CHRYSOS CORPORATION

Assays at the speed of light

Technical Note TN-001

Chrysos PhotonAssay™ Measurement Performance for Gold on Certified Reference Materials

Executive Summary

This note reports on extensive tests of PhotonAssay™ performed on a wide range of certified reference materials over the period 2019-2022.

Operating at a throughput of 72 samples per hour for a Standard Gold Analysis (SGA), a 2-sigma detection limit of 0.010 ppm is observed on reagent-blank materials. The 1-SD measurement precision is approximately 14% relative at 0.1 ppm, 8% relative at 0.3 ppm, 4.5% at 1 ppm, and below 2.5% for samples with gold grades above 3.5 ppm. The upper limit of the SGA service is 350 ppm, but the high-grade and ultra high-grade services extend this limit to 3,500 and 35,000 ppm respectively.

Generally excellent agreement is observed between PhotonAssay™ and certified fire-assay grades for all material types and grades. Good agreement on carbon CRMs is observed at the higher grade ranges.

Based on this test work, we provide a list of recommended PhotonAssay™ mean grades and measurement precisions for a range of commercially available CRMs. These recommended values can be used to establish control limits for a laboratory QC program. A version of these recommendations in spreadsheet format is available on request.

This note replaces Revision 1 released in November 2021.

Related Documents

Performance Note PN-001 PhotonAssay™ Gold Services

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Introduction

Chrysos PhotonAssay™ is a novel approach to gold measurement based on photon activation analysis. High-power x-rays produced by a linear accelerator are used to activate the nuclei of target elements in a sample. The excited nuclei produce measurable gamma-rays with characteristic energies allowing the grade of the target element to be quantified.

The first PhotonAssay™ system was deployed to a Perth laboratory operated by MinAnalytical Laboratory Services in 2018. This was followed by the installation of additional units in Perth, Kalgoorlie and Bendigo. To date more than one million gold sample measurements have been performed using these units.

PhotonAssay™ received NATA accreditation in 2018, following extensive testing and validation. The PhotonAssay™ technology has also been used in both NI 43-101 compliant studies and JORC-compliant ASX reports. Comparative studies of PhotonAssay™ and fire-assay on materials sourced from over 50 mining operations across the globe have demonstrated that PhotonAssay™ can be used interchangeably with fire-assay for a wide range of deposit types. In addition, PhotonAssay™ offers the benefits of speed, non-destructive assay, reduced sample preparation requirements and measurement of larger volumes of material and consequently smaller sampling errors.

An important *part* of the validation of PhotonAssay™ is repeat analysis of materials with accurately known gold grades. Certified Reference Materials (CRMs) are materials that are carefully prepared to be highly uniform and have well-determined gold grades, typically determined by repeat measurements performed by many reputable laboratories. CRMs are supplied commercially by several companies.

In this report, we evaluate the precision and accuracy of the PhotonAssay™ method as a function of gold grade using repeat measurements on CRMs and compare mean grades for the same materials measured using both PhotonAssay™ and fire-assay. Measurements on blank materials are also performed to determine the detection limit of PhotonAssay™.

Results from five separate studies are presented in this report:

S1. Measurements on blank materials over a 6-month operating window.
S2. Factory acceptance testing of the first PhotonAssay™ unit performed in early 2018 using materials from OREAS, Rocklabs, AMIS and RRM. Whilst superseded by more recent test work, the results of this study were reported in an earlier version of this note and we include them here for completeness.
S3. A study of PhotonAssay™ performance carried out shortly after commissioning of the first PhotonAssay™ unit using materials provided by Gannet Holdings.
S4. A recent study of CRMs from OREAS, CDN, Rocklabs and Geostats.
S5. Measurements on high-grade gold carbon materials.
S6. Measurements on 9 low-grade CRMs ranging from 19 ppb to 323 ppb.

Methodology

Sample Preparation

The PhotonAssay™ system accepts samples in custom plastic screw-top jars with a capacity of approximately 320 mL (Figure 1). A single jar typically holds between 250 g and 650 g of pulverised ore, depending on bulk density, or about 200 g of carbon material. Each jar is uniquely identified by a barcode on the lid, which is used to register each sample onto the system.

Figure 1. CRM samples in labelled plastic jars. Samples remain in their jars throughout the assay process.

As the PhotonAssay™ method provides a true bulk analysis of the entire contents of the jar, minimal sample preparation is required. For the CRMs, which are prepared to be highly uniform, material was transferred directly into sample jars from the tubs or sachets provided by the manufacturers. All results are reported on an as-received basis, as the CRMs are prepared to have very low moisture contents (generally much less than 1%) and were stored in sealed containers.

Measurement Procedure

Material remains sealed in the jar throughout the measurement process, reducing the risk of cross-contamination. Filled jars are electronically weighed and their fill-level determined using an optical camera system. The mass and fill-level are used to determine the sample density which is required for the instrument calibration. An operator scans jars into the PhotonAssay™ console and then places them on an input conveyor.

A fully automated transport system moves each jar from the input conveyor into the path of the x-ray beam, where the sample is irradiated for 15 seconds before being transferred to a detection system which records the gamma-ray emission for a further period of 15 seconds. The measurement process is then repeated to generate the required number of cycles for a given service. Averaging the results across multiple cycles improves the measurement precision. Results presented in S2-4 of this report were generated with the Standard Gold Analysis (SGA) service, which uses two measurement cycles, resulting in a throughput of approximately 70-72 samples per hour.

The gold grade is then computed based on the measured gamma-ray signal intensity. No operator intervention is required for the analysis process. Once a designated batch of samples has been measured, a grade report is automatically generated and sent to the customer's LIMS for local QC checks and client reporting.

Once each sample has been analysed it is returned intact to the operator. Samples can be safely discarded or retained for further analysis if required.

Results

Detection limit estimation from measurement of blank samples

A suite of blank samples was prepared that comprised crushed road-base material used for performing barren washes between pulverisation of samples being prepared for traditional fire-assay. The gold content of this material had been previously determined via fire-assay to be less than 0.005 ppm.

One of these blanks was included in every batch of samples run through the PhotonAssay™ instruments. A large number of measurements over a period of approximately 6 months demonstrated a 2-sigma lower detection limit of approximately 0.010 ppm. The distribution of measured grades for these blank samples is shown in Figure 2.

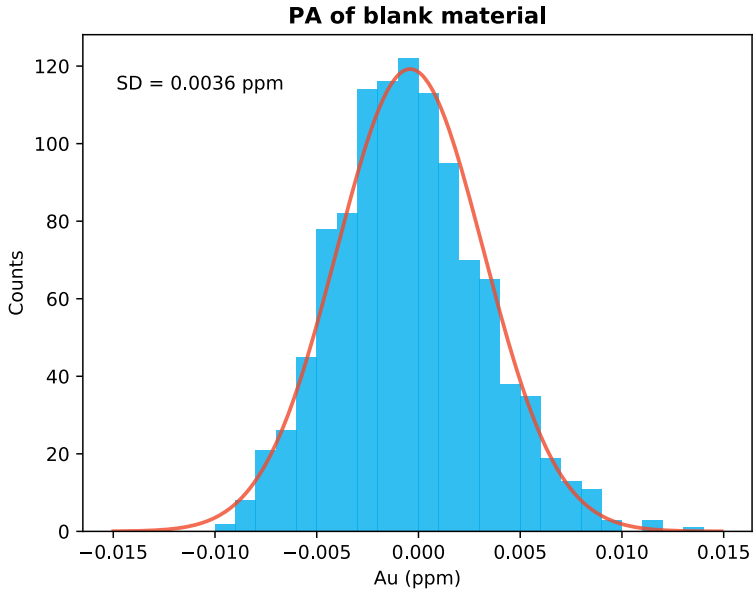

Figure 2. Histogram of over a thousand 2-cycle gold grade measurements of blank samples run between January and July 2020.

The blank material contains very low levels of uranium, thorium, and barium. Elevated levels of these elements raise the gamma-ray background underneath the gold signal and lead to an increase in detection limit. Consequently, the observed 2-sigma detection limit for the SGA service for typical ores ranges from 0.015-0.03 ppm. The upper measurement limit for this service is 350 ppm.

PhotonAssay™ instrument precision

As a non-destructive assay method, the PhotonAssay™ instrument precision can be determined most directly by performing repeat measurements on the same sample. Where a material is known to be highly uniform, such as a CRM, the repeat measurements can also be performed on different samples prepared from the same bulk material.

Figure 3 plots the measured PhotonAssay™ precision as a function of gold grade for the CRM materials measured in studies S3-S4. A trend line through the results is also shown.

