Characterisation of gold ores by X-ray computed tomography - Part 1: Software for calibration and quantification of mineralogical phases

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Characterisation of gold ores by X-ray computed tomography -
Part 1: Software for calibration and quantification of mineralogical phases

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Abstract

Micro-computed tomography (Micro-CT) is an x-ray imaging technique that produces high-resolution 3D computerised 'virtual' models of geological specimens based on the x-ray attenuation of different materials in the specimen. The 'virtual' specimens are made up of voxels, the 3D equivalent of pixels, each assigned a gray value based on x-ray absorption. Micro-CT has enormous potential for allowing non-destructive, digital analysis of structure and composition when the mineralogical phases can be digitally separated. However, variation in x-ray flux between scans results in highly variable grayscale values for identical materials. Consequently, materials usually have to be segmented manually, which is subjective, inaccurate, labour intensive and time consuming. Here we present a protocol and imaging software package that can be used to accurately and precisely extract quantifiable information in a repeatable and objective fashion. The software will allow the separation, visualisation, measurement and analysis of spatial and volumetric distribution of different mineral phases without damaging the specimen. This paper explains the potential use of this protocol and software package to ultimately allow automatic segmentation and quantification of gold in drill core samples, removing subjectivity and inaccuracies from data processing.

Introduction

Accurately calculating and quantifying the modal abundance of key mineralogical phases, such as precious metals, in drill core or hand samples is a vital stage in assessing if an ore prospect is economically viable to mine. Traditionally, this is achieved using techniques such as elemental analysis in a scanning electron microscopes (SEM) or physical assays of the sample. Elemental analysis using the SEM is an accurate technique for determining the abundance and distribution of mineralogical phases in a 2-dimentional section, but this is often expensive,
time consuming and only gives you information on a small portion of your sample. Furthermore, it requires the sample to be destructively sampled in order to prepare a polished cut section. In contrast, physical assays provide accurate measures from a larger 3-dimensional volume, but can only be used to ascertain the abundance of a few selective phases (i.e. gold/silver/platinum) and provide no contextual information about the key phases, such as the physical distribution of a phase in the rock or its association with other mineralogical phases, which can be crucial for determining the extractability of the precious metal phase and thus, how cost effective it will be to mine. This process can also be expensive and will completely destroy the sample, preventing any further investigative analyses that require intact sample material. With diamond drilling costing around A$150 per meter to obtain, it is desirable to be able to obtain the information required from the sample, without damaging it, thus allowing the sample to be re-assessed in the future.

X-ray computed tomography (CT) provides a non-destructive technique for assessing the abundance and distribution of mineralogical phases within a sample, while encompassing the advantages of other more conventional analytical techniques. X-rays are used to produce a 2-dimensional radiograph/shadow-graph of a sample (Fig. 1), where differences in grayscale represent changes in x-ray absorption. X-ray absorption is a function of thickness, density, and atomic number, thus, changes in grayscale reflect these parameters. In order to convert 2D images into 3D data, radiographs are acquired during 360 degrees of rotation of the sample, and the data is reconstructed, using a cone-beam back-projection, to generate two-dimensional cross-sectional slices, perpendicular to the axis of rotation. These slices are stacked to generate a computerised 3D 'virtual' reconstruction of the sample. The reconstruction can be rendered and segmented, allowing the 'virtual' separation, visualisation and quantification of phases with different absorption coefficients within a sample.
X-ray CT was originally developed as a medical imaging technique in the early 1970s (Hounsfield 1972,1973), since this time the development of microfocus x-ray sources has allowed significant improvements in resolution. Microfocus computer tomography systems (micro-CT) are now capable of achieving resolutions on the micron scale. Computing developments have also meant that micro-CT is now quick (e.g. 10-15 mins per scan) and affordable (a commercial scanner typically costs between A$250,000 - A$700,000). Furthermore, because x-ray CT enables quantification and analysis of features with varying atomic number/density, its use for geological applications is becoming widely recognised. The strong variation in x-ray absorption between rock and air, has meant that x-ray CT has commonly been used for porosity studies, including soil porosity (e.g. Perret et al., 1999) and reservoir rock characterization (e.g. Van Geet et al. 2009, Cnudde et al., 2010). Visualisation of the distribution of phases within a sample requires pronounced variation in atomic number/density and thus such studies tend to concentrate on samples with an abundance of heavy metal phases, such as characterising Fe-bearing minerals in an active hydrothermal mound (e.g. Tivey 1998) and platinum-group minerals in sulphide deposits (e.g. Godel & Barnes, 2010). Thus, this technique is ideally suited to analysing precious, heavy-metal phases in drill core samples to evaluate the mining potential of an ore body.

