical species (copper, iron, and gangue) that affect the leaching process and its outcome.
- To quantify the degree of conversion of the copper and iron species and characterize their behavior as the leach cycle progresses.
- Identify the Cu losses to the final residue and define possible opportunities for additional recovery.
- Identify additional value that this information may provide to the metallurgists, geologists, mine planners, and operators.

Figure 4 represents the sample area on Pad 4 and the Cu assay reconciliation between the wet assays and QEMSCAN^{TM}. One important and critical dimension of the QEMSCAN^{TM} technology is the ability to generate recovery from the electronic assays generated from the processing of the modal-analysis measurements. This allows data users to calculate recoveries and reconcile those recoveries with conventional analytical Cu assays. The assay reconciliation and QEMSCAN^{TM}-calculated recoveries for this project were excellent. Obtaining this level of assay reconciliation illustrates that the SOP developed for the entire program was executed at the highest possible level and that the team had achieved our first objective of establishing a robust sampling SOP for heap leach surveys.

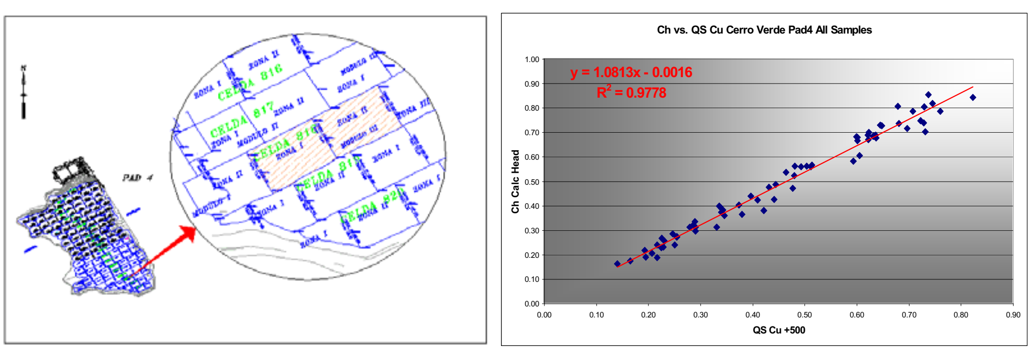


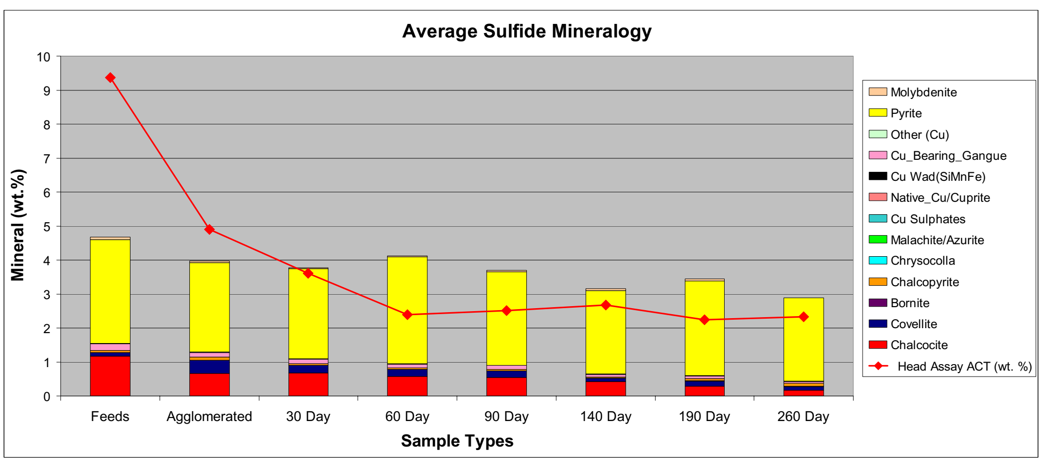
Figure 4 Cerro Verde–Pad 4 Sample Locations and Cu Assay Reconciliation

Table 2 shows the Cu assays and metallurgical balance from three independent sources, exhibiting excellent reconciliation from the head to the final 260-day residue. The average feed grade during the survey period was approximately 0.73% Cu and the average recovery was approximately 75%. This table also outlines a recovery target of 0.18% Cu (25% dist of the head Cu assay) remaining in the final residue after leaching for 260 days. The next step was to review the Cu mineralogy and Cu deportment in the 260-day residue that was measured and quantified by the QEMSCAN™ to further delineate the opportunities for additional recovery.

