

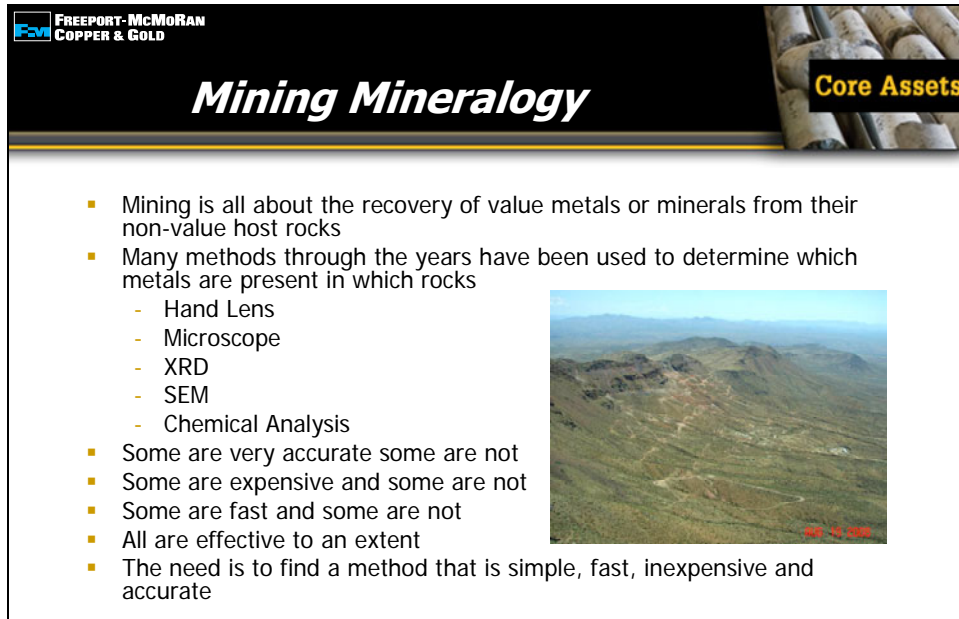
NIR Mineralogical Analysis in Mining

Steve Eady

Freeport-McMoRan Copper and Gold

I started working in the mining industry as a mineralogist about 35 years ago. I found out quickly that mining was all about the recovery of value metals from their non-value host rocks. Everything we did was to decide where the value metals and minerals were and what could we do to recover them. I found there were many ways used to define the value metals.

Hand lens, Microscope, X-Ray Diffraction, SEM, Chemical analyses




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Mining Mineralogy

Core Assets

- Mining is all about the recovery of value metals or minerals from their non-value host rocks
- Many methods through the years have been used to determine which metals are present in which rocks
 - Hand Lens
 - Microscope
 - XRD
 - SEM
 - Chemical Analysis
- Some are very accurate some are not
- Some are expensive and some are not
- Some are fast and some are not
- All are effective to an extent
- The need is to find a method that is simple, fast, inexpensive and accurate

