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Placer gold sampling—the overall measurement error using gravity concentration on particle size ranges during sample treatment

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Placer deposits are generally characterized by low grade of free gold. This is the case in French Guiana where the main placer deposits are in the river bed. Most have already been exploited by very small mining companies using sluices. If this technology is efficient for coarse gold, it releases fine gold in the tailings. During the last years, studies have been performed on various sites and recoveries have been estimated between 40 and 60% depending on the size distribution of gold particles and of the quality of the sluice configuration. Many recent or ancient tailings are available with a non-negligible quantity of remaining gold, offering retreatment opportunities. They are generally found in the form of sand heaps with the shape of an alluvial fan originating at the sluice discharge. Due to the resulting large distribution heterogeneity it is necessary to take many samples at many strategically deployed locations. These samples have to be large enough to be representative of the local material. As gold is mainly liberated in this type of lot, traditional sample treatment with successive size reductions and sub-samplings is not efficient and can be very expensive. Another approach using sieving and gravity concentration per particle range is preferred and presented here. After presentation of the sampling and measurement protocol used, this paper focuses on estimation of the overall sampling error. Various tailing cases are presented for which retreatment decision depends on the level of confidence obtained for the estimate of the quantity of recoverable gold.

Introduction

Most of the historical gold production in French Guiana came from placer deposits. It is still the situation case today even though more and more primary gold deposits are also exploited. The main technology used for gold recovery has been the sluice approach which is efficient for coarse free gold but less so for fine free gold and remaining embedded gold associated with minerals coming from the primary deposit sources. This is why sluice rejection lots contains a non-negligible quantity of gold, which can be valuable when the gold price is high enough as it is the case today. During the years 2006 and 2007, measurement campaigns have been performed on several production sites to estimate the remaining gold in the sluice residues and the technical and economic feasibility of their retreatment.

The objectives of the sampling campaigns were:

- Estimate the quantity of gold remaining in sluice rejects;
- Design of the retreatment process and estimation of its profitability;
- Design of a processing plant for placer gold deposit able to maximise the recovery and minimise the quantity of gold losses in the tailings.

Knowing the accuracy of the measurements (or, conversely, designing the measurement procedures to achieve the Data Quality Objective) is a key step in the financial risk assessment.

The preparation method of such placer samples using screening and gravity concentration has been used since the beginning of the gold deposit sampling. Ancient miners were just using the pan[1]. The last century has seen the emergence of heavier sample preparation plants using various technologies from sluice to centrifugal concentrators[2]. If these techniques have been mentioned in the theory of sampling[4, 5], their advantage in terms of overall measurement error has been rarely treated.

This paper describes the sampling and measurement protocol with a detailed presentation of the procedures for sample collection, sample preparation and various measurements performed on it. From this well-structured process, it is possible to estimate the sampling and analytical errors through the moments of their calculable components (such as fundamental sampling error, grouping and segregation error or direct measurement error linked to devices). In addition to the objective of material characterisation for processing, the results obtained from this sampling campaign are used to design a sampling plan for the sole measurement of gold. Then a general procedure is proposed for the measurement of the gold content of such placer deposits or tailings.

Sampling and measurement procedures

The set of studies presented here have been performed at the demand of several Small and Medium Enterprises (SME) producing gold from small alluvial placer deposits or primary gold ore bodies in the department of French Guiana situated between Brazil and Surinam. It mainly concerns permits of exploitation of small areas in the middle of the rain forest only accessible by air or river, rarely by road.

In this context, the means for sample collection and preparation are limited on mine site. It is why, in the following description of the procedures, we define four different locations:

- The site: location of the sluice reject or placer deposit;
- The camp: close to the site where the personnel is living and where some means are available for sample preparation;
- The preparation laboratory: situated in the main city with available equipment for concentration, sieving and water management;
- The analysis laboratory: subcontractor performing fine sieving, pulverisation and analysis by Fire Assay.

Some mine sites were sufficiently equipped to perform at the camp the work normally done in the preparation laboratory. In addition to the objective of obtaining accurate measurements, these campaigns allowed to optimise the procedures in order to minimize the material handling and to reduce the number and masses of samples and sub-samples to carry between the site and the camp and between the camp and the laboratory. Indeed, the cost of transportation by air can be too high and the risk of sample contamination or losses is not negligible when carried by river or other land transportation.