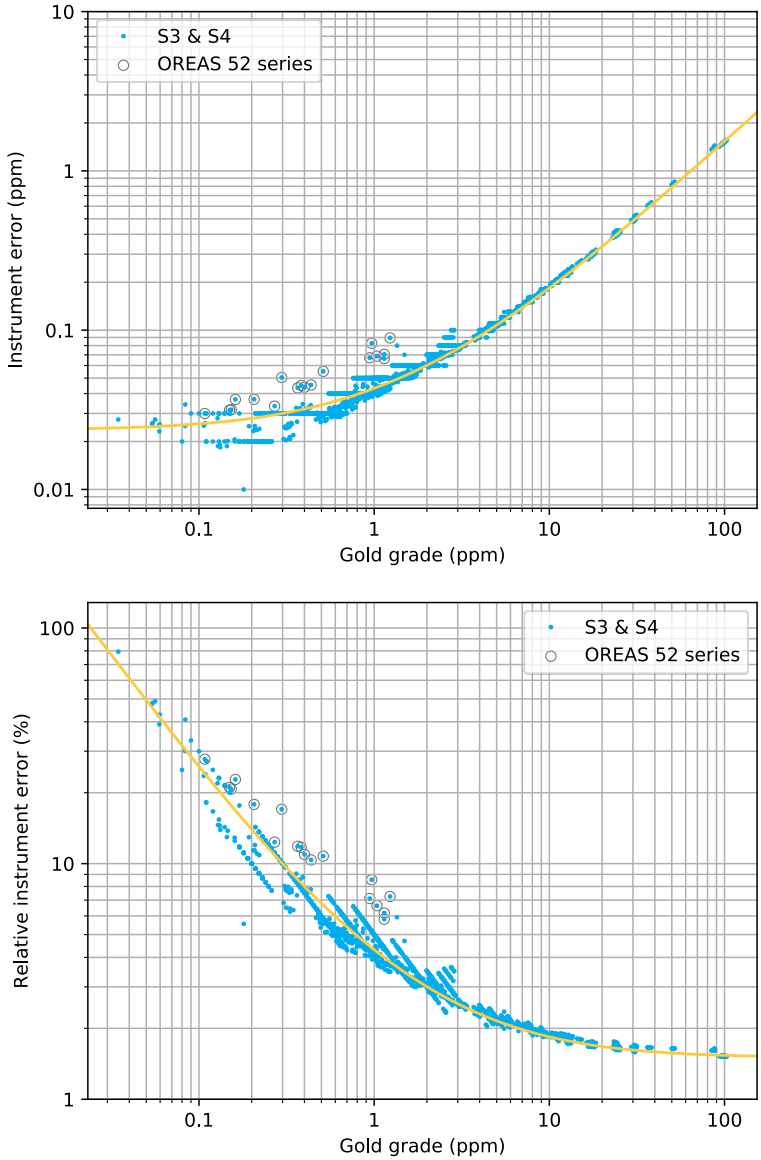

Figure 3. PhotonAssay™ absolute (top) and relative (bottom) instrument error plotted against gold grade for the CRM materials measured in studies S3-S4. The OREAS 52x series, with elevated levels of uranium and/or thorium are circled in grey.

For fire-assay, repeat measurements of the same aliquot are impossible as the sample is consumed during the analysis. Instrument precision can then be determined only by performing repeat measurements on different aliquots. CRM manufacturers normally only provide a small number of samples of each material type to the laboratories that contribute to the round-robin grade measurements. Their reported variability is then the inter-lab variation,

which includes error contributions from both instrument precision and overall laboratory normalization. Against this, some CRM manufacturers calculate the inter-lab variability using the average of several individual measurements from each participating laboratory, and aggressively exclude any outlying results; both practices reduce the inter-lab variability.

These factors make an accurate estimate of the precision of fire-assay difficult. Nonetheless, we have estimated indicative precision ranges as a function of gold grade using data provided by Geostats on their CRMs. The Geostats round-robin CRM tests generally send a single sample to a large number of laboratories.

For PhotonAssay™, the 1-standard deviation (1 SD) instrument precision varies from about 7% at 0.25 ppm, 4% at 1 ppm, to 2% for samples with gold grades above 10 ppm (see Table 1 and Figure 3). At grades above 2-3 ppm, the precision of PhotonAssay™ generally matches or exceeds that of fire-assay; in the range of 0.3-3 ppm, the precision of the two methods is comparable, and at grades below about 0.3 ppm, fire-assay is more precise.

Table 1. Typical performance of PhotonAssay™ (SGA service) and fire-assay on certified reference materials. For fire-assay, detection limits are from (Hoffman, Clark, & Yeager, 1999); accuracy ranges estimated from inter-laboratory standard deviation values reported for a range of Geostats certified reference materials, available from www.geostats.com.au/crm_list_download.php.

Gold assay performance	Value for fire-assay	Value for 2-cycle PhotonAssay
Detection limit (2σ)	1 ppb (ICP) 5-10 ppb (AAS) 20-30 ppb (grav.)	10 ppb (blanks) 15–30 ppb (typical ore)
Grade at which 10% precision (1 SD) is achieved	0.1-0.2 ppm	0.2-0.3 ppm
Repeatability @ 0.35 ppm	5-8%	7%
Repeatability @ 1 ppm	3-7%	4%
Repeatability @ >10 ppm	2.5-3.5%	2%

PhotonAssay™ comparisons with fire-assay

Factory acceptance tests (suite S2)

A total of 50 different CRMs sourced from OREAS, Rocklabs, AMIS and RRM were used for the commissioning of the first PhotonAssay™ unit in early 2018. The majority of CRM samples were measured on multiple occasions, and where sufficient material was available, multiple samples were prepared from each supplied CRM. A comparison of PhotonAssay™ and certified fire-assay grades for these materials is shown in Figure 4 and table A1. Materials from different CRM suppliers are represented using separate colours. The R^2 value for the comparison is 0.9996.

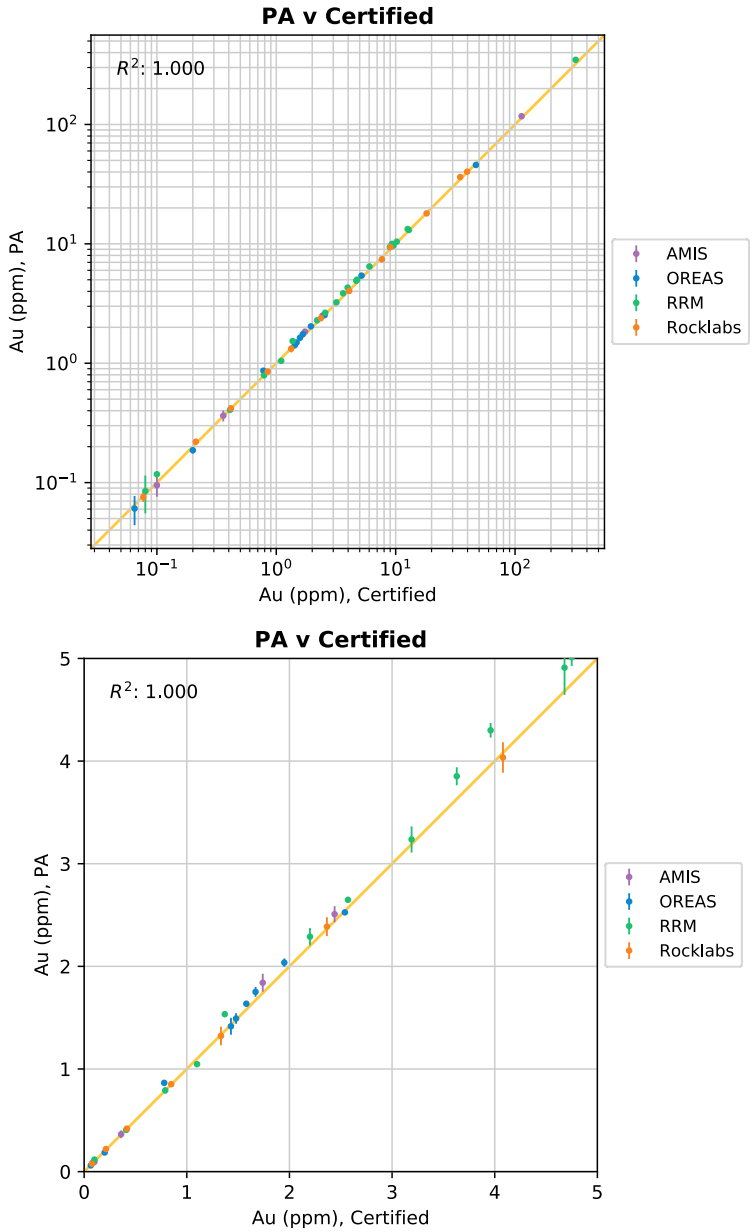

Figure 4. Comparison of PhotonAssay™ gold grades (y-axis) and certified reference grade (x-axis) for 50 CRMs measured during factory acceptance testing of the initial PhotonAssay™ unit in 2018. (Top) all samples on a logarithmic scale. (Bottom) Samples below 5 ppm on a linear scale.

A detailed comparison of the PhotonAssay™ and certified grades for materials from the different CRM supplies showed a small but statistically significant normalisation bias. We observe that the average ratio of the PhotonAssay™ grade to the certified grade for the

materials from the African suppliers (RRM and AMIS) is 4.1% larger than the average value of the same ratio for the Australian/New Zealand suppliers (OREAS and Rocklabs).

We choose arbitrarily to normalise our reported grades to the OREAS/Rocklabs sample suites. Consequently, our reported grades for the RRM and AMIS materials are generally slightly higher than the certified values, as can be seen in Figure 4 (lower plot).

Unlike traditional chemical assay, where no indication of the measurement uncertainty is possible, the data analysis process used to determine the gold concentration in PhotonAssay™ also returns a statistical spectrum fitting error, which provides a good estimate of the measurement repeatability or precision.

The lower plot in Figure 4 zooms in on the important 0-5 ppm range, and plots PhotonAssay™ grade versus certified CRM grade on a linear scale. The error bars, which are only clearly visible at lower grades, correspond to 1-standard deviation precision values. Statistically, 68% of measured grades should lie within one standard deviation of the mean value.