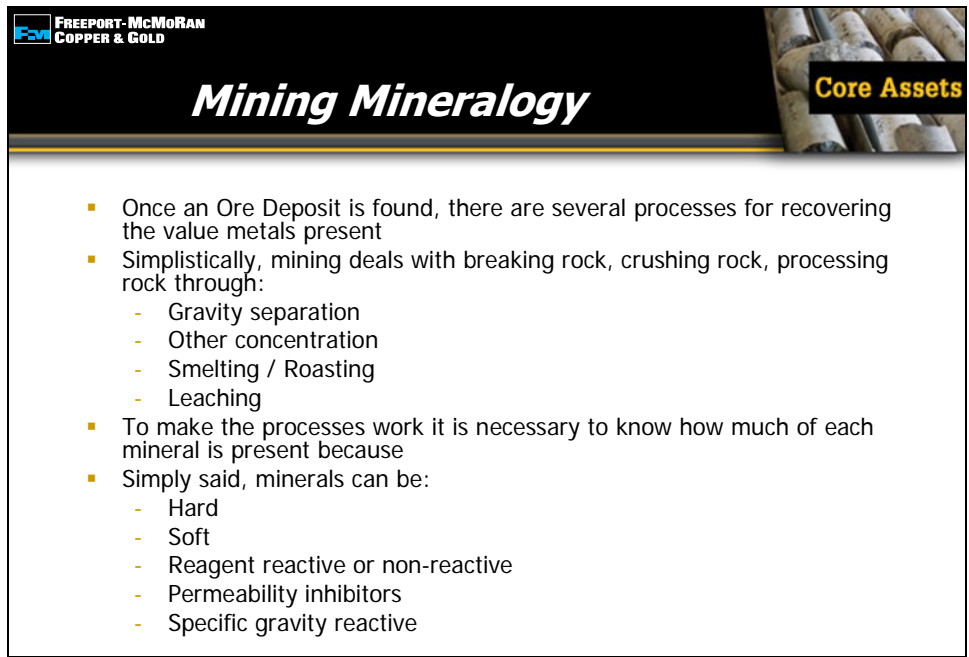


Some of these are very accurate and expensive, some are not. Some are fast and some are slow. They are all effective to a degree, but everyone was looking for a method that was simple, fast, inexpensive and accurate.

In my first job I was challenged to identify the minerals present in various processing streams at the mine production plant. The plant operators would often have problems with the plant and could not figure out what was happening. After checking to make sure no operating parameters had been changed, we all agreed that the issue had to be that the mineralogy had changed from the “normal” to something else. What had changed was then the question. That sent me back to my lab with samples from the plant. I started with my hand lens to see what I could determine. Because of the size of the grains, between 50 and 150 microns, the particles were too small to identify. I then tried the polarizing microscope. This required a lot more sample preparation time, but allowed very good identification of the minerals present. However, it was difficult to estimate percentages of the minerals present in the samples because of the huge variety of textures and intergrowths of some very fine-grained minerals.

This is still the situation today. The problems with plant upsets still occur every day somewhere in our world-wide operations. People still call and want to know what happened to the ore. The difference today is that we have many more methods available to help answer the question. We still have hand lenses and microscopes. They still have the same limitations. Today we also have X-ray diffractometers

and electron microscopes available. Both of these are very good options and our company makes good use of them. They do have some limitations.



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Mining Mineralogy

Core Assets

- Once an Ore Deposit is found, there are several processes for recovering the value metals present
- Simplistically, mining deals with breaking rock, crushing rock, processing rock through:
 - Gravity separation
 - Other concentration
 - Smelting / Roasting
 - Leaching
- To make the processes work it is necessary to know how much of each mineral is present because
- Simply said, minerals can be:
 - Hard
 - Soft
 - Reagent reactive or non-reactive
 - Permeability inhibitors
 - Specific gravity reactive

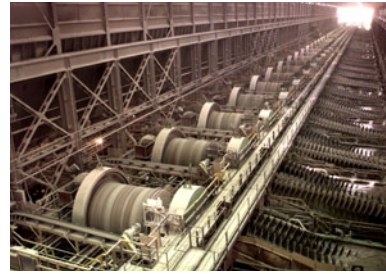
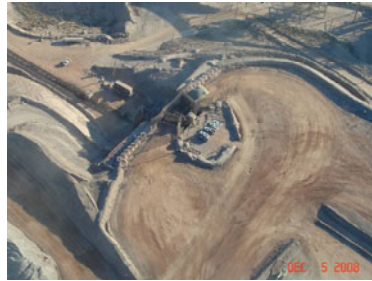
Generally when an ore deposit is finally found and completely outlined and tested, there are then several different ways to recover the value metals. Which of these methods is used is dependent on the mineralogy of the value metal. Simplistically, mining deals with breaking the rock, crushing the rock and processing the rock through:

Gravity separation
Concentration
Smelting / Roasting
Leaching

You have to know exactly which value minerals are present in the ore in order to determine which of these processes can be used effectively to recover the value metal.

To make the processes work, it is necessary to know how much of each mineral is present in the ores. Once you know how much of each mineral (value metal minerals as well as host rock or gangue or waste as it is called in mining) is present in the rock, one can determine or predict issues about the ore such as:

Hardness
Softness
Reagent reactive minerals
Reagent non-reactive minerals
Permeability inhibitors
Specific gravity reactive minerals



These factors and others have an impact on what must be done in order to extract the value metal from the rock. For example, hard and soft minerals have a tremendous effect on drilling of the rock. The rock must be drilled and then loaded with explosives so that it can be broken into a size that can be loaded into trucks for transportation to the milling plant. If the rock has hard minerals present, it will require more time to drill the blast holes and cost more money for drill bits. It will take more explosives to break the rock.