The material characteristics required for this study are: the particle size distribution of sand and the gold content per size class, from which gold particle size distribution and global gold content are deducted. The measurements performed on each sample are then: mass of sample, masses of each size fraction after sieving, gold assaying on each size fraction for finest size classes.

Gold concentration process and rejection heap description

The mainly used concentration technique for alluvial placer deposit in French Guiana is the sluice. The sand is extracted from a production cell by mechanical shovel feeding an inclined hopper where water is added for scrubbing. Some hoppers are equipped by a grate (20 to 35 mm opening) for scalping allowing a better concentration efficiency of the sluice. The oversized particles are stored in a heap close to the sluice. The slurry is then feeding a nugget box where very coarse gold can be caught. Slurry is then passing through the sluice channels where gold flakes and heavy minerals are concentrated. Overflowing barren slurry is discharged in a previously exploited cell in which sand particles constitute a sandbank as an alluvial fan. Fine gold flakes and fine heavy minerals that have not been recovered by the sluice mainly report in this heap. Very fine and colloidal particles of clay are entrained with water up to the decantation pond with some very fine gold flakes that float.

The objective of the sampling campaign was to estimate the quantity of gold remaining in these rejection heaps and select the more appropriate process for their retreatment. Figure 1 shows a typical shape of such heap with a symmetry axis in the direction of the sluice channel. As they are constituted by accumulation of layers corresponding to different parts of the production cell (with variability in head content), one can suspect a vertical stratification. The cycles of concentrate recovery are also sources of this vertical distribution heterogeneity. Nevertheless, the kinetics of gold particle settling will generate a higher heterogeneity of distribution in the horizontal plan where coarsest gold particles are accumulated just after the sluice discharge, the finer the gold particles are the farer they are deposited. The gold content in tailings is then decreasing from the top to the toe.

Due to the relative constant regime of the water flowing on the surface of the sandbank, the size distribution of the sand particles appears the same everywhere except close to the sluice discharge where coarsest gravels are retained.

Sample taking of sluice reject

Due to the heterogeneity of distribution in the horizontal direction, it can be necessary to take several samples on each heap to estimate the gold content distribution and the associated volumes to be able to calculate the weighted average of the various measured parameters. Figure 1 shows a case where two samples, R1 and R2, have been taken. A preliminary study has been performed by taking many samples along the symmetry axis and on both sides. The most untypical sample was the one taken at the sluice discharge where the remaining coarse particles of gold are concentrated. It is only representative of itself. After few meters, the distribution is less heterogeneous. It has been observed that the samples taken between 5 and 10 m from the sluice discharge on the symmetry axis have characteristics (sand size distribution and gold content) close to the average ones. In order to limit the number of samples to manage, and then the sampling campaign costs, only one primary sample has been taken for some rejection heaps.

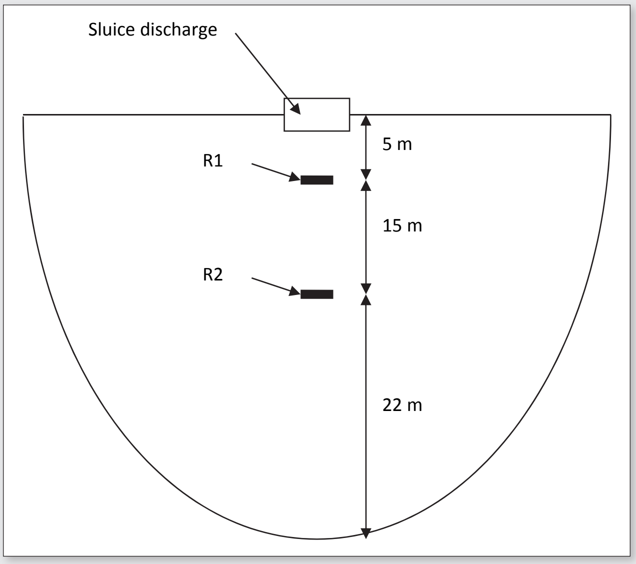

Figure 1. Overview of the typical shape of a sluice rejection heap and location of samples R1 and R2.

