RUBEN ALCALDE MARTÍN [1]*, ISIDRO DIEGO [1],
CESAR CASTAÑÓN [1], TERESA ALONSO [1]

A GRADE CONTROL METHOD WITHOUT SAMPLING PREPARATION BASED ON SPECTROMETRIC TECHNIQUES AND THE USE OF ELECTRONIC DETONATORS IN AN OPEN PIT TUNGSTEN DEPOSIT

Grade control is crucial for ensuring that the quality of extracted ore aligns with the geological model and mining plan. This process optimises production, reduces dilution, and maximises profits. It involves geological modelling, sampling, assaying, and data analysis. However, adhering to short-term planning in mining operations can be challenging due to operational bottlenecks that arise during the grade control process and blast design, along with their associated costs. Industry standards for grade control require acquiring extensive information and knowledge to achieve a high level of certainty, which takes time. Despite that, time constraints may necessitate making decisions under risk with incomplete information. In such cases, it is important to consider the opportunities, risks, likelihood, consequences, and potential success associated with each alternative. This study presents the testing results of alternative quantitative analytical methods on samples from the Barruecopardo tungsten deposit in Spain. Spectrometric techniques, including Delayed Gamma Neutron Activation Analysis (DGNAA), Laser-induced Breakdown Spectroscopy (LIBS), and Field Portable X-ray Fluorescence (FPXRF), were employed to determine the tungsten content. Based on the findings of this investigation, a real-time decision-making tool for grade control in open-pit mining has been developed. This tool utilises representative samples directly from the blasting debris, considering the inherent risks and uncertainties associated with the process.

Keywords: Spectrometry; Geostatistics; Open Pit; Tungsten; Sample Preparation; Grade Control

1. Methodology and introduction

Metallic mine deposits are highly variable in terms of the distribution of the ore within them. The ore is disseminated in pockets of varying grades, meaning that certain areas contain higher concentrations of valuable minerals than others. According to Runge [1], a high-grade

1　OVIEDO UNIVERSITY, OVIEDO SCHOOL OF MINES, SPAIN

*　Corresponding author: rubenalcalde@gmail.com
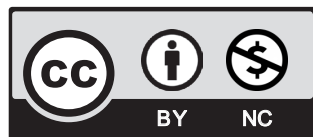
ore deposit can be uneconomical to mine if the reserves are low and the distribution of the ore within the deposit is highly variable.

The bench blasting method is used in most open pit mines to allow the predetermined rock mass volume removal.

Grade control in open pit mines involves the process of ensuring that the quality of the ore being extracted is consistent with the geological model and mining plan. This step is critical for optimising production, minimising waste, and maximising profits and requires a combination of geological modelling, sampling, assaying, and data analysis, which takes time.

Anyone who has been involved in a mining operation knows how difficult it is to avoid non-compliance with the established short-term planning. One of the main reasons is the operational bottleneck created during the grade control process and its consequent blast design.

Following Minnith [2], current grade control industry standards are making decisions by acquiring large amounts of information and knowledge to reach a certain level of certainty, requiring time for this purpose.

Due to the lack of time available for any other reason, it is possible to make decisions at risk of having incomplete information when knowing the opportunities and risks associated, the likelihood and consequences of each alternative, and the likelihood and extent of the success.

During the development of this work, alternative quantitative analytical methods were tested on samples from the tungsten deposit at Barruecopardo, located in Salamanca, Spain.

These analytical methods are based on spectrometric techniques, and they are used to study their feasibility to determine the tungsten content: Delayed Gamma Neutron Activation Analysis (DGNAA), Laser-induced Breakdown Spectroscopy (LIBS) and Field Portable X-ray Fluorescence (FPXRF) (Fig. 2).