For concentrator ores, before the hard rock is delivered to the plant, there must be more crushing to reduce the rock to a useable size to feed into the plant.



Once in the plant the value metals must be released or liberated from the host or gangue rock. This is done with even more grinding in large SAG mills and ball mills. All crushing and grinding requires the use of tremendous energy to reduce the rock to the correct size. The percentage of hard and soft minerals present can make a huge difference in the operation of a mine and plant.

Once the ore is ready to be processed, other factors must be considered in order to recover the metals such as which reagents are the metal minerals reactive to? Can the metal be leached from the mineral? Will acid do the leaching? Do other gangue minerals consume the acid? Are there gangue minerals that will inhibit the permeability of an ore leaching pile? Does the mineralogy require that the whole mineral be floated away from the gangue rock? Are the minerals heavy enough that they can be separated from the gangue by gravity or do they need to be melted in a smelter to be separated?

- The easiest and most acceptable method to identify minerals used in mining is XRD
- Advent of computer Rietveld Refinement programs and fast XRDs
- SEMs are today automated and work very well
- There are limitations with XRD and SEM



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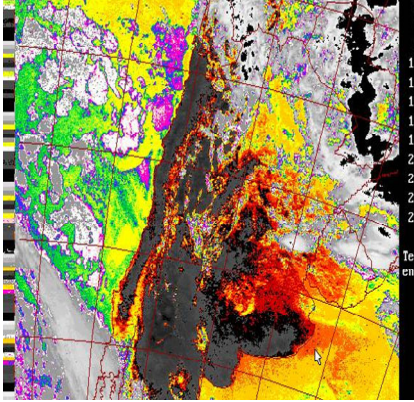
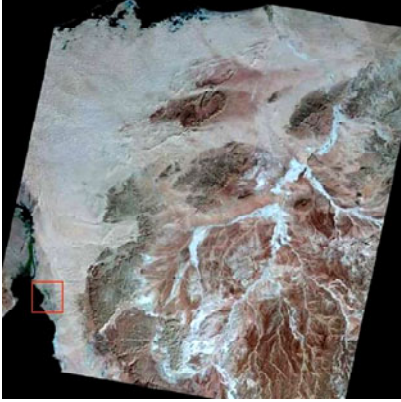
So how do we determine the mineralogy of ores and host rocks? XRD is the standard that is used most of the time. We also have automated mineral analyzers like QEMSCAN. Both work very well, but have limitations. They can be expensive to buy, especially the QEMSCAN, which is a scanning electron microscope that has been fitted with 4 fast detectors for collecting elemental spectra, which is then converted into mineralogy based on a defined Species Identification Program (SIP). Sample preparation can be extensive for both instruments. Computerized Rietveld Refinement programs for XRD can now make quantification of minerals very fast and accurate. XRD has a limitation of materials that must be crystalline to be identified and QEMSCAN identifies minerals based on percentages of elements present in minerals, which can vary substantially. There is a need for an instrument that is simple, fast, inexpensive and accurate. Enter infrared.

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Infrared and Mineralogy

Core Assets

- Enter Infrared Used for mineral identification for at least 35 years
- Especially known today for use in Satellite Imagery

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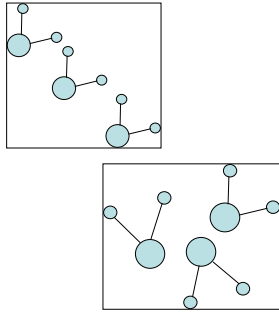
Infrared has been used for mineral identification for at least 35 years. It is especially known for its use in Satellite Imagery.

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Infrared and Mineralogy

Core Assets

- Many years of use in characterization of various clay minerals which are complex hydrous aluminum silicates, especially in the Near Range
- Works using detection of molecular vibration and the % absorption or reflection of infrared light frequencies by these molecular bonds
- Thus infrared can be used to identify minerals that are amorphous or non-crystalline
- XRD can only identify crystalline minerals
- Swelling clays such as montmorillonite have a high cation exchange effect which can disrupt the crystal lattices of the mineral and make it appear as an amorphous mineral to XRD
- Swelling clay is a very critical mineral in mining processes



For many years infrared spectroscopy, especially the near range, has been used for the characterization of various clay minerals, which are complex hydrous aluminum silicates. These instruments work by using the detection of molecular vibrations and the percent absorption or reflection of infrared light frequencies by these molecular bonds. Thus infrared can be used to identify minerals that are amorphous or non-crystalline as well as crystalline.