QA/QC Cu Assay and Metallurgical Balance								
Sample Type	**Feeds**	**Agglomerate**	**30 Day**	**60 Day**	**90 Day**	**140 Day**	**190 Day**	**260 Day**
PTC Chemical (Avg. Assayed	0.74	0.74	0.49	0.38	0.38	0.26	0.27	0.18
Cu Recovery			33.29	48.81	48.52	65.35	63.42	75.48
QEMSCAN (Avg. Calc. Head)	0.71	0.71	0.45	0.37	0.35	0.24	0.24	0.18
Cu Recovery			36.62	47.89	50.70	66.20	66.20	74.65
Cerro Verde (Avg. Assayed Head)	0.73	0.71	0.48	0.38	0.40	0.26	0.27	0.18
Cu Recovery			32.39	46.48	43.66	63.38	61.97	74.65

Table 2 Cerro Verde–Pad 4 Cu Recoveries and Metallurgical Balance

This information is supplied in Figure 5 by two bar charts. The first graphically represents the average sulfide mineralogy from the head to the final-260 day residue. The second provides the average Cu distribution by mineral deportment from the head to the final 260-day residue. The final 260-day residues show an average Cu mineral distribution of 34% chalcocite, 44% covellite, 18% chalcopyrite, and 4% other Cu. The premier targets for additional recovery are the 34% chalcocite followed by the 44% covellite.



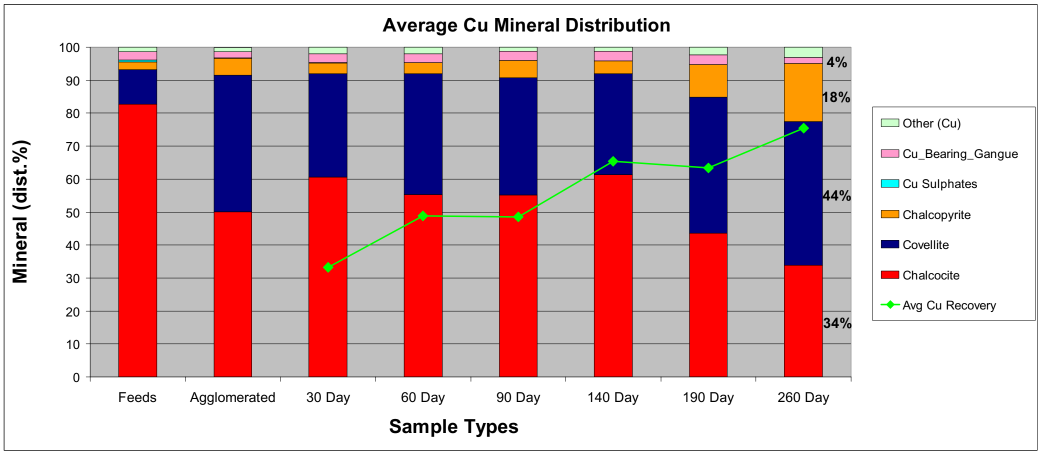
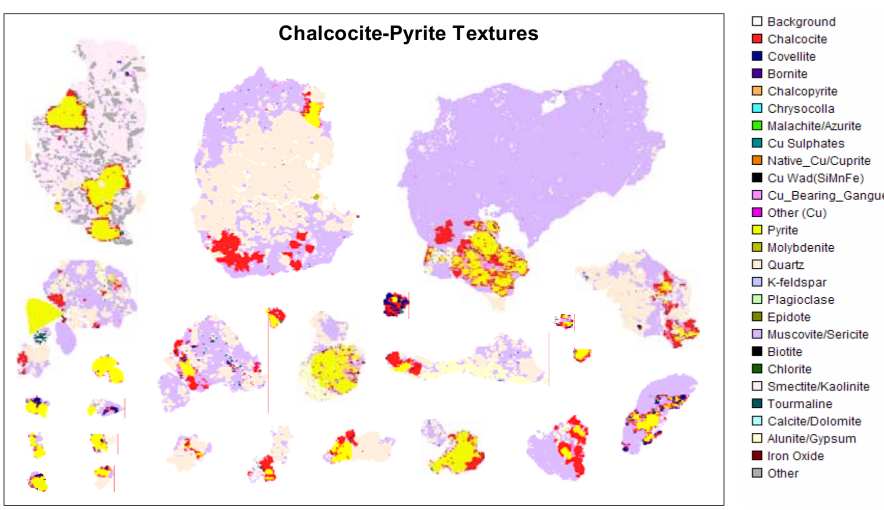