A single calibration was used for all the CRMs, which span a wide range of ore types and a nearly 5,000-fold range of gold concentrations. The plots illustrate the accuracy of the PhotonAssay™ method for analysis of gold in different matrices.

A Tukey plot showing the ratio of the PhotonAssay™ grade to manufacturer certified fire-assay grade for each sample, plotted against the mean of the measurement pair is presented in Figure 5.

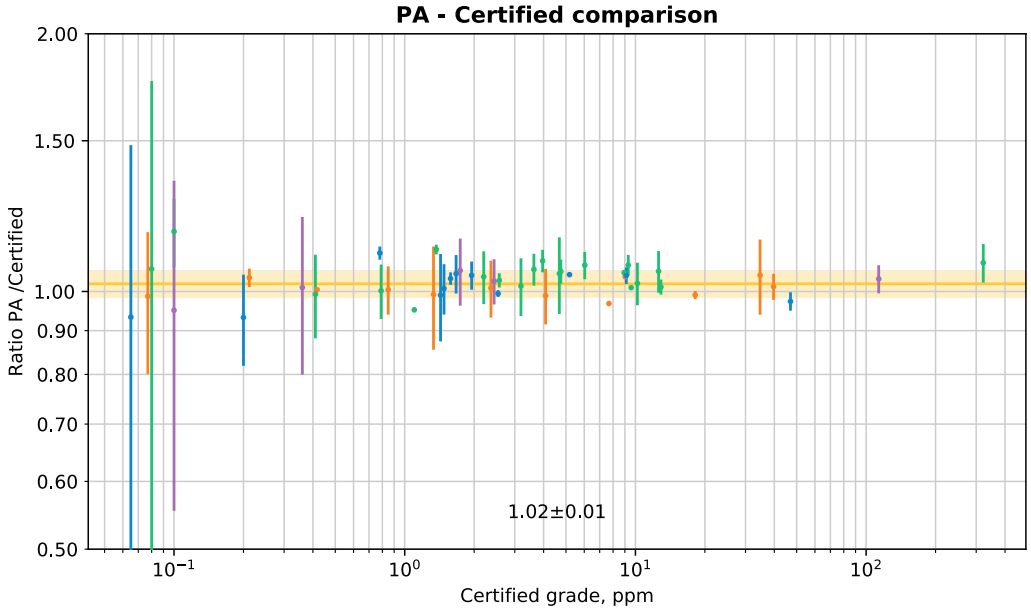

Figure 5. Tukey mean-ratio plot comparing PhotonAssay™ grades with manufacturer certified fire-assay grades for the suite of 50 CRMs measured during factory acceptance testing of the first PhotonAssay™ unit. The ratio of the paired grades is plotted as a function of the mean sample grade, determined from the average of the two methods. The yellow band indicates the mean ratio and grade ratio variation (±1 SD) averaged over all samples. 2 SD error bars are shown for each sample.

As the PhotonAssay™ measurements were normalized to the OREAS and Rocklabs fire-assay results, the higher grades observed for the AMIS and RRM materials lifts the overall normalization slightly above unity, with a mean grade ratio of 1.02 ± 0.01. The log error weighted standard deviation of the PhotonAssay™ to fire-assay grade ratios is 3.6%, which provides an estimate of the combined PhotonAssay™ instrument error and uncertainty on the true sample grades.

Gannet Holdings CRMs (suite S3)

In mid-2018, measurements of 73 CRMs provided by Gannet Holdings were performed using the first deployed PhotonAssay™ system in Western Australia. The results from this study are presented in Figure 6 and Figure 7 and table A2. Between 5 and 95 repeat measurements were performed for each material. A number of jars were prepared for each CRM material, so the results represent the variation both from the PhotonAssay™ instrument precision and the variability between aliquots of the same CRM material.

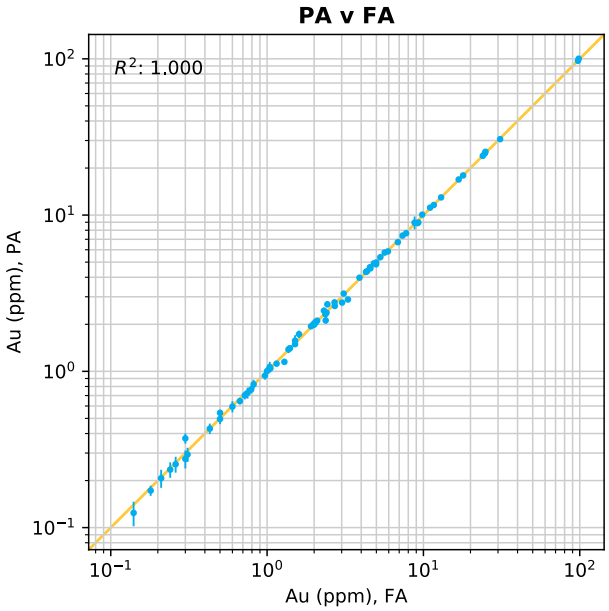

Figure 6. Comparison of PhotonAssay™ and certified reference grades for 73 CRMs sourced from Gannet Holdings.

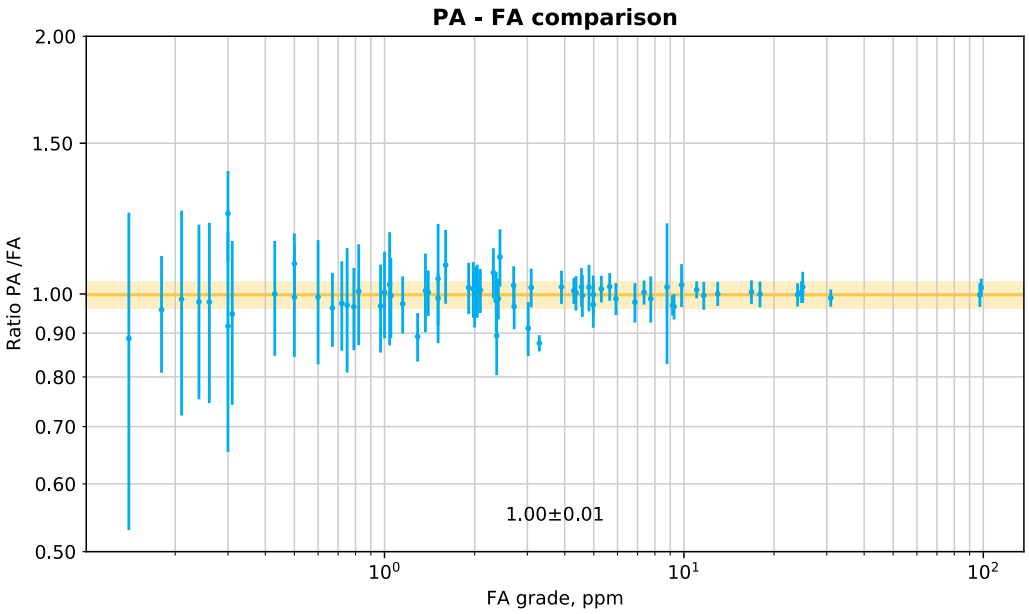

Figure 7. Tukey mean-ratio plot comparing PhotonAssay™ grades with manufacturer certified fire-assay grades for the suite of 73 Gannet Holdings CRMs. The ratio of the paired grades is plotted as a function of the mean sample grade, determined from the average of the two methods. The yellow band indicates the mean ratio and grade ratio variation (±1 SD) averaged over all samples.

The R^2 value for the comparison is 0.9998. The log weighted mean ratio of PhotonAssay™ to fire-assay grades is 1.00±0.01, which is consistent with unity to 1 SD. This implies PhotonAssay™ and fire-assay methods are interchangeable for this range of materials. The log weighted standard deviation in the PhotonAssay™ to fire-assay grade ratios is 3.2%.

Of the 73 CRM materials assayed, 65 had a mean grade within 2 standard deviations of the manufacturer certified grade. All except 2 of the samples (ST_494 and ST_508, with certified grades 1.29 ppm and 3.29 ppm, respectively) had a mean grade within 3 standard deviations of the certified value.

Combined manufacturer study (suite S4)

Results from a 2020 study using CRMs from four manufacturers are presented in Figure 8 and Figure 9. A suite of 94 CRMs, including sulphides, combinations of gold/copper ores and concentrates, oxide ores, basalt, Greenstone, Magdala ore, etc., was measured, with each jar undergoing at least six standard 2-cycle analyses. A comparison of PhotonAssay™ and certified grades for these materials is shown in Figure 8, Figure 9 and Table A3.