Testing with Laser-induced breakdown spectroscopy (LIBS) technology was conducted on pulverised (tungsten grade known) samples from exploration drill core intercepts following procedure by Llamas [3] and Alvarez-Llamas et al. [4] and using the experimental LIBS analyser available in the Mieres Polytechnic School (Spain). Delayed Gamma Neutron Activation Analysis (DGNAA) was tested using an experimental analyser located in the Oviedo School of Mining, Energy and Materials Engineering (Spain) and basing the procedures on the previous works of Rey Ronco [5] and Castro García [6].

LIBS and FPXRF techniques were tested on samples directly from blasting detritus, following Hussain and Gondal's procedure [7]. The samples were not previously prepared and had a lower grade than pulverised ones. Glanzman et al. [8] describe the contributions to onsite real-time project evaluation of FPXRF.

As Engström et al. [9] indicate, with so many mineral commodities and mining methods in use globally, there is no universal best practice for open pit drill sampling, and each case must be evaluated individually.

As the possibility of future outcome is anticipated, the objective of this work is to develop a real-time decision-making tool applicable to open pit mining, using representative samples directly from the blasting debris in the grade control activity. In the mining industry, it is increasingly common to make decisions under an acceptable range of uncertainty as Khan et al. [10] have proposed a method based on a cut-off grade optimization model that accounts for the grade uncertainty and maximises the net present value subject to the production capacity constraints over the life of the operation.

The handheld data will be used to interpolate the different values obtained using software R and then import its results to blasting software RIOBLAST.

Maxam´s blasting software (RIOBLAST) is designed to assist with the planning, optimisation, and execution of blasting operations, helping engineers and technicians to design blast patterns, calculate blast parameters, and predict blast outcomes. It incorporates advanced algorithms and modelling techniques to optimise fragmentation, vibration control, and safety. As Miranda et al. [11] explain, RIOBLAST designs the position and explosive loads of each borehole in a blast, as well as the initiation procedure, depending on factors such as the direction of the blast output or the required fragmentation.

Fig. 1. Panoramic view of Barruecopardo tungsten deposit Feb-2020 (www.saloro.com)

2. Results

In the first experimental phase, seven pulverised samples (Fig. 3) with known grades were used, having been previously analysed in an external laboratory by the conventional X-ray fluorescence (XRF) method, covering values between 0,340% and 11,829% of tungsten trioxide (WO_3). LIBS and DGNAA methods were employed during this phase.
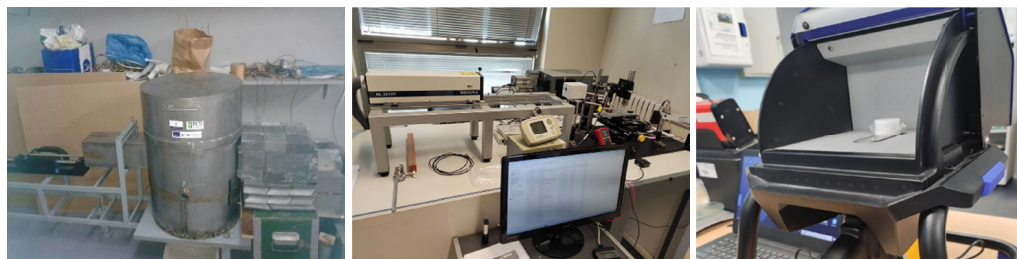

Fig. 2. Equipment used in this study: DGNAA (left), LIBS (centre), FPXRF (right)

The second phase was finalised using nine additional representative samples coming directly from the blast hole detritus. After conducting a granulometry analysis on each sample and selecting subsample of medium – coarse fraction, measurements were first taken using the LIBS method, followed by FPXRF. Once the necessary data was obtained, they were sent to the laboratory for

analysis, being pulverised and using the XRF method, delivering values between 0.004% and 0.971% of WO_3 (TABLE 1).