Figure 5 Pad 4 Average Sulfide Mineralogy and Average Cu Mineral Distributions

At this stage of the project, the team has accomplished many of the original goals outlined on page 9 of this paper. Opportunities for additional recovery have clearly been identified and quantified, but what metallurgical methodology do we apply to the remaining chalcocite and covellite so as to get additional recovery? Maybe a better question is this: why did the chalcocite and covellite not leach after 260 days? How can the sulfide mineralogy be further described to obtain the answers to the two previously asked questions? The authors believe that the answer is in the particle textures and mineral associations. Figure 6 shows two QEMSCAN^{TM} particle maps illustrating the typical chalcocite-pyrite textures in the feed and the corresponding 260-day residue. The key to additional recovery may be in understanding the particles and the textures being leached during the leach cycle. This work will be continued at the Cerro Verde material-characterization laboratory to achieve the ultimate goal set forth at the beginning of this project in late 2003. It should be kept in mind that process mineralogy has been applied to mill ores and concentrator operations for many years, and therefore has the advantage of those years of knowledge and information that the leaching process does not posses. Mineralogy does have a direct effect on the leaching process, as mineralogy changes throughout the leach cycle have been profiled. The next step is to find the key mineralogical factors that affect the metallurgy and match them to the metallurgical performance.



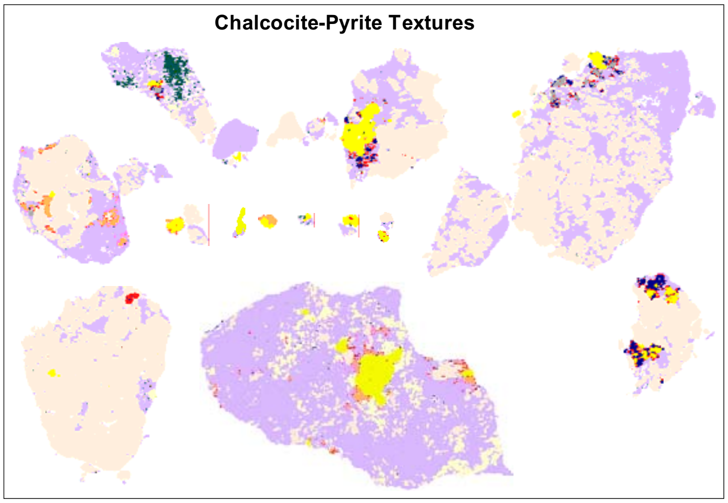


Figure 6 QEMSCAN™ Image Maps of the Typical Feed and 260-Day Residue Particles

3 CONCLUSIONS

The QEMSCAN™ Technology and process mineralogy will be used widely across the Cerro Verde mining complex in a variety of areas. This paper highlighted two of the key areas that the QEMSCAN™ will focus on—but to which it will not be limited—in the first years of service. The Cerro Verde primary sulfides will benefit from quantitative process mineralogy and the ore characterization program is well advanced. The next step is to introduce the key mineralogical features (sulfide deportment, grain size, and gangue mineralogy) into the geologic block models so this data/information can be used by the mining engineers for advanced mine planning and the concentrator metallurgists to optimize mill conditions to match that of the ore feed. The mineralogy of an ore body has a direct impact on the profitability at which it can be developed, modeled, and eventually mined.

The remaining leach reserves are a very important part of Cerro Verde's future and Phelps Dodge is investing in technology to get the most out of that material. The Pad 4 project has demonstrated that the leaching cycle can be profiled using the QEMSCAN™ technology and produce results with very high confidence levels. This project has developed the SOP by which the ongoing operation will be monitored for opportunities of improvement. This is the beginning of this type of work and the model will continue to be refined and optimized. The information to be produced will be evaluated and interpreted by geologist, metallurgist, and mineralogist to extract the crucial pieces of information in order to increase our knowledge of the leaching process.

Finally, the data and information that is produced on a daily basis at the Cerro Verde material-characterization laboratory will be used for multiple metallurgical challenges and issues which will ultimately lead to greater opportunities to make better decisions in the mine, on the leach pad, and in the concentrator.

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