While the scan time to acquire a dataset can be relatively short, the task of processing the 3D data into something meaningful, using currently available software, can be incredibly time consuming and may take several days to achieve something useful. In addition, variations in x-ray flux from scan to scan prevent easy manual segmentation or automatic processing of the data, because the grayscale values, used for thresholding and segmenting the data, vary.

In the case of mineralogical phase quantification for rock samples, the ideal outcome is that the mineralogical phase/s of interest are identified and segmented and statistics calculated to provide quantitative information such as
volumes and grain sizes. Commonly the evaluation of an ore body will require the analysis of many samples from different locations and manual segmentation and quantification of the data is not ideal. Not only is it time consuming but it is also subjective. If the person segmenting the data has little understanding of geological systems/processes then they may not correctly identify the mineralogical phase of interest, resulting in an overestimate or underestimate of the phase they are trying to quantify. Furthermore, inaccuracies/inconsistencies during the processing of multiple samples could give a misleading interpretation of the ore body as a whole, this could be disastrous in assessing the economic viability of an ore deposit.

The problem of x-ray flux variation between scans is addressed in medical CT by the use of the Hounsfield unit (HU) scale. This was developed by Sir Godfrey Hounsfield and is a quantitative scale for describing radiodensity (the relative transparency of a material to x-rays). The Hounsfield unit scale uses standards of air and water to transform the original linear attenuation coefficient measurement from an x-ray CT scan into a linear scale which defines the radiodensity (or more simply, grayscale value) of distilled water (at standard pressure) as zero and the radiodensity of air as -1000. The significance of this is that it calibrates the instrument so that all other radiodensities/grayscales plot relative to these, but more importantly, always have the same value (e.g. fat is always -120, Muscle +40 etc.), thus, automatic identification and segmentation of a patient into key materials is possible.

This scale is used routinely in medical scanning, but this is not the case for industrial/commercial CT scanners, and as a result, automatic phase identification and segmentation is not possible for such systems. The reason for a lack of calibration in industrial/commercial CT scanner is unclear, but it is likely to be a result of the fact that most industrial CT scanners are used for quality assurance, to check for defects or impurities in industrial products. Such analyses do not require data segmentation or quantitative analyses of the CT
data and therefore variation in grayscale values from one scan to the next is not problematic. However, for studies where abundant data segmentation and quantitative analyses are required, calibration of the system is crucial.

This paper presents and assesses a protocol and software program, which is being developed to calibrate CT scans produced on industrial/commercial scanners. This will result in normalized CT data in which grayscale values are consistent from one scan to the next. This will ultimately allow automatic phase identification and segmentation of mineralogical phase information from multiple rock samples (both drill cores and hand specimens), thus removing the problem of user subjectivity and inaccuracies. In order to assess the accuracy of this technique our study will also compare the results of processing micro-CT data through the new protocol and software to those produced by processing through currently available software and the results produced by more traditional techniques, such as SEM analysis and physical assay.

**Methods**

A scanning protocol and software, which allows calibration, normalization and quantification of gold in drill cores, is currently being developed by staff in the computed tomography laboratory at the Natural History Museum, London.

In this study we present the results of analysis of two drill core samples (A and B) from the Tasmania Mine, Beaconsfield, Australia using a variety of techniques in order to assess and quantify the abundance of gold in the cores, and begin to validate the scanning protocol and software.

**Background on samples**
The Tasmania Mine is a narrow vein gold operation, which produces approximately 70,000 oz of gold per year from the Tasmania Reef (Hills, 1998). It is located under the town of Beaconsfield in the State of Tasmania, Australia.