Tungsten samples used in the two experimental phases

Phase	Hole	Sample	WO_3 (%)
1 (Pulverised)	A	1	0,340
		2	0,782
	B	3	2,194
	C	4	3,443
		5	6,444
	D	6	11,224
		7	11,829
2	E	8	0,004
	F	9	0,005
	G	10	0,025
	H	11	0,072
	I	12	0,175
	J	13	0,200
	K	14	0,219
	L	15	0,339
	M	16	0,971

Fig. 3. Sample 3, pulverised (left) and Sample 12, without preparation (right)

2.1. DGNAA

There are public databases that will provide an orientation of where to focus the efforts on the measurements that will be made in the laboratory.

Delayed gamma neutron activation analysis is the nuclear system used for determining the elemental concentration of elements in many types of samples. It is based on the detection of gamma radiation produced by the bombardment of a sample with neutrons. This radiation is characteristic of the atomic nucleus and is independent of the state of the sample.

To get started by studying the reactions produced between the stable isotopes of the tungsten sample and the neutrons emitted by the radioactive source (TABLE 2).

TABLE 2

Stable isotopes of tungsten

Nuclide	Abundance (%)
$^{180}_{74}W$	0,13
$^{182}_{74}W$	26,3
$^{183}_{74}W$	14,3
$^{184}_{74}W$	30,67
$^{186}_{74}W$	28,6

After the bombardment, the delayed gamma rays were analysed to identify their characteristics. The following databases are available:

- EXFOR (Experimental Nuclear Reaction Data), where an extensive library of nuclear reaction experiments is compiled. Information is obtained about the effective sections of the isotopes as a function of the neutron energy, which can be represented using the viewer provided by the ZVView software [12].
- NUDAT (Nuclear Structure and Decay Data), which allows searching and obtaining graphical representations of structures and radioactive decay from various databases. It has been developed by the United States National Nuclear Data Center (NNDC) at Brookhaven National Laboratory [13].

Regarding the laboratory work, with the seven pulverised samples with known tungsten content, a sample that was used as a blank using a cyclic neutron activation spectrometric equipment that has a 1 Curie (Ci) Americium Beryllium radioactive source of activity.

To carry out the experimental phase, an automated displacement equipment was used, which allows the sample to be moved and exposed for a given time in front of the source and later in front of the detector. The methodology and instrumentation used are described by Ronco [5]. Using the "Gamma Acquisition & Analysis" software, it is possible to capture the spectrum corresponding to each activation and reading time.

Four experiments are carried out with an irradiation and reading time of 100, 200, 300 and 900 seconds each. 5 exposures to the neutron source are made.

It was verified that the intensity (pulses) registered throughout the spectrum is directly proportional to the reading and exposure times used in the experiment.

In the channels where there is a good correlation, there is no visible peak due to the blank introduced in the experiment, and the proportionality is direct or inverse depending on the experiment.

2.2. LIBS

Using the Laser-induced Breakdown Spectroscopy analytical method, two phases of tests were conducted, which are described below.

First Phase:

An Nd:YAG laser NL301HT from EKSPLA has been used to generate high energy 4.5 ns laser pulses at 1064 nm. The signal is collected by a Czerny-Turner spectrometer Shamrock SR-500i-D1 from Andor Technology and registered by an iCCD (intensified Charge-Coupled Device) camera Andor iStar. The samples are displaced to avoid incising twice on the same point with a Newport TRA25CC positioner.

To determine the most interesting wavelengths, the database NIST (National Institute of Standards and Technology) [14] and OSCAR (Optical Science Center for Applied Research) were used, consulting the pure standard emission data along the spectrum using the LIBS technique.

To identify the optimal wavelength on which to base the work, 138,600 shots (300 shots per sample, 2 repetitions, 33 spectra, 7 samples) were necessary in this phase.