The heterogeneity of distribution in the vertical direction suggests to take a sample on the entire height of the heap. But, as explained above, this heterogeneity is certainly smaller than the horizontal one. It is why it has been decided to limit the depth of sample taking to several tens of centimetres. When sampling ancient rejection heaps, the superficial layer can be considered as altered by weather (such as entrainment of fine particles of sand with rain and wind, or migration of gold particles with rain water infiltration) or by working activity. A superficial layer of 30 cm is then systematically removed before taking a parallelepiped-shape sample in one operation using a mechanical shovel. The bucket is then unloaded into a container constituting the primary sample with a mass between 140 and 320 kg depending on the sand fineness. Depending on the transportation conditions, it can be decided to perform some sample preparation tasks on site to reduce the quantity of material to carry to the camp.

Coarse size distribution

For such sluice rejects, there is no chance to have gold particles larger than 1 mm. The sample mass can then be reduced just by sieving. It can be performed on site or in the camp to beneficiate of better conditions for sample preparation. Sample sieving also allows the measurement of the proportions of the coarsest size classes of the sand size distribution.

The sieve series used here was: 50 mm, 25 mm, 10 mm and 2.5 mm. If a grate is used before sluicing, the 50 mm sieve is not used. Otherwise, a larger sample is taken and the passing fraction can be divided by riffle splitter after each sieving. Up to 10 mm, dry sieving is performed. If the sand is sufficiently dry, the oversize particles are clean and the retained fractions can be directly weighed and subject to a visual inspection to detect presence of coarse particles of gold or of potentially-bearing minerals. If the sand is wet, involving sticking of fine particles on the coarse ones, the retained fractions are washed with a minimum volume of clear water into a vessel, then dried and weighed. The washing water is clarified by decantation, gently siphoned off before to mix the recovered sediments (after rough drying) with the passing fraction. Wet sieving is performed for 2.5 mm, generally just before concentration in the preparation laboratory. The +2.5 mm fraction is dried and visually inspected to verify the absence of coarse gold particles or potentially-bearing minerals. In two specific cases, an additional sieving has been performed respectively at 1100 µm and 500 µm before concentration. The 1100–2500 µm and the 500–2500 µm have been washed by panning and the heavy particles have been visually inspected to verify the absence of coarse gold or potentially-bearing minerals.

In all studied cases, the retained fractions were free of coarse gold or of bearing minerals. It is then supposed all the remaining gold in the sluice rejects is concentrated in the –2.5 mm fraction which represents between 20% and 60% of the tailings, rarely more. Sieving allows to divide the sample mass by a factor between 2 and 5 keeping more or less the same fundamental sampling error regarding the gold content. A simple calculation using theory of sampling approach shows that sand crushing to produce –2.5 mm has practically no effect on the Constant Factor of Constitution Heterogeneity. That is to say crushing, conversely to sieving, is unable to reduce the sample mass and, for such low grade materials, sub-sampling can be affected by the Poisson process.

Gold concentration using shaking table

Considering that finer sieving is more difficult to perform and that size classes under 2.5 mm can contain gold particles, gravity concentration is another way to reduce the mass of sample by concentrating most of the gold in a small fraction of the sample. All the –2.5 mm sub-samples have been entirely treated by a Gemini shaking table well adapted for free gold and heavy minerals recovery; such heavy minerals potentially being gold-bearing minerals. The operating conditions have been tuned visually to recover the black minerals into the concentrate output. The dry mass of the –2.5 mm material subjects to concentration has to be known as accurately as possible. For that, the passing –2.5 mm has to be drained as much as possible before wet weighing and a small sample has to be taken for moisture content measurement.

The Gemini shaking tables have three outputs: heavy, mid and light products. Here, the heavy and mid products have been combined as "concentrate" and light product reports as "tailings". The concentrate yield varies between 1.2% and 78.5%. This corresponds to a concentration factor between 1.3 and 82. Most of the treated samples have their concentrate yield between 5% and 20% (concentration factor between 5 and 20). Great attention has been paid to reduce flotation of fine gold particles, specifically in the container receiving the products of the table from which water is overflowing and not recovered. Fortunately, sluice rejects don't contain very fine and colloidal particles which have been reporting into the decantation pond during primary treatment.

Size distribution and gold contents of table concentrates and tailings

The table concentrate is screened at 500 µm in the preparation laboratory. The +500 µm fraction is dried, weighed, washed by panning and the heavy particles are visually inspected to verify the absence of coarse gold or potentially-bearing minerals. In case of presence, this pan concentrate can be dried, weighed and then sent to laboratory for assaying. The –500 µm fraction is dried, weighed and sent to the analysis laboratory for fine sieving at 250 µm, 125 µm and 63 µm. In rare cases, the –500 µm fraction has been divided to perform sieving on a smaller quantity; a sub-sample has been then taken from the second part for a direct assaying. The 250–500 µm and 125–250 µm size classes are pulverised to –125 µm. The four size classes are divided to obtain 50 g of pulp for Fire Assay.