The Tasmania Reef is a steeply dipping structure hosted by siliclastic sediments. It has an overall mineral inventory of around 2.5 Moz of gold. The current resource base of 0.52 Moz gold (BCD, 2010) comprises 1,170,000 t at 11.6 g/t Au (Measured and Indicated Resources) and 277,000 t at 9.5 g/t Au (Inferred Resources).

The 2.7 m wide reef is a single, quartz-carbonate-sulphide dilational vein with minor splays and bifurcations. The principal gangue minerals are quartz and ankerite. Calcite is a relatively minor gangue mineral. The principal sulphide mineral is pyrite with lesser arsenopyrite and chalcopyrite. Sphalerite and galena are relatively rare components.

Mineralogical studies indicate that gold is hosted in both sulphides and quartz. An initial stage is characterised by fine-grained gold (<30 µm down to a few µm) in sulphides (mainly pyrite). Later generations appear related to fracturing of pyrite and re-mobilisation of gold. These generations are also dominated by finer gold below 60 µm in diameter. A late major phase of pyrite replacement and quartz hosts coarse gold greater than 100 µm and up to 1 mm in diameter. It is generally noted that visible gold (assuming >250 µm) is rarely seen in reef material with a grade below 20 g/t Au.

The studies grossly indicate two populations of gold particles based on fine- (less than 30 µm in diameter) and coarse-gold (greater than 100 µm in diameter). The fine-grained population is more disseminated throughout the sulphide bodies within the reef, whereas the coarser gold is likely to be more localised. The fine-gold population is considered to contribute to a background gold grade, which is likely to be in the 3-5 g/t Au range.
Samples A and B represent contiguous drill core sections from intersection B31 (1056.7 m to 1056.9 m) into the upper (above 1000 m RL) high-grade zone of the Tasmania Reef. They are dominated by brecciated quartz with minor carbonate and sulphides (mainly pyrite). Sample A had abundant fine-grained visible gold on the surface.

Metallurgically, Tasmania reef ore comprises coarse gravity-recoverable gold (30% to 50%), fine free-leachable gold (20% to 50%) and very fine-refractory gold (35% to 55%) that requires bacterial oxidation prior to leaching.

**Gold quantification**

*Analysis A: SEM analysis*

One of the drill cores (A) was cut into 2 halves, using a rock saw, and one half analysed in a LEO 1455 variable pressure SEM, located at the Natural History Museum (London), allowing elemental mapping and backscattered electron imaging of the surface. Analyses were carried out at 20kV, spot 500 (this is an arbitrary value and is not a measure of beam diameter), 15pa vacuum, working distance of 15mm and magnification x99. Energy dispersive x-rays were mapped and recorded using an Oxford Instruments X-Max, silicon drift detector. The 2D elemental maps and backscattered electron image of the core were analysed using the threshold and measurement tools in ImageJ (freely available software; http://rsbweb.nih.gov/ij/) to determine the area of gold in the sample. In order to allow comparison with subsequent 3D analyses from the core (from the CT data and physical assay) the 2D % area of gold was calculated from the SEM data and this was scaled to the volume of the core to give an estimated 3D volume of gold in the core based on the SEM data. This does assume that the gold abundance is uniform throughout the core (the accuracy of this assumption will be discussed later), but is the only way to allow a direct comparison with the other data.
Analysis B: Micro-CT scanning and mineralogical phase quantification of uncalibrated data

Both drill cores (A – cut; B – whole) were scanned (without standards) using a Nikon Metrology HMX ST 225 micro-CT system, housed at the Natural History Museum (London). The optimal conditions for CT scanning were employed for each sample. Core A (cut) was scanned using a tungsten target, 225 kV, 150 uA, 4.5 mm copper filter, 1000 ms exposure at a pixel size of 0.0467 mm. Core B (whole) was scanned using a tungsten target, 225 kV, 140 uA, 4.5 mm copper filter, 500 ms exposure at a pixel size of 0.0467 mm. Both datasets were acquired with 3142 projections over 360 degrees, at 0.11 degree increments of rotation.