Once the 484,31 nm channel, where tungsten emits without interference from other elements, has been chosen due to the excellent correlation (Fig. 4) has been obtained ($R2 = 0,9937$)
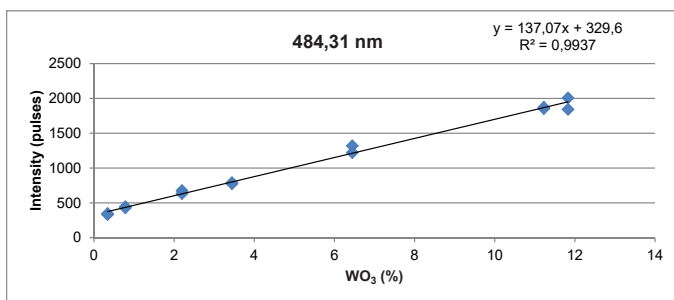

Fig. 4. Regression line at 484,31 nm

Second Phase:

In this phase, 7 repetitions were carried out on each of the 9 samples, and in each repetition, 20 shots were carried out, resulting in the accumulated value of all of them.

Another crucial difference between both phases is that the first took information from the entire spectrum, and the second only focused on the environment of the optimal channel for the existing mineral matrix in the sample of the deposit to be studied (484,31 nm).

Despite carrying out the summation of the intensity of 20 shots, as it contains little concentration of tungsten and the sample is not homogenised, the results were very poor. Only in 6 of 63 spectra analysed was the tungsten peak detected in the chosen channel.

2.3. FPXRF

Due to the poor results obtained by the LIBS method for tungsten samples of low grades and without previous preparation, it is decided to carry out a new test. This time, a less novel method in the mining industry is used, but it delivers results practically in real-time.

The field portable analyser XRF of the OLYMPUS brand, model VANTA of the C series, was used in the data acquisition using the samples without preparation in the second phase of the experimental stage of this paper.
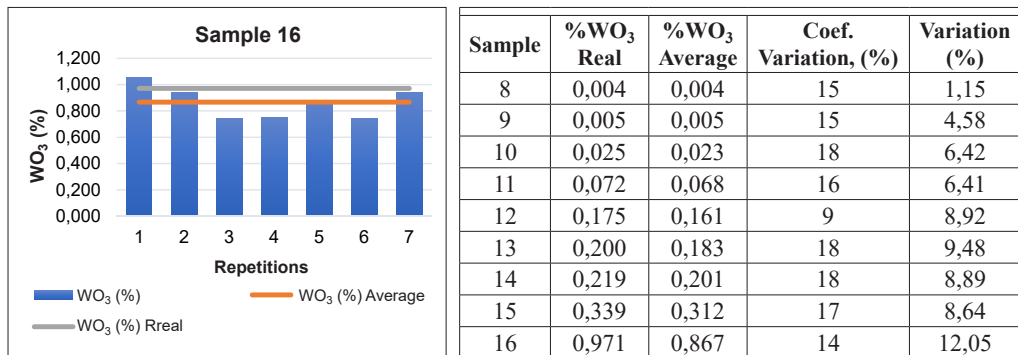
The analyser was calibrated using the GeoChem 2 Beam method, previously correcting the matrix effect with samples of known composition.

As shown in TABLE 3, only in 7 repetitions of the FPXRF analytics on unprepared samples, the maximum percentage variation between the real grade of the sample and the average of the seven measurements was 12,05%, while the minimum variation was 1,15%. Furthermore, a comparison can be made between the real tungsten content in the sample and the average of the seven measurements. The coefficient of variation indicates that the measurements obtained in each experiment do not significantly differ from the average.

To aid comprehension, a graph illustrating the results obtained with sample 16 accompanies the TABLE 3.

TABLE 3

Statistic analysis of the 7 measurements to each low-grade sample without preparation

Sample	$\%WO_3$ Real	$\%WO_3$ Average	Coef. Variation, (%)	Variation (%)
8	0,004	0,004	15	1,15
9	0,005	0,005	15	4,58
10	0,025	0,023	18	6,42
11	0,072	0,068	16	6,41
12	0,175	0,161	9	8,92
13	0,200	0,183	18	9,48
14	0,219	0,201	18	8,89
15	0,339	0,312	17	8,64
16	0,971	0,867	14	12,05

Depending on the urgency of the blast to be fired and the intention to start the ore loading and hauling to the ROM crusher, the following methodology is proposed using the values obtained from the FPXRF when analysing a sample without preparation in the grade control process, as is described in the following section.