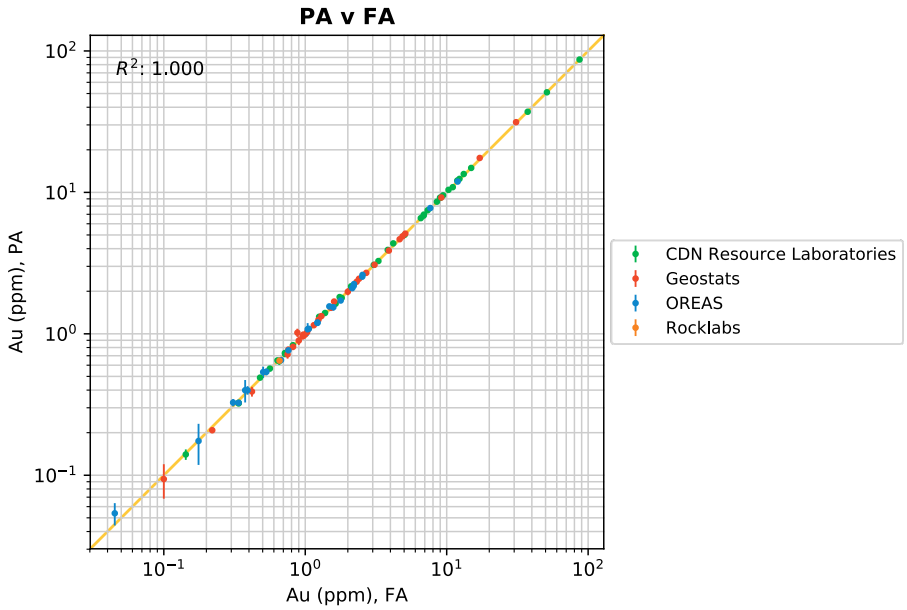

Figure 8. Comparison of PhotonAssay™ gold grades (y-axis) and certified reference grade (x-axis) for 94 CRMs measured using the PhotonAssay™ system operating in Perth, Western Australia.

The R^2 value for the comparison is 0.99994. The log-weighted mean ratio of the grade ratios is consistent with unity, indicating that PhotonAssay™ and fire-assay can be used interchangeably on these materials. The standard deviation in the PhotonAssay™ to fire-assay grade ratios is 2.1%.

Five of the 94 CRMs analysed as a part of this suite reported mean PhotonAssay™ grades that differed from the certified grades by more than 2 standard deviations. Of these 5, two samples were more than 3 standard deviations from the certified fire-assay values (CDN-GS-13A and G312-5, with certified grades of 13.2 ppm and 1.6 ppm, respectively).

Overall, the excellent consistency between fire-assay and PhotonAssay™ grades indicates that the two techniques can be used interchangeably for a wide range of sample types.

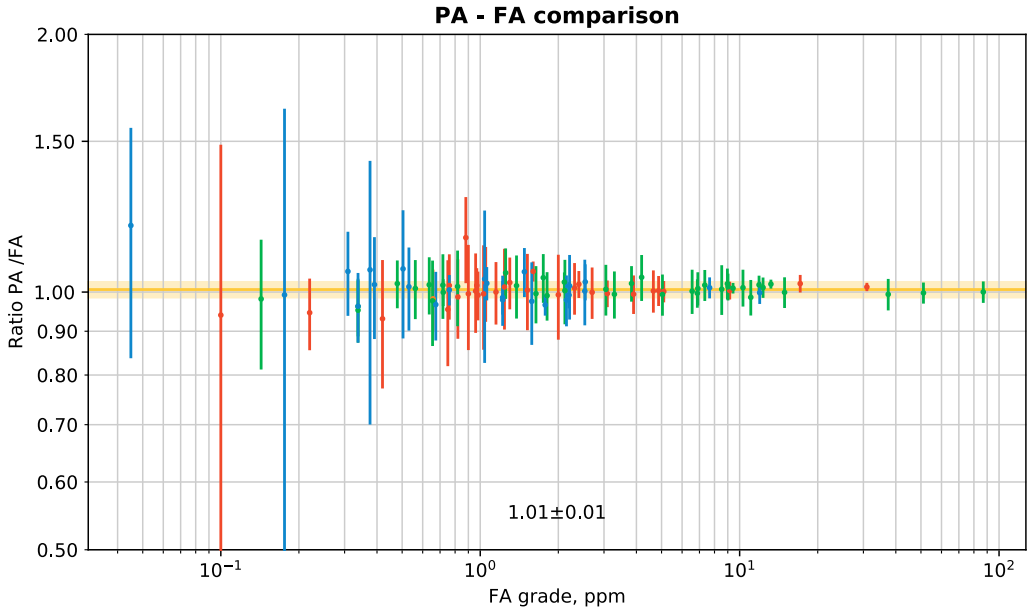

Figure 9. Tukey mean-ratio plot comparing the grades from PhotonAssay™ and fire-assay for the suite of CRMs. The ratio of the paired grades is plotted as a function of the mean sample grade, determined from the average of the two methods. The yellow band indicates the mean ratio and grade ratio variation (±1 SD) averaged over all samples.

High-grade Carbon Samples (suite S5)

A set of 10 Geostats carbon CRMs were used to assess the performance of the PhotonAssay™ method on high grade samples. The 10 CRMs were run alongside 9 standard CRMs using both the 2-cycle PhotonAssay™ high grade service PAAU02H, and the 2-cycle ultra-high-grade service PAAU02U, which utilise different machine operating settings to extend the measurement range of the standard gold analysis service. These two services are optimised for samples with grades between 50 ppm and 3,500 ppm, and for samples with grades above 3,500 ppm, respectively.

The samples were run twice, once using each of the high-grade services, on one PhotonAssay™ unit. A further two repeats were performed using the PAAU02U service on a second PhotonAssay™ unit. The standard CRMs interleaved with the carbons were used to calibrate the normalisation for the two services. The 1-SD error in the weighted mean ratio of PhotonAssay™ to certified grades for these CRMs was 2%.

Comparing the results of the repeat PhotonAssay™ measurements with the certified grades for the carbon materials, an R^2 value of 0.9998 was obtained (Figure 10). The weighted mean ratio of PhotonAssay™ to certified grades for the carbon CRMs is consistent with unity to within 2 SD, with a weighted mean ratio of 1.02 ± 0.01 (Figure 11).

A comparison of the repeat PhotonAssay™ measurements of these samples using the PAAU02H and PAAU02U services for samples below 3500 ppm (the upper limit of the PAAU02H service) is shown in Figure 12. The R^2 value for the comparison is 0.99999. The two services demonstrate a high level of consistency for the materials assayed.

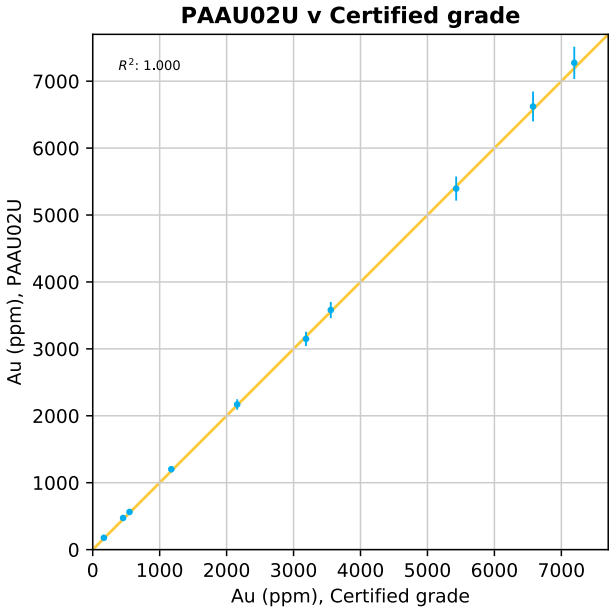

Figure 10. Comparison of the mean PhotonAssay™ PAAU02U gold grades and certified reference grades for 10 CRMs measured using two PhotonAssay™ systems operating in Perth, Western Australia.

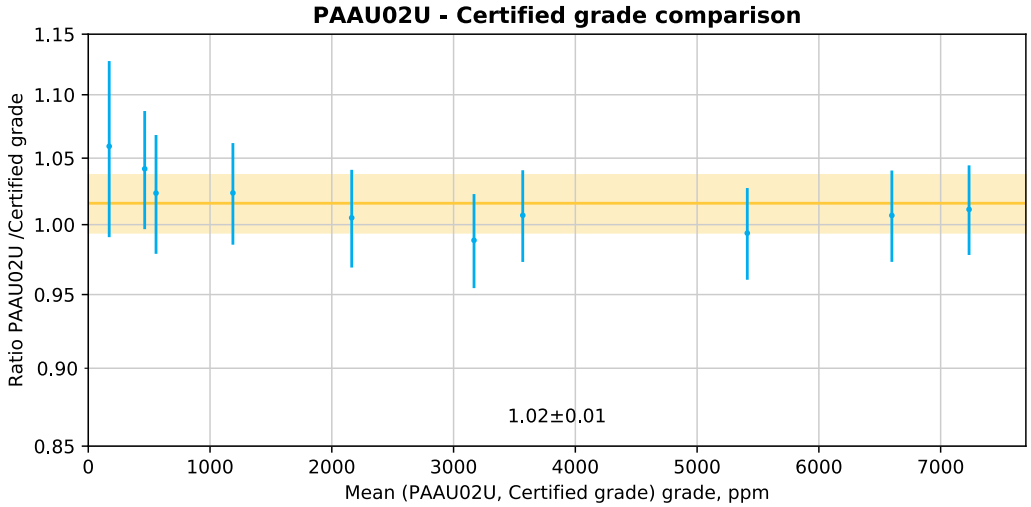

Figure 11. Tukey mean-ratio plot comparing the mean PAAU02U grades and certified grades for 10 carbon CRMs. The ratio of the paired grades is plotted as a function of the mean sample grade, determined from the average of the two methods. The yellow band indicates the mean ratio and grade ratio variation (±1 SD) averaged over all samples. Also shown are the 2 SD error bars representing twice the RMS statistical error in the repeat PhotonAssay™ grade measurements for each sample.