Swelling clays have a high cation exchange effect, which can disrupt the crystal lattices of the mineral and make it appear as an amorphous mineral to XRD. The chemical composition of these clays can be almost exactly the same as that of the original feldspars from which the clays altered, so QEMSCAN identification can be problematic.



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Infrared and Mining

Core Assets

- Swelling clay can be very detrimental or very helpful in various metal mining processes
- How does it effect the process
- Important for us to know how much is present in the ores
- Develop a method to determine how much is present

Helpful



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Swelling clay is potentially one of the most detrimental or helpful minerals present in the mining industry. It is critical to know how much swelling clay is present in the ore being processed. When dealing with various ores, we need to determine if the presence of clay is going to be detrimental or helpful. For example if we need to do a lot of drilling, the presence of clay will make the drilling go much faster and thus cost much less. This will allow much more ore to be mined and moved faster.

If we need to construct an impermeable liner below a stock pile, then the more swelling clay present the better.

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Infrared and Mining

Core Assets

Detrimental



However, on the other side of the coin, if we are trying to get leach solutions to pass through a stockpile to extract the copper, swelling clay can plug the stockpile and completely stop solution flow.

In the concentrating process, the presence of any clay can make the froth bubbles that we form to collect the copper collapse and very little copper will be recovered.

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Infrared and Mining

Core Assets

- XRD could not be used without extensive time-consuming sample treatment methods
- Quantifiable results are still questionable
- NIR can identify the swelling clay (SC) without difficult preparation
- Percentage of SC is quantified by wet chemical cation exchange capacity
- A quantitative SC model is built using CEC measurements of matrix specific samples with variable SC percentages over the full range of clay values
- This model is then loaded into Indico Pro Software of the ASD NIR and used to predict the percentage of SC in mine samples
- The SC value is determined in a matter of seconds with the NIR; then used to replace the SC value obtained from normal XRD analysis; then run through Rietveld Refinement to obtain a truly quantitative percentage of all minerals present in ore samples

NIR can identify the swelling clay without difficult preparation. The percentage of swelling clay present can be quantified by a wet chemical cation exchange capacity (CEC) test. A quantitative NIR model can be built using the wet CEC measurements of matrix specific samples with variable swelling clay percentages over the full range of clay values present in the ores. This model is then loaded into the Indico Pro software on the ASD NIR and used to predict the percentage of swelling clay in mine samples. The swelling clay value is determined in a matter of seconds with the NIR and this value is then used to


replace and add to the mineral values obtained by XRD Rietveld Refinement for mine samples. The combination of these two methods gives a truly quantitative percentage of major and minor minerals present in the ore.