3. Conclusions

The following section intends to present an innovate methodology for performing grade control tasks in an open pit mine when there is restricted timeframe to apply the current industry method. A generic methodology is proposed to be explored in each unique mining project. Finally, the concluding remarks of this study are provided.

3.1. Proposed methodology for grade control

A methodology was developed to perform grade control using a mineral deposit generated by conditional simulation as a model. Grade control is crucial in metallic mines as it involves separating ore from waste in each of the blasts based on sampling data obtained from drill holes. Acquiring accurate and reliable data is challenging, as the economic success of the mine operation relais on it. To obtain data, to perform this research and to control the way the grade

is distributed over the bench, a conditional simulation will be used to generate the deposit that will be sampled to be studied.

Then, both Inverse Distance Weighting (IDW) and Kriging will be used to apply the grade control methodology. The deposit generated by conditional simulation and the geostatistical techniques used to perform the grade control will be made in R, using RStudio as the frontend and RGeostats [15] as the main calculation libraries (Center for Research in Geosciences of the Paris School of Mines, MINES Paris Tech).

The geometry of the bench and the drill holes position ("collar") provided by the surveyors and available in Maxam software RIOBLAST, are exported as an ASCII file with XML [16] structure, which can be easily imported into RStudio (Fig. 5) for further analysis and implementation of the grade control methodology.
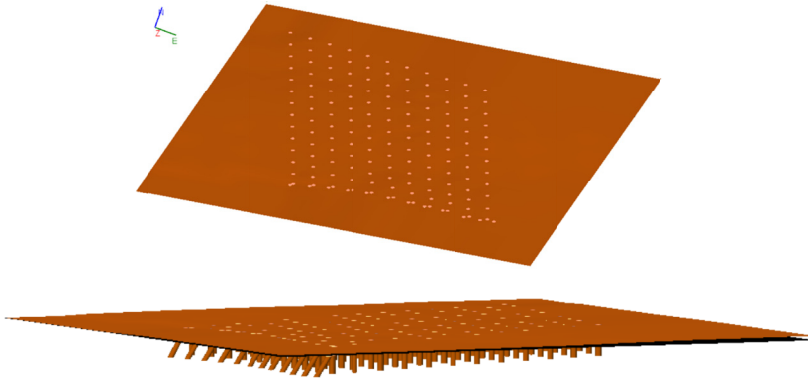

Fig. 5. Views of the blasting pattern (RIOBLAST)

Using RStudio as the front end, a polygon is digitised surrounding the boreholes, and that will conform the simulation area. Inside this polygon, a 200×200 two-dimensional mesh is created, totalling 40,000 calculation points (Fig. 6), stored as a db object in the notation of the RGeostats library.

To demonstrate that this method is useful for any metallic deposit, an advanced three-dimensional interpolation tool, conditional simulation as Dimitrakopoulos procedure [17], will be used to generate an ore body, assigning the pseudorandom values of metallic content to the drill holes samples, both negative and positive, eliminating the first values. The grade values, while randomised in origin, follow a variogram pattern that must be established (Fig. 7, left). In this case, a theoretical range of 40/30 will be used, with main mineralisation occurring at bearing 45°. The conditional simulation generated the grades for each node in the database, representing the simulated deposit (Fig. 7, right).

From now on, the work will continue as this simulated data is from a real deposit. A routine has been programmed to extract the grade in the hole locations, thus generating the sampling data.