The table tailings are entirely recovered as wet material and drained as much as possible taking care to not lose the fine and light particles. They are homogenized (as segregation took place in the reception vessels) and spread onto a plastic sheet to obtain a sub-sample by many increments. This sub-sample is sent to the analysis laboratory to be dried, weighed, pulverised and divided to obtain 50 g for Fire Assay.

Calculation of sampling and measurement errors

The main objective of the following demonstration is the calculation of the overall measurement error of the mean gold content of the sluice rejection heap. The calculation of the measurement error of the size distribution has been discussed in previous papers[6,7]. As the aim of this paper is to show the advantage to use screening and gravity concentration to increase the sampling accuracy, for the sake of simplification, the rejection heap is supposed to be homogeneous in distribution or, as we know it is not the case, the part of the heap around the sample location is supposed to be homogenous and constitutes a lot sufficiently large compared to the sample mass. To summarize, the only error taken into account at the primary sampling stage will be the fundamental sampling error.

Heterogeneity model

The base formulae of the theory of sampling[3,4,5,8,9], such as the heterogeneity of constitution, are considering particles individually with their key parameters: unit mass (mass of one particle) and content of critical component. As it is impossible to have such a fine description, particles are classified in numerous families in which they are supposed identical. Each family is then characterised by three parameters: the mean unit mass and the mean critical component content of the member particles, and the mass proportion of that family into the lot. These families have to be as homogenous as possible but in a reasonable number. Their parameters have to be obtained by measurement through specific experiments. It is why the first approach used in the field of ore sampling has been the classification in terms of size and density[5,8,9,10]. It is the more relevant approach as the unit mass is mainly dependant on the particle size and density, and the critical content is linked to the density. If it is not the case, specific experiments have to be performed to classify the particles of the same size class regarding their critical content[11]. In some cases, sources of heterogeneity are suspected

Table 1. Heterogeneity model.

Family name	Size range	Mean size	Unit mass	Gold content	Density (g/cm^3)	Shape factor
+50 mm sand	50–100 mm	76 mm	591 g	0%	2.7	0.5
+25 mm sand	25–50 mm	38 mm	73.8 g	0%	2.7	0.5
+10 mm sand	10–25 mm	17.7 mm	7.47 g	0%	2.7	0.5
+2.5 mm sand	2.5–10 mm	6.3 mm	332 mg	0%	2.7	0.5
+500 µm sand	0.5–2.5 mm	1.5 mm	4.5 mg	0%	2.7	0.5
+500 µm gold	0.5–2.5 mm	1.5 mm	10.7 mg	100%	16	0.2
+250 µm sand	250–500 µm	380 µm	73.8 µg	0%	2.7	0.5
+250 µm gold	250–500 µm	380 µm	175 µg	100%	16	0.2
+125 µm sand	125–250 µm	190 µm	9.23 µg	0%	2.7	0.5
+125 µm gold	125–250 µm	190 µm	21.9 µg	100%	16	0.2
+63 µm sand	63–125 µm	95 µm	1.16 µg	0%	2.7	0.5
+63 µm gold	63–125 µm	95 µm	4.13 µg	100%	16	0.2
–63 µm sand	–63 µm	35 µm	0.056 µg	0%	2.7	0.5
–63 µm gold	–63 µm	35 µm	0.266 µg	100%	16	0.2

but no measurement method exists or the technique is not available or too expensive regarding the study challenge. Hypothesis can then be done and a sensitivity analysis can be performed to estimate the impact of such assumptions[7].