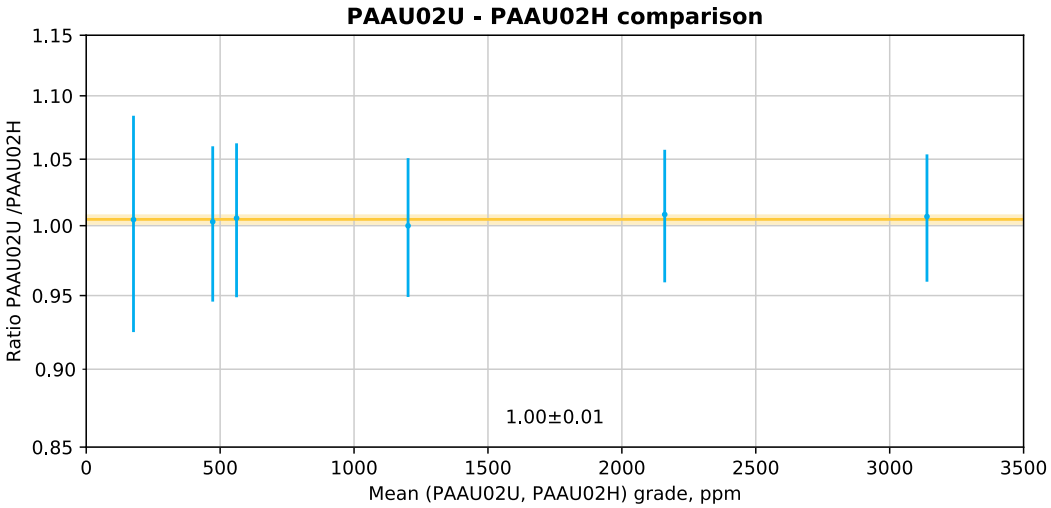

Figure 12. Tukey mean-ratio plot comparing the mean PAAU02U grades with the PAAU02H grades for 6 carbon CRMs with grades below 3500 ppm. The ratio of the paired grades is plotted as a function of the mean sample grade, determined from the average of the two services. The yellow band indicates the mean ratio and grade ratio variation (±1 SD) averaged over all samples. Also shown are the 2 SD error bars representing twice RMS statistical errors in the PAAU02H and PAAU02U measurements added in quadrature for each sample.

Low Grade CRM Measurements (suite S6)

A set of 9 low-grade CRMs from OREAS and Geostats were used to assess the performance of the PhotonAssay™ method on low grade samples. The 9 CRMs with grades ranging from 19 ppb to 323 ppb were run 24 times over a period of 12 days using the 8-cycle PhotonAssay™ high precision service PAAU08. Pairs of consecutive cycles were combined to simulate measurement using the 2-cycle service.

Comparing the 2-cycle results of the PhotonAssay™ measurements with the certified grades for the low-grade CRM, an R^2 value of 1.000 was obtained (Figure 13). The weighted mean ratio of PhotonAssay™ to certified grades for the low-grade CRMs is consistent with unity to within 2 SD, with a weighted mean ratio of 0.99 ± 0.02 (Figure 14).

One of the 9 low-grade CRMs reported a mean PhotonAssay™ grade that differed from the certified grade by more than 2 standard deviations. Geostats GLG304-1 with a certified fire-assay grade of 0.154 ppm, reported a mean PhotonAssay™ grade of 0.146 ppm, which is still within 3 standard deviations.

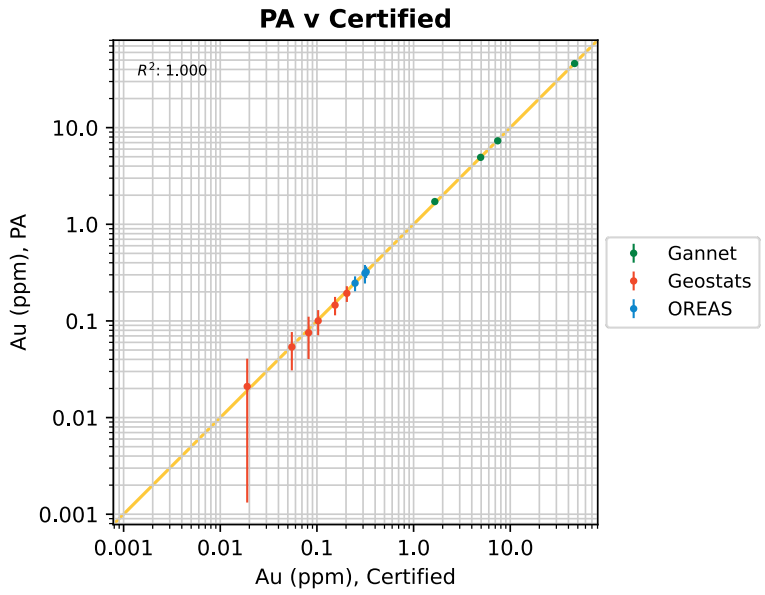

Figure 13. Comparison of the mean PhotonAssay™ PAAU02 gold grades (extracted from PAAU08 cycle results) and certified reference grades for 9 CRMs.

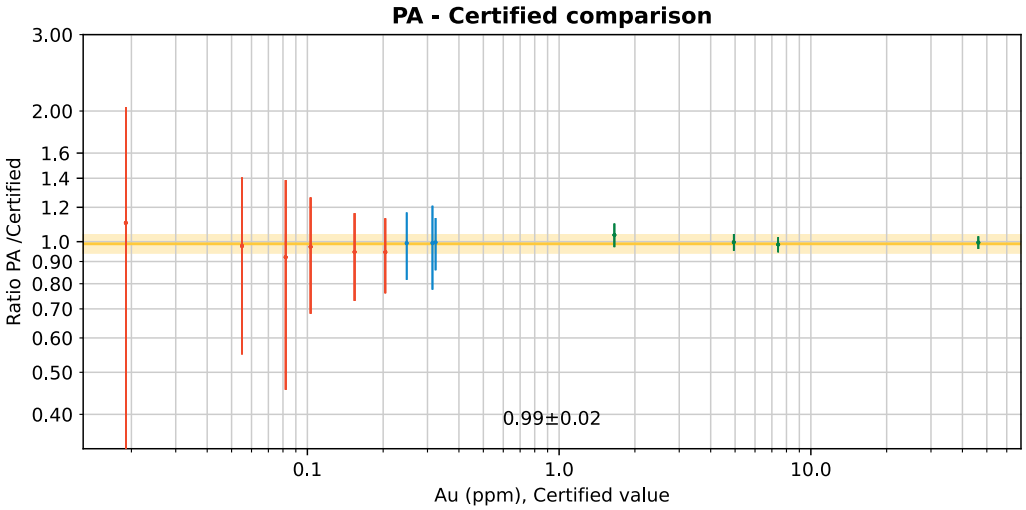

Figure 14. Tukey mean-ratio plot comparing the mean PAAU02 grades with certified reference grades for 9 low-grade CRMs. The ratio of the paired grades is plotted as a function of the mean sample grade, determined from the average of the two grades. The yellow band indicates the mean ratio and grade ratio variation (±1 SD) averaged over all samples.

The comparison of standard deviations between PhotonAssay™ and Certified Fire Assay methods shown in Figure 15 reveals that PhotonAssay™ provides increased precision, particularly with an increased number of cycles.

PhotonAssay™ 2-cycle data has an SD ranging from 0.010 to 0.024 ppm, which demonstrates relatively low variability. However, on the 8-cycle service, the standard deviation further decreases, ranging from 0.005 to 0.017 ppm, indicating improved precision.

In contrast, the Certified FA method exhibits higher variability with standard deviation values ranging from 0.006 to 0.033 ppm. This data highlights that PhotonAssay™, especially at 8 cycles, meets or outperforms the Certified FA measurement precision, offering a more reliable analysis of gold concentration.

Overall, the excellent consistency between PhotonAssay™ grades and certified grades indicates that PhotonAssay™ measurements are suitable for low-grade material.

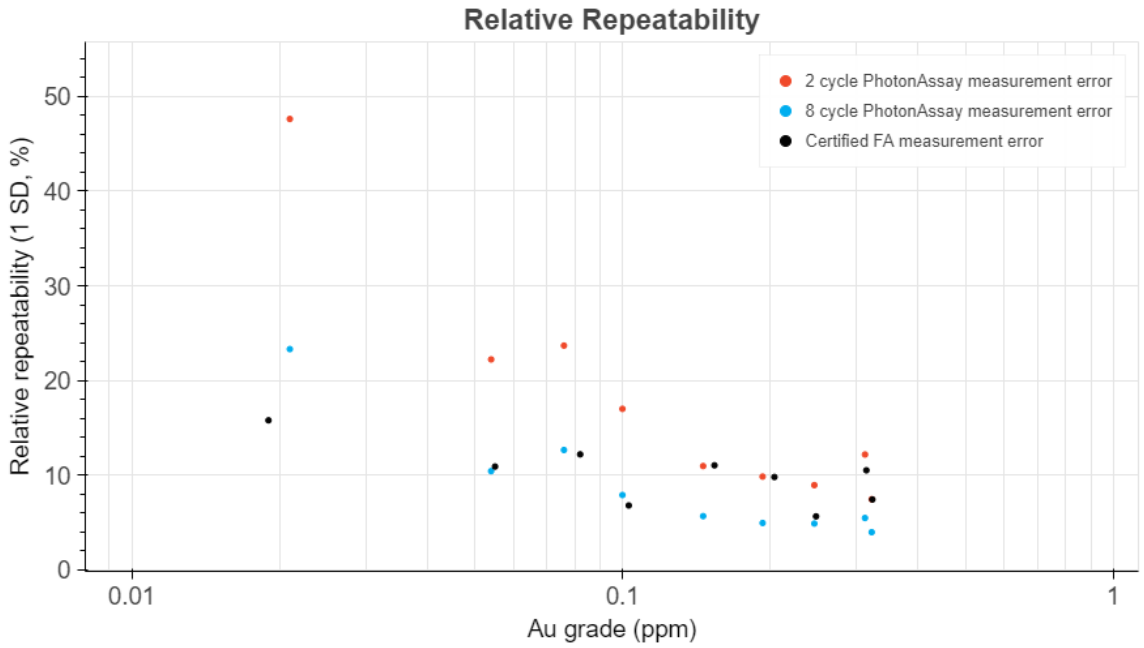

Figure 15. Relative Repeatability plot showing the standard deviations of PhotonAssay™ results on the 2-cycle and 8-cycle services alongside certified fire assay measurement errors. While the 2-cycle service offers comparable precision to fire assay up to about 0.1 ppm, the PhotonAssay™ relative repeatability is generally comparable to or better than fire assay on the 8-cycle service across the full grade range.