The data obtained from the sampling of the boreholes is analysed by calculating the variogram. Lag values and their number must be selected to obtain the most useful variograms. After several attempts, 10 lags at 5 metres are selected as the best option. The sampling data shows an omnidirectional variogram, as shown below (Fig. 8).
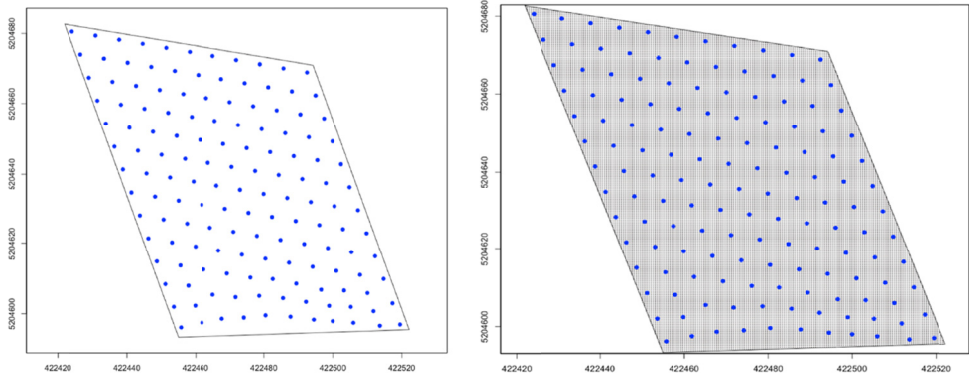
Fig. 6. Plan view of the coordinates of the holes (left) and Plan view of 200×200 two-dimensional mesh (right)
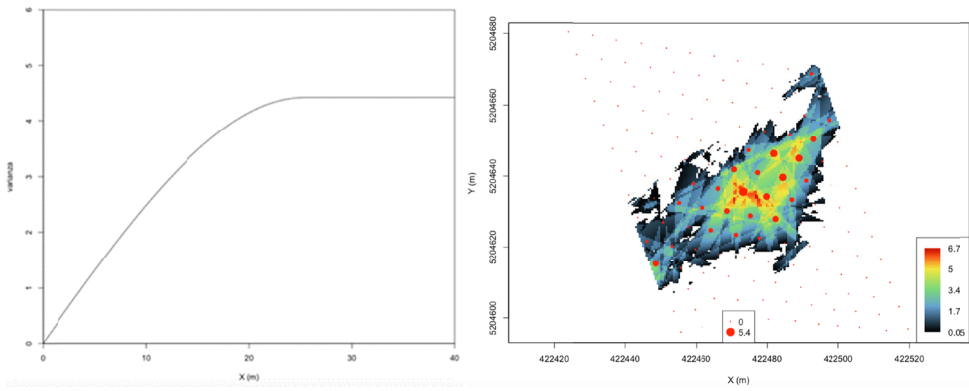

Fig. 7. Theoretical variogram pattern (left) and Bench sampling generated by conditional simulation (right)
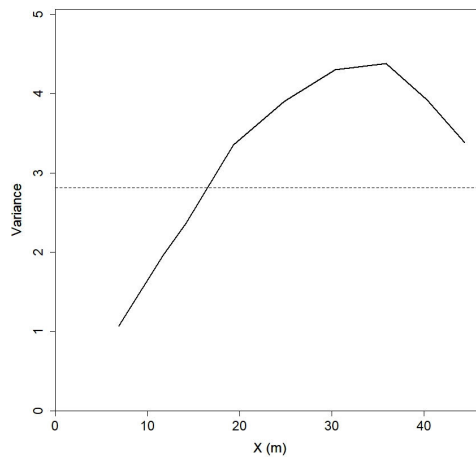

Fig. 8. Omnidirectional variogram for the sampling data of the simulated deposit

From the omnidirectional variogram we can observe a plateau at about 30 metres.