Generally, the size classes used as primary family description are the ones coming from the sieve series used for the size distribution measurement. The opening ratio between two successive sieves is too large to consider a uniform particle size in such a range. The choice of the mean unit size has to be conservative but preventing excessive overestimate of the sampling variance[7]. Table 1 gives the used size ranges and the associated mean particle size for unit mass calculation. Gold is supposed to be present only in liberated pure gold particles. If some bearing minerals can contain a small content of gold, the proportion of such locked gold compared to total gold is sufficiently low to not have large effect on the sampling error estimate. In addition, the assumption of only liberated gold is conservative. As no gold or bearing minerals have been observed in the +500 µm size classes during this study, only the size classes below 500 µm have been divided into two families: sand and gold. Unfortunately, only the size distribution of the shaking table concentrate has been measured, not the one of the tailings, which is certainly different. As this difference has a low effect on the estimate of the fundamental sampling error, the size distribution of the concentrate will be used for the size distribution of the –2.5 mm sand. The gold content per size class of the concentrate gives the size distribution of the gold particles. The size distribution of gold particles in the tailings cannot be deducted without the sand size distribution and the gold content per size class. It is then assumed that only fine gold reports to the tailings as observed in many cases[12], that is to say in the –63 µm class. The set of families listed in Table 1 is used for the various heterogeneity models corresponding to the different stages of the sampling and measurement protocol. A special attention has to be paid in the number of selected particles in each family, specifically for coarse gold particles, to verify the validity of the Normal distribution assumption, and when there is a risk to be confronted to a Poisson process[5].

Fundamental sampling error of the primary sample

The relative variance of the fundamental sampling error (FSE) for the measurement of the content a_L of the critical component in the lot is given by the equation (1).

$$\sigma^2(a_L) = \left(\frac{1}{M_S} - \frac{1}{M_L}\right) \sum_{i \in I_F} m_i t_i \left(\frac{a_i - a_L}{a_L}\right)^2 \qquad (1)$$

In this formula, M_S is the mass of sample and M_L the mass of the lot. The N_F families, numbered with index $i \in I_F = \{1...N_F\}$, should be as homogenous as possible, meaning that all the particles in one family have more or less the same unit mass, m_i, and the same critical component content, a_i. t_i is the mass proportion of the family in the lot. The mass of lot being significantly larger than the mass of sample, the second term of the difference is negligible.

In the case of only free gold, the gold particles are distributed in a set of families, with indexes in the subset $I_G \subset I_F$, following their size and shape. These families are characterised by a gold content $a_i = 1$ and the sum of their mass proportions is the gold content in the lot:

$$\sum_{i \in I_G} t_i = a_L$$

The other ore particles are distributed in the other families following their size, density and shape. These families are characterised by a null gold content. Taking into account this heterogeneity model and considering that the gold content in the lot is very small compared to unity, the equation (1) becomes[5,10]

$$\sigma^2(FE) = \left(\frac{1}{M_S} - \frac{1}{M_L}\right)\left[\frac{\overline{m}_G}{a_L} + \sum_{i \notin I_G} m_i t_i\right] \qquad (2)$$

where the mean mass of gold particles is defined by:

Table 2. FSE for primary sampling of various sluice rejection heaps.

Sample	Sample mass (kg)	Proportion of −25 mm	Proportion of −2.5 mm	Proportion of gold + 250 µm	Proportion of gold −63 µm	Variance (×10^{-6})	Error	Proportion of IH_{golg} [a]
#1	220	83%	49%	61.8%	4.8%	738	5.4%	83%
#2	209	89%	50%	0.7%	93.6%	52	1.5%	14%
#3	220	92%	44%	0%	71.8%	52	1.5%	33%
#4	242	95%	49%	6.6%	77.5%	59	1.5%	65%
#5	300	67%	21%	21.3%	18.3%	1084	6.5%	86%
#6	180	99%	65%	10.9%	74.1%	242	3.1%	96%
#7	190	99%	67%	6.4%	66.4%	294	3.1%	98%
#8	220	99%	55%	13.7%	50.0%	431	4.1%	98%
#9	200	98%	78%	17.6%	52.8%	1615	7.9%	99%
#10	240	97%	56%	15.7%	15.5%	425	4.1%	97%
#11	200	88%	68%	5.8%	73.8%	452	4.2%	90%
#12	15	100%	57%	19.3%	3.6%	1293	7.1%	99%
#13	40	81%	37%	17.3%	32.2%	9294	18.9%	96%

[a]Proportion of the first term of the sum of equation (2) in the sum of the constant factor of constitution heterogeneity IH.

$$\bar{m}_G = \frac{\sum_{i \in I_G} m_i t_i}{\sum_{i \in I_G} t_i}$$

Table 2 gives the variance and the error (approximately two times the standard deviation corresponding to a 95% confidence interval) of the FSE for various samples treated during this campaign. The mass of the lot is supposed to be very large compared to the mass of sample.