PhotonAssay™ control limits for laboratory monitoring

The standard deviation of the fire-assay grade values for CRMs are provided by the manufacturers of these materials to allow the uncertainty on the mean reported CRM grade to be determined. Secondarily, this information also provides an indication of the material homogeneity. These certified standard deviations are not intended to be used as quality control limits: neither for fire-assay, nor other techniques such as PhotonAssay™ where the variation in precision with grade may differ.

Excerpts from material data sheets provided by the manufacturers OREAS[1] and Rocklabs[2] expand on this idea.

- OREAS: "In the application of SD's in monitoring performance it is important to note that not all laboratories function at the same level of proficiency and that different methods in use at a particular laboratory have differing levels of precision. Each laboratory has its own inherent SD (for a specific concentration level and analyte-method pair) based on the analytical process and this SD is not directly related to the round robin program."
- Rocklabs: "Some users have used our consensus testing statistical data to establish control limits for assessing acceptance of laboratory results. Our certification process produces precise statistical data based on the proficiency program and not on an individual laboratory. Such use inevitably leads to many apparent out-of-control points, leading to doubts about the laboratory's testing, or of the reference material itself. Our suggested best practice would be to accumulate a history of the test results obtained, and plot them on a control chart to determine any laboratory bias and variability. The appropriate centre line and control limits for this chart should be based on the average level and variation exhibited in the laboratory's own data. This chart will provide a clear picture of the long-term stability or otherwise of the laboratory testing process, providing good clues as to the causes of any problems."

To determine suitable standard deviations and hence control limits for PhotonAssay™, we follow the procedure recommended by Rocklabs. A history of PhotonAssay™ results for a given CRM is accumulated and the PhotonAssay™ certified grade and standard deviation are determined by plotting them on a control chart.

Figure 16 and table A5 show the PhotonAssay™ relative standard deviations against gold grade for 29 CRMs measured between December 2020 and May 2021 on four deployed PhotonAssay™ units. The CRMs were selected to span a wide range of grades and material types. Several of the materials were also measured using the high-range PAAU02H. As this service is optimised for samples with grades above 100 ppm, precision is lower on lower-grade materials.

For the standard gold assay service, the relative standard deviation shows a decreasing trend with grade, flattening out at grades above about 10 ppm. The repeatability ranges from about 8% (1 SD) at 0.3 ppm, 4.5% (1 SD) at 1 ppm to less than 2% at grades over 10 ppm. For the high-grade gold service, precision ranges from about 5% at 10 ppm to about 2% for samples with grades over 100 ppm.

Four CRMs of note in this study are the OREAS 52x series (OREAS 521, 522, 523 and 524), which show significantly higher variation than other CRMs in the same grade range. These materials contain significantly elevated levels of uranium and/or thorium, which raise the

[1] https://www.oreas.com/downloads/?fileId=1491
[2] https://www.scottautomation.com/assets/Reference-Materials/30-11-20/OxE166-signed.pdf

gamma-ray background beneath the gold peak, giving rise to increased spread in gold grade measurements. For this reason, these materials are not recommended for routine quality control applications and are not included in table A5.

In passing, it should be noted that PhotonAssay™ precisions for real gold ores where sampling effects limit measurement precision generally exceed those of fire-assay for grades down to about 0.2 ppm, simply due to the much larger mass of material being measured.

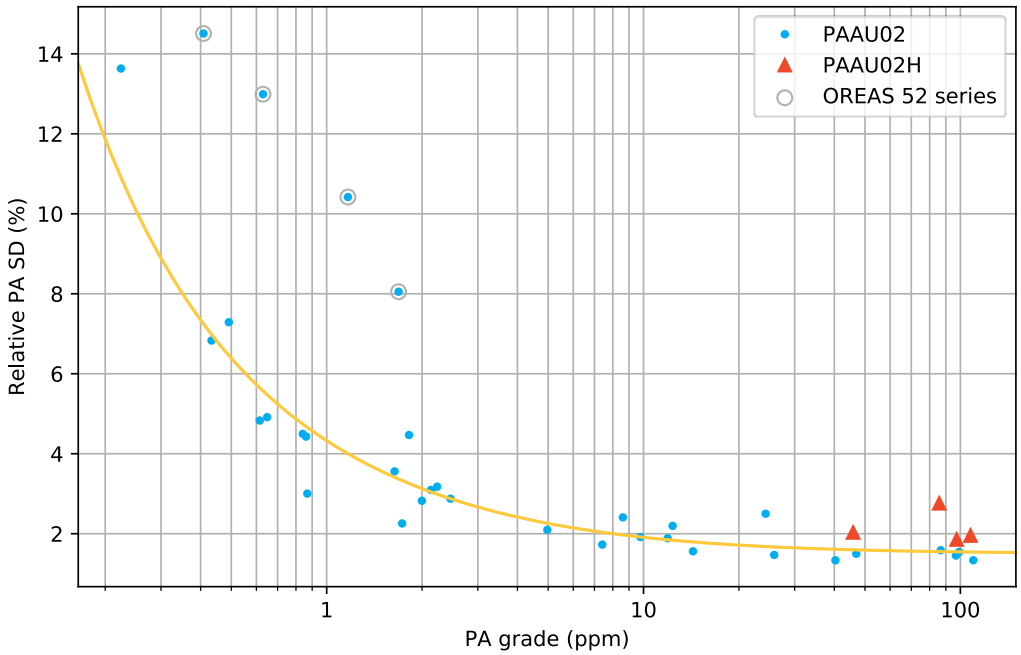

Figure 16. Plot of PhotonAssay™ measurement errors (1-SD) for the standard gold analysis (PAAU02) and the high-grade gold analysis (PAAU02H) services. Samples OREAS 521-524 are circled in grey, as these contain significant levels of uranium and/or thorium which degrade the gold grade repeatability. The predicted PhotonAssay™ instrument error is shown by the yellow curve.

Conclusions

Chrysos' PhotonAssay™ technology has been demonstrated to provide rapid and accurate analysis of gold grade in a wide range of sample types.

Operating at a throughput of about 72 samples per hour for a Standard Gold Analysis (SGA), measurement precision on certified reference materials is approximately 14% relative at 0.1 ppm, 8% relative at 0.3 ppm, 4.5% at 1 ppm, and below 2.5% for samples with gold grades above 3.5 ppm. These precisions are comparable or superior to those obtained using fire-assay under ideal conditions.

Extensive testing of the PhotonAssay™ technology on a large number of CRMs sourced from seven separate manufacturers demonstrates that the same instrument calibration can produce accurate assays for a wide variety of ore types.

References and further reading

Hoffman, E., Clark, J., & Yeager, J. (1999). Gold analysis - fire assaying and alternative methods. *Exploration and Mining Geology, 7 (1+2)*, 155-160.

Appendix

Table A1. Mean PhotonAssay™ and certified fire-assay grades for samples analysed as a part of S2.

Sample ID	PhotonAssay Au Mean (ppm)	PhotonAssay Au SD (ppm)	N (PhotonAssay)	Certified Fire-Assay Au (ppm)	Certified Fire-Assay Au Err (ppm)
AMIS RM 0224	117.3	2.3	10	113.4	6.8
AMIS RM 0336	0.1	0.02	15	0.1	0.007
AMIS RM 0432	0.36	0.04	13	0.36	0.018
AMIS RM 0440	1.84	0.09	13	1.74	0.04
AMIS RM 0441	2.51	0.08	12	2.44	0.113
OREAS 151b	0.06	0.02	3	0.065	0.006
OREAS 209	1.64	0.01	2	1.58	0.04
OREAS 600	0.19	0.01	2	0.2	0.006
OREAS 601	0.87	0.01	2	0.78	0.031
OREAS 602	2.04	0.04	2	1.95	0.07
OREAS 603	5.42	0	2	5.18	0.15
OREAS 604	1.42	0.08	2	1.43	0.06
OREAS 605	1.75	0.05	2	1.67	0.09
OREAS 62e	9.53	0.11	3	9.13	0.41
OREAS 6Ca	1.49	0.05	4	1.48	
OREAS 7Ca	2.53	0.01	2	2.54	
OREAS 991	45.77	0.55	3	47	0.2
Rocklabs OXA131	0.08	0.01	2	0.077	0.007
Rocklabs OXC145	0.22	0	2	0.212	0.007
Rocklabs OXD144	0.42	0	2	0.417	0.009
Rocklabs OXJ120	2.39	0.09	2	2.365	0.063
Rocklabs OXN117	7.44	0.01	2	7.68	
Rocklabs OXQ132	36.2	1.9	2	34.7	0.8
Rocklabs SF85	0.85	0.03	3	0.848	0.018
Rocklabs SH82	1.32	0.09	2	1.333	0.027
Rocklabs SK93	4.04	0.15	2	4.08	0.09
Rocklabs SN97	9.4	0.02	2	9.03	0.2
Rocklabs SP72	17.99	0.1	2	18.16	0.35
Rocklabs SQ88	40.23	0.71	4	39.7	0.9
RRM Au001	0.12	0.01	2	0.1	
RRM Au005	0.08	0.03	2	0.08	
RRM Au008	9.68		1	9.58	0.32
RRM Au009	0.41	0.02	2	0.41	0.021
RRM Au010	0.79	0.03	2	0.79	
RRM Au011	1.05		1	1.1	
RRM Au012	1.53	0.01	2	1.37	0.06
RRM Au013	9.41	0.04	2	8.94	0.35
RRM Au014	13.06	0.13	2	12.9	0.5
RRM Au015	5.01	0.09	3	4.75	0.24