Variograms are calculated in several directions, searching for anisotropy. It is found with a preferred mineralization direction of 45°. This variogram is automatically adjusted by RGeostats, generating a theoretical variogram that will be used to interpolate (Fig. 9).
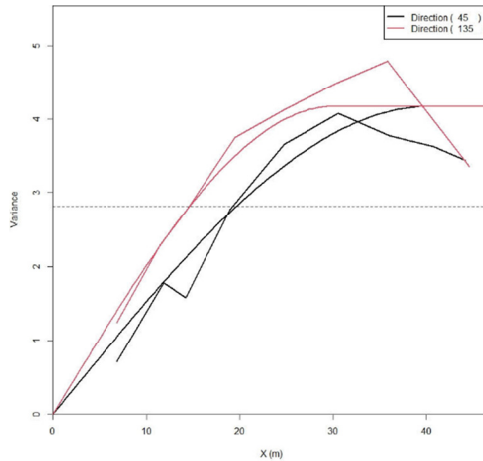

Fig. 9. Variogram in two directions (black, 45° direction; red 135° direction, corner shaped lines) and its automatic adjustment (black, 45° direction; red 135° direction, smooth shaped lines)

The observed anisotropy is defined with a direction of maximum continuity at heading 45 and minimum continuity at 135, with respective ranges around 40 and 30 metres.

Based on the geostatistical information obtained, an interpolation will be made by the inverse of the distance, IDW; and by using kriging with anisotropic values of radius 40/30 m. The kriging data is used to calculate grade contours at 0.5 and 1.0 values (Fig. 10).

Several methods can be used to infer the grades of the whole bench from the borehole samples. While the nearest-neighbor interpolation method is commonly used, Amadu et al. [18] discovered that the inverse distance weighting method with an exponent of 2 is more effective than the nearest neighbour method. Additionally, Vasylchuk and Deutch [19] recommend using kriging for this work.
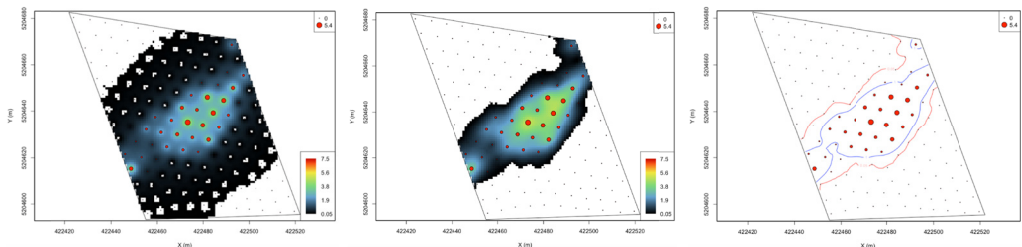

Fig. 10. Interpolation results using IDW (left), Kriging 40/30 m (centre) and contours of samples of the kriging interpolation data at two cutoff grades (right)

For this study, and to simplify the values of the different grades under study, it is considered 0.5% WO_3 as the cut-off grade, which is not a conventional grade for this type of deposit. This decision has been made to explain the method and not think of a single deposit where this methodology will be applied. Each deposit is unique, and the grade values to be studied will be provided by the corresponding economic studies.

Based on the results obtained and taking advantage of the criteria of an experienced grade control geologist in the deposit under exploitation, and with the help of the grade contours at 0.5 and 1.0 values referred to above, the final contours of areas that are considered ore can be easily created digitising over the image, and taking into account other considerations as the minimum selectivity values (related to the size of the loading machinery) and the cost of the earth movement. The result is shown in the yellow polygon in the image below.
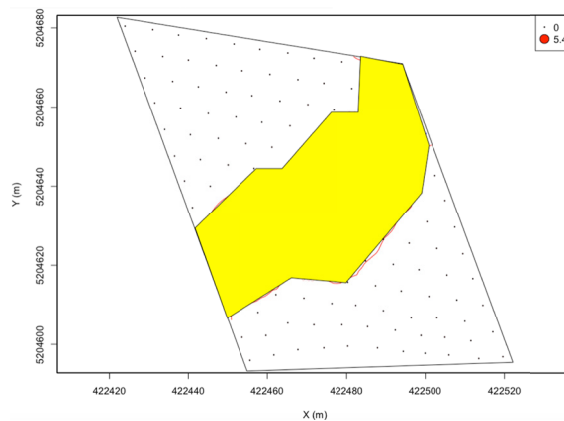

Fig. 11. Digitised polygon created following interpolation results

These polygons are saved in ASCII format and are easily accessible from other software. In Fig. 12, the digitised ore area imported to RIOBLAST software from R is illustrated above. Below, the ore and waste areas that have been defined and will be used for programming the blast using electronic detonators, are shown.