If the ratio between the largest sand particles and the largest gold particles is sufficiently small, the second term in the sum of the equation (2) is negligible and the simplified formula for free gold can be applied[3–5]. As shown in Table 2, it is not always the case when the proportion of the first term, the heterogeneity carried by the gold particles, is less than 95% of the constitution heterogeneity. In some cases, the number of particles of one family in the sample is too small. It mainly concerns the coarsest size class of sand or the coarsest size class of gold. In the first case, the impact on gold content variability is low. In the second case, it can be worst and the sample size has to be increased.

The calculation of the FSE for the primary sampling allows to specify the sample mass to achieve a desired level of confidence. From this primary sample, various preparation procedures can be proposed. The current study was using scalping of coarse sand particles to reduce the mass of sample to analyse and then gravity concentration. In the following sections, more conventional procedures, using sample crushing and grinding, are compared in terms of overall measurement error.

Sample screening

It has been observed that the size classes larger than 2.5 mm in the sluice rejection heap are free of gold. Removing the +2.5 mm has the effect to reduce the quantity of sample for subsequent preparation without generating fundamental sampling error. Naturally, preparation errors can take place but can be avoided by good practice.

Following the formalism proposed by Pierre Gy[9] for the general case of probabilistic sampling, the sample screening can be considered as a secondary sampling without equiprobability. The limit of non-probabilistic selection is achieved for perfect classification during sieving for which the probability of a particle coarser than 2.5 mm to be selected is 0 whereas it is 1 for finer particles. Such "sampling stage" has the particular property to have a null variance but a large bias which is absolutely manageable as it gives the link between the primary sample content and the scalped sample content. If $t_<$ is the proportion of sample passing the 2.5 mm sieve and $a_<$ the gold content in this passing fraction, the content in the primary sample is $a_S = t_< a_<$ and

$$t_< = \sum_{i \in I_<} t_i$$

where $I_< \subset I_F$ is the subset of the indexes of the families of particles finer than 2.5 mm.

The variance of the measurement error of the gold content in the primary sample is then given by the rule of error propagation:

$$\sigma^2(a_S) = \sigma^2(t_<) + \sigma^2(a_<) \quad (3)$$

providing the measurements of the proportion $t_<$ and the gold content $a_<$ have a small variance and are independent. It is true concerning the analytical error even though weighing (to obtain proportion) and subsequent processing (to obtain gold content) are performed on the same passing material. The proportion of passing material and the gold content are both subject to FSE as measured from the primary sample. If one suppose all the sample can be analysed, the gold content is then calculated by the ratio between the measured mass of gold and the mass of sample. As in first approximation the mass of sample is considered as a constant, the variance of the gold content is the variance of the mass of gold in the sample. As this mass of gold is the same in the primary sample and in the screened primary sample, the variance of the FSE is well the one calculated by equation (2).

Considering a reduction of 50% of the sample mass after sieving, an alternative procedure can be done with crushing of the primary sample up to –2.5 mm followed by a division to produce a secondary sample. During crushing, there is no chance to have size reduction of gold particles. It is then supposed that the size distribution of gold particles is conserved and the crushed sand has the same size distribution under –2.5 mm as the one of the table concentrate. In that case, the variance of the FSE of the secondary sampling has to be added to the previous one. As it is of the same order of magnitude than the primary one, the advantage of screening is largely demonstrated.

After screening, the heterogeneity model is limited to the 10 last families of Table 1. Their proportion in the scalped sample is:

$$t_{<i} = t_< t_i \quad i \in I_<$$

If the passing material is divided before concentration, the secondary sampling generates a FSE for which the variance is given by the equation (1) using the new heterogeneity model and the mass of passing material as lot mass. For the cases treated here, when dividing by 2, the variance is of the same order, but when dividing by 4, it is generally larger than the one of the primary sampling. If the sample is divided between two screening stages, intermediate FSE has to be considered for the proportion of undersize[7].