The CT data was subsequently analysed using VGStudiomax, which is a commercially available 3D rendering and segmentation software (http://www.volumegraphics.com/en/products/vgstudio-max.html), to determine the volume of gold in the sample.

Analysis C: Micro-CT scanning and mineralogical phase quantification of calibrated data

The two drill cores were scanned with the same scanner as above, but this time a set of standards were included in the scan (Fig. 2) and the conditions of scanning were the same for both samples, to demonstrate the variability in grayscale values from one scan to the next. The drill cores were scanned using 225 kV, 200 uA, 2.5 mm copper filter, 1000 ms exposure, a pixel size of 0.063, with 3142 projections over 360 degrees of rotation.

The presence of standards in the scans allows calibration of scans acquired from different samples, at different times, and even on different instruments. In medical CT the Hounsfield unit scale calibration uses standards of air and water, because they are universally available and well suited to the key application for
which CT was developed, biological material. However, CT scanning of geological samples encompasses a much greater range of material densities than medical scanning and thus, standards which span a broad range of densities are required in order to produce a calibration which can be used for geological materials. The standards used in this study for CT calibration consist of 2.5 cm discs of polytetrafluoroethylene (PTFE or Teflon; density 2.2 g/cm$^3$), aluminium (density 2.7 g/cm$^3$), titanium (density 4.5 g/cm$^3$) and steel (density 7.85 g/cm$^3$). The calibration presented here uses the actual density of the standards, giving a true density scale once normalized.

Post-scanning, the CT data was calibrated, normalized and the volume of gold calculated using the software, PhaseQuant. PhaseQuant has been written by researchers at The Natural History Museum, London, to enable calibration, processing, quantification and validation of micro-CT scans (Elangovan et al. 2011 a, b). At present this software is still under development, but it has been written with the aim that it will become freely available as a plug-in for ImageJ, which is an open source imaging tool, that is widely used by researchers to exchange imaging algorithms. PhaseQuant has four modules, (a) density calibration, (b) phase segmentation, (c) phase measurement and (d) ground truth optimization. The density calibration module allows a user to include density standards and calibrate the micro-CT image stack. The phase segmentation module allows image segmentation using a variety of methods, some of which may require prior information about the sample. The phase measurement module includes measurement options such as porosity, modal abundance and grain size distribution. The ground truth optimisation module enables the user to input a ground truth image and perform validation. Modules a-c were used in this study.

A sequence of reconstructed virtual 2D slices (containing grayscale data from the sample and the standards) is loaded into ImageJ and the density calibration program launched. The next step is to register grayscale values corresponding to
the density standards in the software for calibration. For example, for the aluminium density standard, an area of pixels is select (by dragging a box) within the density standard (Fig. 3a) and the grayscale values recorded. These pixels will then be assigned a value that is representative of the specified density standard, which is 2.7 in the case of aluminium. This is repeated for all of the standards. Once the density values are recorded for all standards, the software automatically performs linear regression on the recorded density data and fits a straight line (Fig. 3b). Once the equation relating density with gray values is established, the gray values in the whole dataset are transformed into the corresponding density values. The resulting calibrated image is a 16-bit image with gray values in a linear density scale. This process can be applied to multiple samples, converting highly varying grayscale values, from one sample to the next, into grayscale values that relate to the density of the phases in the samples. This calibration will remove variations in grayscale values, which result from x-ray flux instability, from one sample to the next, resulting in mineralogical phases having the same grayscale values in different samples, and ultimately allowing automatic segmentation and quantification.

For example, if a series of drill cores are scanned and processed from the same ore body, which would mean they have similar mineralogies, then this calibration process should give rise to a series of datasets whereby each mineralogical phase has the same grayscale value for all samples, allowing automated quantification.

After calibration, the phase segmentation module of PhaseQuant is used for segmenting the data with respect to the mineralogical phase of interest, which is gold in this case. Following this, the modal abundance option, in the phase measurement module of PhaseQuant, is used to estimate the volume fraction of the segmented component.

*Analysis D: Physical Assay*
Both drill cores were assayed for gold in their entirety to determine the volume of gold in the cores. Each drill core was crushed and pulverised to 70 per cent passing 75 microns, and screen fire assayed using a 105 micron screen. Three fire assays were undertaken on the pulp undersize and the entire screen was fire assayed. This data is the validation data for the above analytical techniques.