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Infrared and Mining

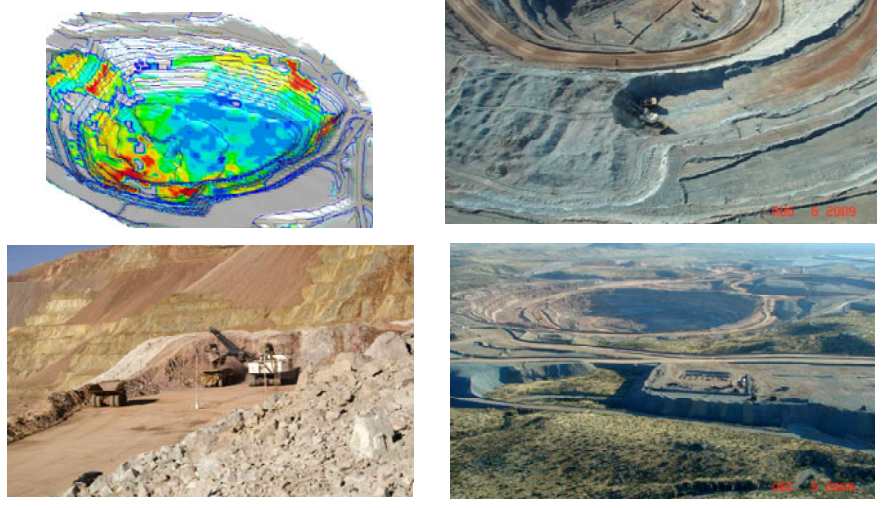
Core Assets

- Often a complete mineralogy of ore samples is not needed
- Maybe the process only needs to know “hard” and “soft” minerals
- For example, drilling, blasting, crushing and grinding are dependent on “hard” versus “soft” minerals present
- NIR can be used to identify the individual “soft” minerals such as clays, micas, talc and others that have vibrational modes in the near range
- The quantification of these additional minerals is calibrated with XRD measurements and used as predictive models as was CEC measurements for SC
- The “hard” minerals are measured indirectly using the total “soft” minerals
- This measurement is done each day on hundreds of blast holes



Often a complete mineralogy of ore samples is not needed. It may only be necessary to know if the material is “hard or soft”. For example drilling, blasting, crushing, and grinding are dependent on “hard” versus “soft” minerals. NIR can be used to identify the individual “soft” minerals such as clays, micas, talc, and others that have vibrational modes in the near range. The quantification of these additional minerals is calibrated with XRD measurements and used as predictive models as was the CEC measurements for swelling clay. The “hard” minerals are measured indirectly using the “soft” minerals as measured on the NIR. This measurement is done each day on hundreds of blast hole samples.

Ore Control Routing



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With the information obtained daily from NIR analysis of blast holes, the ore control geologist and mining engineers can make many decisions about what to do with the material from various parts of each blast. For example, before material is loaded into a truck a decision must be made whether there is enough clay to cause permeability issues in a leach stockpile or is there too much clay to send the material to a concentrator. If there is too much clay, then the material must go to a different type of process that minimizes the effect of clay. If the clay content is ok, then how much “hard” mineral is present and how will that affect the crushing and grinding circuits. Will too much extra time be needed? If so does the material need to be blended with softer ore to preserve throughput? Will metal recovery be lowered from lack of correct grinding time?

Crushing / Leaching



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After the decision is made to route the ore material to one of the processes, decisions need to be made from this same information that affect the various processes. For example, the size of the blasted material may dictate which crushing unit is used. Once material gets on a conveyor after the first stage of crushing, water is added to keep dust down and ready the ore for treatment. In the leaching process the amount of water added is critical in order to form agglomerate balls that will not break down during the leaching process. The amount of water that needs to be added to form these agglomerates is dependent on the percentage of absorptive and adsorptive minerals present.



In the concentration process, the retention time needed in the various types of grinding mills, be they SAG or Ball mills, will be dependant on the percentage of “hard” and “soft” minerals present. The concentration process is built on the mixing of oily reagents with the water/ore slurry and then the addition of air to form bubbles. The bubbles then float to the surface of the slurry. The value metal minerals that have been liberated during the grinding have a surface reaction with the reagent bubbles so that they stick to the bubbles and are brought to the surface with the bubbles. This separates the value metal from the non value gangue minerals. However some of the gangue minerals have effects on the bubble production and the surface adherence of the minerals to the bubbles. This can cause non value minerals to float with the value minerals and dilute the percentage of metal recovered. If we know what kind and how much of the detrimental mineral are present, we can make adjustments in the type of reagents added and/or the time and amount of flotation steps needed to clean the gangue minerals from the concentrated value minerals. Once the value minerals have been separated from the gangue minerals, the gangue minerals must be separated from the water so that it can be recycled. This requires the addition of flocculant reagents.

Currently the measurements we make with the NIR are on blast holes in the mine before the material is actually mined and crushed. There is almost always a lag time between the day of mining and the day of


processing of the material. Sometimes there is a physical sampling device on a crushed ore conveyor belt from which samples can be prepared for testing. Usually once the result is returned from these samples, the ore has already been processed.

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Infrared and Mining

Core Assets

- We are working on an instrument for use on conveyor belts to help determine the minerals present in a real-time, at-the-process, situation



We still need to have a method of measuring the material being processed just as it is entering the processing plant so that correct decisions can be made about grinding times and reagent addition. We are currently working with ASD on an instrument for use on a conveyor belt to help determine the minerals present in the process circuit in a real-time, at-the-process, situation. Hopefully this will help us to work smarter, not just harder, to produce the metals needed for our civilization.

In the End

Core Assets



In the End,
Hopefully this will help us be better neighbors to the other inhabitants of our world.