Sample concentration

After screening and division (if required), the sample is passing through a shaking table to concentrate gold. The gold content is then measured size by size for the concentrate and globally for the tailings. The separation cannot be considered as perfect and fine gold particles are reporting to the table tailings. As the shaking table is operating more to maximize the recovery than for concentration, only very fine gold particles, less than 63 µm, can be rejected with tailings as it has been observed in some concentration plants[12]. In absence of gold assaying size by size for the tailings, this observation is used as assumption in the current case. The separation is then considered as perfect for gold particles coarser than 63 µm and there are only –63 µm gold particles in the tailings. The other particles reporting to concentrate are heavy minerals (mainly black minerals) which can be gold bearing minerals. Nevertheless, in such alluvial placer, the proportion of locked gold is very small compared to the free gold. This effect can then be neglected. Some coarse particles of sand are also reporting to the concentrate. For simplification, we consider a mean density for all minerals other than pure gold. As the size distribution has not been measured for the tailings, it is supposed to be identical to the one of the concentrate.

If Y_c is the mass proportion of the secondary sample recovered into the concentrate, and a_c and a_t the gold content in the concentrate and in the tailings respectively, the content in the secondary sample is $a_< = Y_c a_c + (1 - Y_c)a_t$. Y_c being a constant regarding sampling error (it is a measurement with an analysis error given by weighing accuracy but negligible compared to the sampling errors), the variance of the sampling error is given by

$$\sigma^2(a_<) = \left(\frac{Y_c a_c}{a_<}\right)^2 \sigma^2(a_c) + \left(\frac{(1-Y_c)a_t}{a_<}\right)^2 \sigma^2(a_t) \qquad (4)$$

The heterogeneity model used for the concentrate is then limited to the 10 last families of Table 1. The one of the tailings is limited to the 5 last sand families and the –63 µm gold family. After drying, the concentrate can be divided before pulverisation, depending on the quantity of concentrate and the laboratory milling capacity. Similarly, the tailings are drained, then quartered to reduce the quantity to be dried and then divided before pulverisation.

Concentrate and tailings analysis

Pulverisation of concentrate and tailings are done up to have 100% passing 125 µm. If coarse gold appears retained by the sieve, then a Screen Fire Assay (SFA) is performed: Fire Assay (FA) of the oversize up to extinction, division of the passing material to obtain 50 g of analytical sample for FA. If there is no retained material in the sieve, a simple FA is performed. The advantage of SFA in case of presence of coarse gold has been proved and discussed in a previous paper[13]. To simplify the calculation, only a simple FA is presently considered. To take into account the fact that gold particles have difficulties to be ground, all gold particles larger than 125 µm in the concentrate are supposed to report into the 63–125 µm size class during pulverisation. The size distribution of pulverised sand is the one of the –125 µm fraction of the concentrate. The similar assumption is done for the tailings, all the gold particles remaining in the –63 µm size class.

The heterogeneity model used for the pulverised products is limited to the 4 last families of Table 1. As shown in Table 3, it is difficult to have low FSE variances for tailings sampling before and after pulverisation. The FSE component of the variance for the reconstituted content of the –2.5 mm material is calculated following the equation (4). It depends on the individual variances for concentrate and tailings assaying, but also on the gold split between concentrate and tailings and gold size distribution. For example, the bad level of confidence in the tailings assaying can have low effect as for sample #1 or dramatic consequences as for sample #5. In contrary, apparent better level of confidence for concentrate and tailings assaying (sample #2 compared to #1) generates a larger error.

As for screening, the advantage of using concentration, compared to a more conventional procedure using grinding and sample mass reduction, can be easily demonstrated by calculating the overall FSE variance for this method.

Proposed procedure for sampling and measurement of placer gold content

In conclusion to these calculations concerning various types of sluice rejection material, it appears difficult to propose a general procedure for sampling which can be applied whatever the size distribution of sand and, principally, the size distribution of gold. Nevertheless, it appears necessary to improve the last stages of the sampling procedure—the sampling of concentrate and tailings for assaying—in order to reduce the variance of the FSE components for the measurement of the gold content of the undersize fraction of the material. The use of SFA with a finer sieve (106 µm or 75 µm in place of 125 µm) seems absolutely necessary. In addition, the use of a more efficient concentrator, such as centrifugal concentrator, can reduce the proportion of gold in the tailings (then its impact on the overall error) as well as the quantity of concentrate allowing its entire pulverisation.

Determining the required mass of primary sample has to be conducted by the size distribution of sand. It can be easily adjusted as the size and proportion of the coarsest particles can be visually estimated. The effect of the gold content and gold particle size

Table 3. FSE for sub-sampling after screening and concentration of various sluice rejection heaps.