Results

Analysis A: SEM analysis

Figure 4 shows the backscattered electron image and the gold element map obtained from the SEM analysis of the 2D cut surface of Core A. The backscattered electron image was used to calculate the bulk area of the cut 2D surface, while the gold element map was used to determine the 2D area of gold. These measurements were acquired using the threshold tool in ImageJ, to define and mask the area of interest, and the measurement tool, to determine the number of pixels defined by this mask. The resultant values were used to calculate the percentage area of gold in the cut 2D plane, which was 0.098%. This 2D value was scaled to the volume of the core to give a 3D volume, 115.89 mm³.

The SEM analysis also enables the determination of the mineralogical phases present in the core and their relationships to one another. These included quartz, as the bulk phase, ankerite, as veins, sulphide (pyrite), as discrete grains and as agglomerated areas, and gold, as discrete grains and as smaller grains encompassed in the sulphide.

Analysis B: Micro-CT scanning and mineralogical phase quantification of uncalibrated data
Because core A had been sectioned and scanned in the SEM prior to CT scanning, the two halves were placed back together, with a piece of cardboard (approximately the same thickness of the volume of rock removed by the saw) between the two halves, and the core scanned as a whole, in order to obtain optimum results as the x-ray pathway is uniform in every direction during scanning. This facilitated the identification of the virtual slice in the CT data that is comparable to the cut face analysed in the SEM (see figure 5), enabling the use of the SEM data as a ground truth/guidance for segmenting the CT data.

While the grayscale information in the uncalibrated CT data does yield information relating to the densities of phases in the sample, this is a relative scale, and it is not possible to determine what the phases are. It is therefore useful to use the SEM data in conjunction with the CT data to help define and locate the phases of interest.

For both drill core samples, the CT data was manually segmented, to separate the gold from the bulk sample, and the volume of gold calculated. This segmentation and quantification was carried in VGstudiomax. The segmentation is achieved by simple thresholding of the grayscale frequency distribution plot of the whole dataset. The volume calculation is a mathematical integration calculation of the grayscale frequency distribution curve represented by the segmented phase. The volume of gold in each core was 131.31 mm$^3$ for core A (cut) and 1.79 mm$^3$ for core B (whole).

**Analysis C: Micro-CT scanning and mineralogical phase quantification of calibrated data**

Figure 6 shows the grayscale frequency distribution histograms for the full volume of CT data for each core. It is evident that the grayscale values are highly variable despite the fact that exactly the same scan parameters were used to scan each sample. For example, air, which is the tallest peak in each dataset and should have the same radiodensity in each scan, has a value of 9300 in core
A and 4300 in core B. These variations in grayscale values mean that the data cannot be automatically segmented and quantified.

Once the standards were calibrated with density values and the CT data normalized, the variations in grayscale values between scans were removed. Figure 7 shows a single virtual slice for cores A and B, both uncalibrated and calibrated. Figure 8 shows the histograms for both samples post calibration. It is evident from these figures that, post calibration, the grayscale range is the same for both cores A and B. Furthermore, the grayscale values now reflect true density. Table 1 displays the gray values for the mineralogical phases in the core from the calibrated CT data and their true density values. As you can see the two sets of values correspond nicely. The only discrepancy is with the gold.

Following calibration and normalization of the CT data, the data were segmented and the volume of gold calculated using PhaseQuant. The volume of gold for core A was 252 mm$^3$ and 5.92 mm$^3$ for core B.

Please note that because the gold composition of a grain can be variable within a sample and between samples, depending on the gold-silver compositional ratio of a grain, a single threshold value for gold is not expected. However, because this heavy metal phase is the densest phase in the sample and has a density value significantly greater than the next densest phase, sulphide, the lower threshold value that depicts this phase is all that is required and, if calibrated properly, should be approximately the same value between samples.

**Analysis D: Physical Assay**
The physical assay data gave volume of gold of 136.54 mm$^3$ for core A and 1.97 mm$^3$ for core B.