Sample ID	PhotonAssay Au Mean (ppm)	PhotonAssay Au SD (ppm)	N (PhotonAssay)	Certified Fire-Assay Au (ppm)	Certified Fire-Assay Au Err (ppm)
RRM Au016	10.43	0.3	2	10.2	0.4
RRM Au017	3.24	0.13	3	3.19	0.14
RRM Au018	6.47	0.13	2	6.03	0.26
RRM Au019	10	0.15	2	9.31	0.46
RRM Au020	13.3	0.39	3	12.6	0.6
RRM Au022	2.29	0.08	3	2.2	
RRM Au024	4.3	0.07	2	3.96	0.19
RRM Au026	2.65	0.03	2	2.57	0.12
RRM Au027	3.85	0.09	4	3.63	0.17
RRM Au028	4.91	0.26	3	4.68	0.22
RRM Au029	347.9	9.8	4	322	14

Table A2. Mean PhotonAssay™ and fire-assay grades for samples analysed as a part of S3.

Sample ID	PhotonAssay Au (ppm)	PhotonAssay Au SD (ppm)	N (PA)	Fire-Assay Au (ppm)	Fire-Assay Au SD (ppm)	N (Fire-Assay)
ST_160	7.39	0.12	22	7.36		
ST_161	4.91	0.16	24	4.82		
ST_182	11.6	0.22	12	11.65		
ST_184	4.327	0.077	12	4.29		
ST_186	0.543	0.025	12	0.5		
ST_187	0.372	0.028	12	0.3		
ST_188	0.173	0.013	12	0.18		
ST_233	2.62	0.075	21	2.71	0.14	86
ST_234	5.76	0.11	22	5.65	0.22	88
ST_238	4.37	0.10	24	4.36	0.27	98
ST_247	2.118	0.095	5	2.37	0.14	100
ST_275	2.755	0.091	11	3.02	0.16	89
ST_278	4.64	0.12	24	4.55	0.17	85
ST_458	7.65	0.23	13	7.75		
ST_494	1.15	0.033	24	1.29		
ST_508	2.882	0.028	5	3.29	0.14	127
ST_519	3.144	0.083	24	3.09	0.13	144
ST_525	1.493	0.052	44	1.51	0.06	131
ST_582	1.067	0.083	37	1.04	0.11	141
ST_585	1.57	0.13	48	1.51	0.13	154
ST_586	8.94	0.85	24	8.78	2.65	158
ST_587	5.373	0.098	24	5.3	0.13	155
ST_588	1.73	0.093	22	1.6	0.08	149
ST_595	25.41	0.54	37	24.94	0.94	157
ST_601	2.111	0.063	17	2.09	0.08	163
ST_602	1.943	0.068	20	1.91	0.09	166
ST_612	1.382	0.074	24	1.37	0.04	171
ST_614	1.004	0.058	20	1	0.05	157
ST_622	2.071	0.069	24	2.04	0.07	155
ST_631	2.69	0.11	14	2.43	0.11	164
ST_632	2.007	0.076	20	1.98	0.07	170
ST_652	2.319	0.092	24	2.36	0.18	180
ST_667	2.447	0.088	24	2.31	0.1	181
ST_671	0.826	0.056	24	0.82	0.08	171
ST_672	2.371	0.064	20	2.4	0.08	173
ST_684	0.728	0.059	44	0.75	0.04	173
ST_686	0.124	0.022	19	0.14	0.02	160
ST_707	0.645	0.031	23	0.67		
ST_710	0.275	0.036	23	0.3	0.02	178
ST_718	97.2	1.6	23	97.4	1.8	32
ST_730	10.06	0.30	21	9.82	0.32	178

Sample ID	PhotonAssay Au (ppm)	PhotonAssay Au SD (ppm)	N (PA)	Fire-Assay Au (ppm)	Fire-Assay Au SD (ppm)	N (Fire-Assay)
ST_731	24.85	0.37	23	24.72	0.69	174
ST_732	4.84	0.14	27	4.98	0.2	181
ST_732AR	4.97	0.13	21	4.98		
ST_733	0.496	0.036	20	0.5		
ST_740	8.89	0.12	23	9.16	0.35	177
ST_748	1.406	0.043	23	1.4	0.05	180
ST_750	17.94	0.31	23	17.95	0.86	172
ST_764	30.61	0.35	43	30.94	0.87	169
ST_773	16.90	0.27	24	16.81	0.59	162
ST_774	11.15	0.13	24	11.03	0.37	160
ST_791	12.97	0.21	95	12.97	0.41	157
ST_792	23.93	0.37	48	23.97	0.83	162
ST_810	100.1	1.2	23	98.45	1.6	6
ST_811	5.85	0.12	24	5.93	0.15	175
ST_812	2.763	0.075	24	2.7	0.1	174
ST_813	3.974	0.090	24	3.9	0.13	172
ST_814	2.047	0.067	24	2.04	0.07	179
ST_815	1.045	0.056	47	1.05	0.04	177
ST_816	0.702	0.041	48	0.72	0.03	172
ST_817	0.294	0.030	24	0.31	0.01	159
ST_826	0.207	0.027	48	0.21	0.01	94
ST_829	0.235	0.027	24	0.24	0.01	93
ST_830	0.254	0.030	48	0.26	0.01	88
ST_831	0.763	0.041	48	0.79	0.03	172
ST_833	4.56	0.13	47	4.58	0.17	175
ST_834	1.120	0.042	24	1.15	0.15	175
SU_006	0.430	0.033	24	0.43	0.04	48
SU_009	0.595	0.049	24	0.6	0.05	48
SU_011	0.939	0.054	24	0.97	0.05	48
SU_012	1.990	0.081	24	2	0.09	48
SU_013	6.71	0.17	24	6.86	0.24	48
SU_014	8.96	0.15	24	9.27	0.28	48

Table A3. Mean PhotonAssay™ and certified fire-assay grades for samples analysed as a part of S4.

Sample ID	PhotonAssay Au (ppm)	PhotonAssay Au SD (ppm)	N (PhotonAssay)	Certified Fire-Assay Au (ppm)	Certified Fire-Assay Au SD (ppm)
CDN-CGS-26	1.633	0.062	9	1.64	0.11
CDN-CGS-30	0.325	0.012	3	0.338	0.048
CDN-CM-15	1.320	0.047	6	1.253	0.118
CDN-CM-19	2.168	0.029	6	2.11	0.11
CDN-CM-22	0.731	0.032	9	0.718	0.036
CDN-CM-27	0.649	0.025	9	0.636	0.068
CDN-CM-28	1.40	0.06	6	1.38	0.085
CDN-CM-29	0.719	0.013	6	0.72	0.034
CDN-GS-10F	10.42	0.26	9	10.3	0.19
CDN-GS-11B	10.88	0.26	9	11.04	0.44
CDN-GS-12A	12.46	0.17	9	12.31	0.54
CDN-GS-12B	12.11	0.15	6	11.88	0.285
CDN-GS-13A	13.486	0.083	6	13.2	0.72
CDN-GS-14A	14.89	0.31	6	14.9	0.87
CDN-GS-1P5R	1.793	0.058	9	1.81	0.07
CDN-GS-2T	1.819	0.062	6	1.75	0.05
CDN-GS-2U	2.128	0.092	6	2.12	0.065
CDN-GS-30	0.322	0.013	3	0.338	0.048
CDN-GS-37	37.16	0.78	6	37.39	1.22
CDN-GS-3T	3.07	0.10	6	3.05	0.095
CDN-GS-3U	3.27	0.10	6	3.29	0.26
CDN-GS-4E	4.36	0.14	6	4.19	0.19
CDN-GS-4F	3.920	0.096	9	3.83	0.12
CDN-GS-51	51.00	0.72	6	51.12	1.79
CDN-GS-5X	5.01	0.14	6	5.04	0.33
CDN-GS-6F	6.85	0.13	6	6.87	0.28
CDN-GS-7F	6.97	0.16	6	6.9	0.41
CDN-GS-7H	6.58	0.20	6	6.56	0.25
CDN-GS-7J	7.48	0.16	6	7.34	0.29
CDN-GS-8E	8.60	0.29	6	8.53	0.41
CDN-GS-9B	9.15	0.17	6	9.02	0.375
CDN-GS-9C	9.17	0.20	6	8.97	0.18
CDN-GS-9D	9.529	0.069	6	9.43	0.22
CDN-GS-P1A	0.140	0.012	6	0.143	0.004
CDN-GS-P4J	0.490	0.016	6	0.479	0.0245
CDN-GS-P5E	0.640	0.036	9	0.655	0.031
CDN-GS-P5G	0.568	0.023	6	0.562	0.027
CDN-GS-P8G	0.830	0.043	9	0.818	0.03
CDN_ME_1411	87.0	1.3	13	86.94	1.8
G312-1	1.019	0.068	6	0.88	0.09
G312-5	1.691	0.024	6	1.6	0.08