	Sample #1	Sample #2	Sample #5	Sample #6
Sampling of screened material				
Mass of –2.5 mm (kg)	109	104	61.6	117
Mass for concentration (kg)	27.1	25.9	15.4	29.3
Variance ($\times 10^{-6}$)	1840	21	2800	698
Sampling of concentrate				
Mass of concentrate (kg)	0.60	0.31	1.32	2.4
Mass for pulverisation (kg)	0.60	0.31	1	1
Variance ($\times 10^{-6}$)	0	0	1610	2470
Sampling for concentrate FA[a]				
Variance ($\times 10^{-6}$)	988	80	8840	4460
Sampling of tailings				
Mass of tailings (kg)	26.5	25.6	14.1	27.0
Mass for pulverisation (kg)	1	1	1	1
Variance ($\times 10^{-6}$)	36100	47100	52700	33600
Sampling for tailings FA[a]				
Variance ($\times 10^{-6}$)	368000	16700	171000	92400
FSE of equation (4)				
Variance ($\times 10^{-6}$)	5710	46860	287000	31200
Overall FSE variance[b]				
Variance ($\times 10^{-6}$)	8290	46930	291000	32200
Error (95% confidence)	17.9%	42.5%	106%	35.2%

[a]The mass of sample for FA is 50 g.

[b]Includes the variance of the FSE of the primary sampling as given in Table 2.

distribution is more difficult to appreciate before measurements. Only assumptions can be done at the light of what is known concerning process generating the tailings. A mass of 200 kg seems sufficient when a grate has been used before sluicing and the material is finer than 25 mm. If particles larger than 50 mm appear, it is preferable to increase the mass up to 500 kg. In that case, screening can be done with intermediate division of passing product.

Screening at 2.5 mm seems a good compromise between the maximum feed size to have a good efficiency of the concentration using shaking table and the difficulty to screen a large amount of material with finer sieves. Nevertheless, if the proportion of undersize material is larger than 50%, screening can be performed at 1 mm to reduce the quantity of material for concentration. The same 1 mm screening has to be done to use centrifugal concentrator. The size class 1–2.5 mm has to be washed by panning to verify the absence of coarse gold. The passing material can be divided but the secondary sample for concentration has to be between 30 and 60 kg. If coarse gold (larger than 500 µm) is suspected, this amount can be increased.

As many mine sites are equipped with shaking table, this is preferable. In this case, operating conditions have to maximize the recovery more than the concentration. The objective is to minimize the number of gold particles reporting to tailings. If the quantity of concentrate is too large, it can be reprocessed, then favouring the concentration. The second tailings have to be assayed separately. Concentration operation has to be carefully observed to detect the presence of coarse gold particles (+250 µm) and if fine gold particles are misclassified into the tailings.

The first tailings (as well as the second tailings in case of reprocessing of first concentrate) has to be screened at 1 mm and maybe at 500 µm if it can drastically reduce the mass to be analysed. The retained sand has to be washed by panning to verify the absence of coarse gold. Then the passing is divided and a second screening can be performed at 500 µm or 250 µm with similar treatment of retained sand. Last passing can be dried and divided to obtain between 1 and 2 kg for pulverisation at –106 µm. If gold particles are retained in the sieve, SFA is required. The passing powder is then divided to take 30 to 50 g for FA.

The concentrate (the second one in case of reprocessing of first concentrate) has to be screened at 500 µm. The retained particles have to be washed by panning to verify the absence of coarse gold or bearing minerals. In case of presence, the pan product is weighed and assayed. The passing 500 µm is dried and divided only if its mass exceeds 4 kg. It is then pulverised at –106 µm for a SFA.

Conclusion

Estimating gold content in a low grade placer deposit, or in tailings remaining after sluice treatment, makes it necessary to collect numerous large samples. As these samples cannot be processed *in toto* by grinding, it is necessary to use concentration stages (by screening or gravity concentration) to be able to reduce the quantity of material for final analysis.

The measurements performed during this study were with the objective of placer deposit treatment or tailings retreatment. The obtained material characteristics have been used to build heterogeneity models in order to calculate the components of the variance of the overall fundamental sampling error. The results showed, a posteriori, a relatively low accuracy for the estimate of the global gold content. Considering the local conditions of work, this level appears satisfactory and the reprocessing performed after this study gave the expected gold recovery. Nevertheless, at the light of the results of this study, an enhanced procedure is proposed. It has now to be verified and the variance of the overall measurement quantified.

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