**Discussion**
For the purpose of this study the physical assay data is the validation for the other analytical techniques, since this method is expected to capture all of the gold in the sample.

Table 2 compares the calculated volume of gold for cores A and B for all analyses. Table 3 shows the percentage difference of all analytical methods to the physical assay data.

While the SEM data is crucial for determining the exact mineralogical phases present in the sample, it is evident from table 3 that the SEM assessment underestimates the amount of gold in drill core A. It is clear from a 3D model of the CT data (Fig. 9) that the gold distribution in core A is highly heterogeneous, with large grains of gold being present, but not intersected by the cut plane analysed in the SEM, thus resulting in an underestimation of the true volume of gold present in the sample.

The data generated using micro-CT, without standards, and processed using VGstudiomax gives values very close to the physical assay data. There is a slight underestimate, but this is to be expected as there will always be a portion of gold, below the resolution of the CT scan, that cannot be accounted for. The pixel size for these datasets was 0.0467mm (46.7 microns), which equates to an effective resolution of approximately 94 microns, since at least 2 pixels are required to define an object. Thus, any gold particles less than 94 microns in size will not be included in the CT calculations, which probably accounts for the missing portion of gold. This resolution cut-off is a limitation that needs to be considered, especially if the gold deposit consists of abundant fine-grained gold. It can be improved by reducing the size of the samples scanned, allowing a higher spatial resolution to be achieved. However, this will mean that more samples need to be scanned in order to get a representative characterization of an ore body. Thus, the need for an automatic processing technique will be even
more crucial. It can also be improved by scanning with a system that has a higher resolution x-ray detector panel, but there is a large cost implication associated with this.

Another factor that may contribute to this underestimate in the amount of gold present in the sample could be due to the way the x-rays interact with irregular shaped grains, known as an edge effect. Because x-ray attenuation is a function of density, atomic number and thickness, if grains are irregular in shape then thickness variations will cause x-ray attenuation variations across a grain, giving rise to changes in grayscale values within a single grain. This would be particularly evident at the edge of a grain, where the overall thickness would be less than in the centre of the grain. This would mean that the edges would appear to have a different threshold value to the rest of the grain and could easily be missed from the volume calculation. This concept is poorly characterized for x-ray CT data and at present there is no way of taking this into consideration during the segmentation and volume calculation process. This is something that we plan to investigate further, hopefully enabling us to calculate the margin of error that is introduced by such an effect. Preliminary work would suggest that if the grains are spherical this effect is not evident, but more work needs to be carried out for irregular shaped grains.

Figure 8 (calibrated histogram) demonstrates that the protocol, for scanning with the density standards, and calibrating the data, using the density calibration module in PhaseQuant, does normalize the data, removing gray value variability from sample to sample. This is crucial for allowing the automation of data processing, in which automatic segmentation and quantification can be utilized. Furthermore, the normalized grayscale values do correlate with true density values and can therefore be used to estimate the density of unknown phases within a dataset. However, this correlation with true density appears to breakdown for the densest phase, gold. This is obviously problematic as this is the phase of interest in this study. It is likely that the reason for this discrepancy
is because the range of standards used only extends to a density of 7.85 g/cm\(^3\) and therefore the calibration is not reliable for phases with a density above this. This would also explain why the quantification of the volume of gold, using the calibrated data, is not very accurate. It would seem that because the threshold for gold is poorly defined, user subjectivity applies and, in this case, causes an over estimation in the volume of gold. Further work needs to be carried out to produce a set of standards that span a much greater density range than that of the existing standards.

This exercise needs to be applied to a much larger suite of samples in order to statistically validate the protocol and calibration software. Finally, once the calibration has been achieved for the full range of densities within a mineralogical sample, the software needs to be extended to allow automatic thresholding, segmentation and quantification of samples to remove user subjectivity and inaccuracies that can exist during manual segmentation.

**Conclusions**

Micro-CT provides a non-destructive technique for quantifying the abundance of gold in drill cores. Traditional scanning electron microscopy techniques have a tendency to falsely estimate the abundance of gold in a sample due to the heterogeneity of mineralogical samples and the limited sampling of this technique. However, some SEM reconnaissance work is required in order to determine the mineralogical phases present in the sample, as this cannot be achieved by CT alone.