Sample ID	PhotonAssay Au (ppm)	PhotonAssay Au SD (ppm)	N (PhotonAssay)	Certified Fire-Assay Au (ppm)	Certified Fire-Assay Au SD (ppm)
G312-7	0.208	0.009	6	0.22	0.01
G313-4	1.99	0.11	6	2	0.08
G314-1	0.716	0.048	6	0.75	0.04
G314-8	1.025	0.071	6	1.03	0.04
G314-9	1.528	0.079	6	1.52	0.06
G315-2	0.972	0.032	6	0.98	0.04
G315-5	0.094	0.026	6	0.1	0.01
G316-10	4.66	0.13	6	4.65	0.27
G318-1	1.077	0.055	6	1.05	0.04
G318-5	3.88	0.10	6	3.9	0.13
G318-6	2.698	0.093	6	2.7	0.1
G318-9	1.150	0.048	6	1.15	0.05
G908-4	0.963	0.051	6	0.96	0.05
G910-10	0.987	0.024	6	0.97	0.04
G910-2	0.896	0.063	6	0.9	0.05
G910-6	3.077	0.055	6	3.09	0.13
G911-10	1.334	0.048	6	1.3	0.05
G912-7	0.391	0.031	6	0.42	0.02
G913-1	0.809	0.043	6	0.82	0.03
G913-2	2.451	0.045	6	2.4	0.08
G913-7	2.336	0.082	6	2.31	0.1
G913-8	4.888	0.099	6	4.87	0.16
G915-4	9.20	0.11	6	9.16	0.35
G916-6	31.37	0.18	6	30.94	0.87
G917-4	5.107	0.073	6	5.1	0.18
G917-6	0.773	0.034	6	0.76	0.04
G917-8	17.51	0.21	6	17.12	0.45
G918-4	1.257	0.069	6	1.24	0.05
OREAS206	2.182	0.038	6	2.2	0.08
OREAS209	1.541	0.083	6	1.58	0.04
OREAS217	0.325	0.015	6	0.338	0.01
OREAS218	0.539	0.030	6	0.531	0.017
OREAS219	0.764	0.016	6	0.76	0.024
OREAS221	1.085	0.025	6	1.06	0.036
OREAS222	1.202	0.027	6	1.22	0.033
OREAS223	1.719	0.024	6	1.78	0.045
OREAS224	2.105	0.070	6	2.15	0.067
OREAS229B	11.93	0.18	19	11.95	0.26
OREAS237	2.247	0.099	13	2.21	0.084
OREAS250	0.327	0.019	6	0.309	0.013
OREAS251	0.536	0.049	6	0.504	0.015
OREAS252	0.652	0.029	6	0.674	0.022

Sample ID	PhotonAssay Au (ppm)	PhotonAssay Au SD (ppm)	N (PhotonAssay)	Certified Fire-Assay Au (ppm)	Certified Fire-Assay Au SD (ppm)
OREAS253	1.195	0.039	6	1.22	0.044
OREAS254B	2.54	0.11	6	2.53	0.061
OREAS256	7.75	0.11	6	7.66	0.238
OREAS520	0.175	0.056	6	0.176	0.008
OREAS521	0.399	0.072	6	0.376	0.019
OREAS523	1.08	0.11	6	1.04	0.027
OREAS6CA	1.563	0.054	6	1.48	0.025
OREAS7CA	2.61	0.065	6	2.54	0.04
OREAS904	0.054	0.010	6	0.045	0.004
OREAS905	0.399	0.028	6	0.391	0.009
OXE150	0.646	0.026	13	0.658	0.03725

Table A4. Mean PAAU02U, PAAU02H and certified fire-assay grades for CRMs analysed as a part of S5. Grades that are above the recommended upper limit of the PAAU02H service are marked with brackets.

Sample ID	PAAU02U			PAAU02H			Certified FA	
	Au (ppm)	SD (ppm)	RMS Err (ppm)	Au (ppm)	SD (ppm)	RMS Err (ppm)	Au (ppm)	SD (ppm)
Geostats_GBC319-1	563	4	13	559.8		9.8	550	19
Geostats_GBC616-2	473	6.0	11	471.6		8.2	454	19
Geostats_GBC919-2	176.9	5.8	6.0	176.1		3.6	167	9
Geostats_GLC318-2	5395	110	90	(5445)		90	5429	256
Geostats_GLC318-3	3150	53	54	3129		51	3186	175
Geostats_GLC318-4	7274	64	120	(7300)		120	7193	328
Geostats_GLC319-1	3580	85	61	(3587)		58	3556	220
Geostats_GLC319-2	2169	40	39	2151		36	2158	90
Geostats_GLC916-2	1202	18	23	1202		20	1174	41
Geostats_GLC918-2	6620	82	110	(7020)		120	6577	267
CDN_ME_1411	89.0	6.4	3.9	86.5	0.7	1.8	87.1	2.6
GANNET_ST718	94.8	2.6	2.7	96.7		1.9	97.4	1.8
GANNET_ST792	23.1		1.8	24.31		0.68	23.97	0.83
GLASS_HF	85.3		3.6	85.2		1.7	83.4	1
GLASS_LF	76.8		4.0	79.3		1.7	83.4	1
GLASS_MF	76.7		3.5	79.6		1.7	83.4	1
Gannet_ST810	101.0	0.3	2.6				98.45	1.6
OREAS229B	12.5	1.3	1.4	12.30	0.32	0.47	11.95	0.288
ROCKLABS_SQ88	41.7		2.4	40.05		0.96	39.72	5.1

Table A5. Recommended PhotonAssay™ grades and measurement precisions (1-SD) for quality control charting for a variety of CRMs from CDN, Gannet, Geostats, OREAS, Rocklabs and Klen. For selected materials, the 1-SD precision and number of measurements (in brackets) for the PAAU02H high-grade service are reported in the last column

Manufacturer	Product name	Num. measurements (PAAU02 service)	Au mean	Au (SD, ppm) PAAU02	Au (SD, ppm) PAAU02H
CDN	CDN-ME-1411	6624	86.7	1.4	2.4 (138)
GANNET	ST484	373	7.41	0.13	
GANNET	ST588	296	1.638	0.058	
GANNET	ST620	205	46.93	0.70	0.93 (39)
GANNET	ST643	318	4.97	0.10	
GANNET	ST718	34	96.8	1.4	
GANNET	ST792	33	24.29	0.61	
GEOSTATS	G319-9	21	99.1	1.5	1.8 (100)
KLEN	73988	328	14.32	0.22	
KLEN	74282	303	25.84	0.38	
KLEN	76905	138	109.8	1.5	2.1 (29)
OREAS	220	26	0.861	0.038	
OREAS	223	22	1.730	0.039	
OREAS	224	213	2.133	0.066	
OREAS	228B	34	8.61	0.21	
OREAS	229B	6023	11.91	0.23	
OREAS	237	5706	2.231	0.071	
OREAS	501C	525	0.224	0.031	
OREAS	502C	549	0.491	0.036	
OREAS	602	34	1.997	0.056	
OREAS	605B	34	1.819	0.081	
OREAS	60D	34	2.459	0.071	
OREAS	62F	515	9.78	0.19	
ROCKLABS	HISILP3	34	12.35	0.27	
ROCKLABS	OXD151	34	0.433	0.030	
ROCKLABS	OXE143	119	0.615	0.030	
ROCKLABS	OXE150	5569	0.649	0.032	
ROCKLABS	SF100	10	0.869	0.026	
ROCKLABS	SF85	23	0.841	0.038	
ROCKLABS	SQ88	34	40.33	0.54	

Table A6. Mean PhotonAssay™ grades and certified fire-assay grades of low-grade CRMs analysed as part of S6. 2-cycle data is extracted from the 8-cycle PhotonAssay™ measurement.

Manufacturer	Product name	No. of Measurements (PAAU02)	PhotonAssay			Certified FA	
			Au mean	Au (2 cycle SD, ppm)	Au (8 cycle SD, ppm)	Au (ppm)	SD (ppm)
GEOSTATS	GLG304-1	192	0.146	0.016	0.008	0.154	0.017
GEOSTATS	GLG305-3	384	0.054	0.012	0.006	0.055	0.006
GEOSTATS	GLG310-5	384	0.076	0.018	0.010	0.082	0.010
GEOSTATS	GLG314-3	192	0.100	0.017	0.008	0.103	0.007
GEOSTATS	GLG904-4	192	0.193	0.019	0.010	0.204	0.020
GEOSTATS	GLG920-5	384	0.021	0.010	0.005	0.019	0.003
OREAS	230	192	0.322	0.024	0.013	0.323	0.024
OREAS	264	192	0.312	0.038	0.017	0.314	0.033
OREAS	684	192	0.246	0.022	0.012	0.248	0.014