The results of this study suggest that the presented protocol and software are able to calibrate and normalize CT data to a true density scale, removing variability in gray values from sample to sample, but only for mineralogical phases with densities less than ~7 g/cm\(^3\). It is clear that further work is required
to allow calibration and normalization for more dense phases, such as gold. Until this has been achieved manual segmentation of uncalibrated data seems to yield the most reliable quantitative results.

Micro-CT not only enables the 3D measurement and quantification of mineralogical phases in a sample, but can also provide information on the 3D structure, relationship and distribution of these phases, which cannot be achieved using physical assays or 2D SEM analyses. Some of these aspects will be discussed further in 'Characterisation of gold ores by X-ray computed tomography Part 2, Dominy et al., 2011.'

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The references by P Elangovan et al. (2011 a, b), are currently being prepared for publication.

**References**


**Figure Captions**

Figure 1. 2D radiograph of drill core. Grayscale variations represent changes in x-ray absorption. Dark areas are highly absorbing and indicate the presence of a dense material; light areas are less absorbing and indicate the presence of a lower density material.

Figure 2. 2D radiograph of drill core, with standards.

Figure 3. (a) Image of PTFE density standard and area of selected pixels for density calibration; (b) Graph showing linear regression of density calibration, calibrating gray values with density.
Figure 4. SEM data of cut surface, Core A; (a) Backscattered electron image, (b) Au element map.

Figure 5. (a) Backscattered electron image of cut surface of Core A, (b) Equivalent ‘virtual slice’ from CT data.

Figure 6. Grayscale frequency distribution plots of original CT data for cores A & B, uncalibrated.

Figure 7. (a-b) Virtual CT slices of drill cores A and B with original, uncalibrated gray values. Gray values clearly different between samples; (c-d) Virtual slices (same as (a) & (b)) with gray values calibrated and normalized to density. Gray values the same between samples.

Figure 8. Grayscale frequency distribution plots of density calibrated, and normalized, CT data for cores A & B.

Figure 9. 3D ‘virtual volume’ of core A, highlighting heterogeneous distribution of gold in the sample.

Table Captions

Table 1: Comparison of gray values for the mineralogical phases in the core, from the calibrated CT data, and their true density values.

Table 2: Volume of gold for Cores A and B for all analytical methods

Table 3: Percentage difference of all analytical methods to the physical assay data.
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<table>
<thead>
<tr>
<th>Mineral</th>
<th>Gray value from calibrated CT data</th>
<th>True density value (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>2</td>
<td>2.65</td>
</tr>
<tr>
<td>Ankerite</td>
<td>3</td>
<td>3.01</td>
</tr>
<tr>
<td>Sulphide</td>
<td>4-5</td>
<td>4.84</td>
</tr>
<tr>
<td>Gold</td>
<td>7+</td>
<td>19.30</td>
</tr>
</tbody>
</table>

Table 2: Volume of gold for Cores A and B for all analytical methods

<table>
<thead>
<tr>
<th>Analysis Method</th>
<th>Volume Gold (mm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Core A (Cut)</td>
</tr>
<tr>
<td>A: SEM</td>
<td>115.89</td>
</tr>
<tr>
<td>B: Uncalibrated, VGstudiomax</td>
<td>131.31</td>
</tr>
<tr>
<td>C: Calibrated, PhaseQuant</td>
<td>252.00</td>
</tr>
<tr>
<td>D: Physical Assay</td>
<td>136.54</td>
</tr>
</tbody>
</table>

Table 3: Percentage difference of all analytical methods to the physical assay data.

<table>
<thead>
<tr>
<th>Analysis Method</th>
<th>% difference from physical assay data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Core A (Cut)</td>
</tr>
<tr>
<td>A: SEM</td>
<td>-15.12</td>
</tr>
<tr>
<td>B: Uncalibrated, VGstudiomax</td>
<td>-3.80</td>
</tr>
<tr>
<td>C: Calibrated, PhaseQuant</td>
<td>+84.60</td>
</tr>
</tbody>
</table>