Designing, programming and testing electronic detonators for blasting involves the use of specialised software and hardware to design and control the detonation process.

At this stage, it is considered essential to have an experienced technical team that designs blasts with electronic technology in a precise manner, considering the peculiarities of the blasting bench.

In the blast design, the selection of explosive materials and the proper placement and sequencing of the charges are crucial. This task is typically performed using dedicated software. For this study RIOBLAST software developed by Maxam was utilized.

The muck pile movement or Heave process deals with the description of the motion of the fragmented material under the action of the pressure in the explosive gases and gravity. A good understanding and control of the muck pile movement is crucial for the control of the direction of throw of the blasted material, adequate geometrical shape for digging and haulage systems, ore dilution/loss control, ground vibration control, fragmentation, and wall control, as Domingo
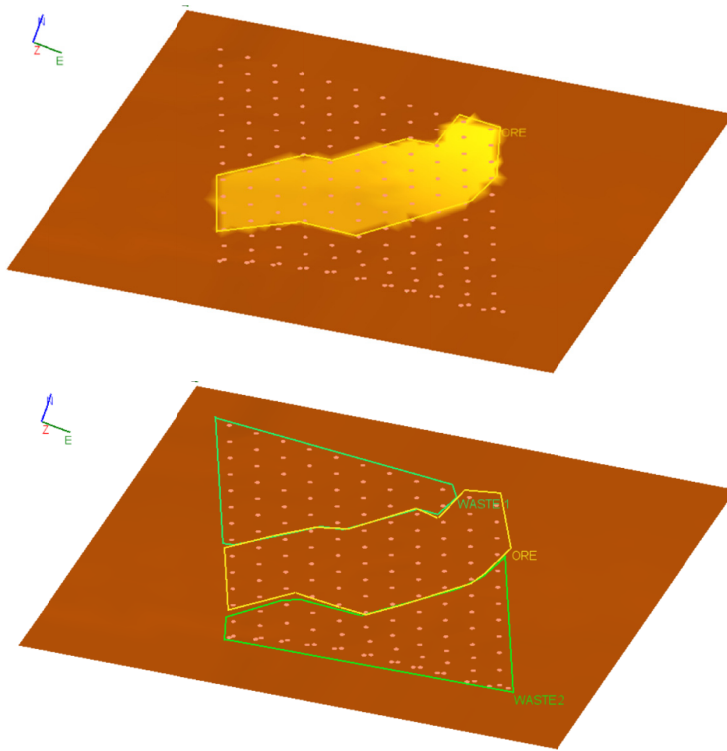
Fig. 12. Ore polygon imported from R into RIOBLAST (above) and ore/waste polygons defined in RIOBLAST (below)

et al point out [21]. With electronic detonator technology, it is possible to predict the movement of the muck pile correctly, sequencing the areas of interest previously obtained.

To successfully execute any blast using electronic detonators, and to maximise the effectiveness of the proposed tool, a brief procedure is described to guide the programming, tie-up, and testing activities.

For safety and operational standards, field programming should occur after all holes in a path are charged and stemmed. This approach allows the programmer to complete the entire path on the first attempt, reducing the risk of errors such as missing holes ore or scanning holes from another path

Before programming begins, the programmer must identify the first hole accurately, and the boundaries of the path should be demarcated with coloured ribbon, paint, or any visible maker.

As the pegs of each drill hole are not always accurate due to displacement during the drilling and explosive charge stages, the programmer needs to be able to reference adjacent holes to correctly follow the path. A digital map on the Planner and a paper copy showing Hole ID and Delay Time should be used for guidance.

The tie-up is best performed after programming is complete to prevent unnecessary damage to the harness wire and connector from activities on the bench and to prevent creating a tripping hazard for the programmer.
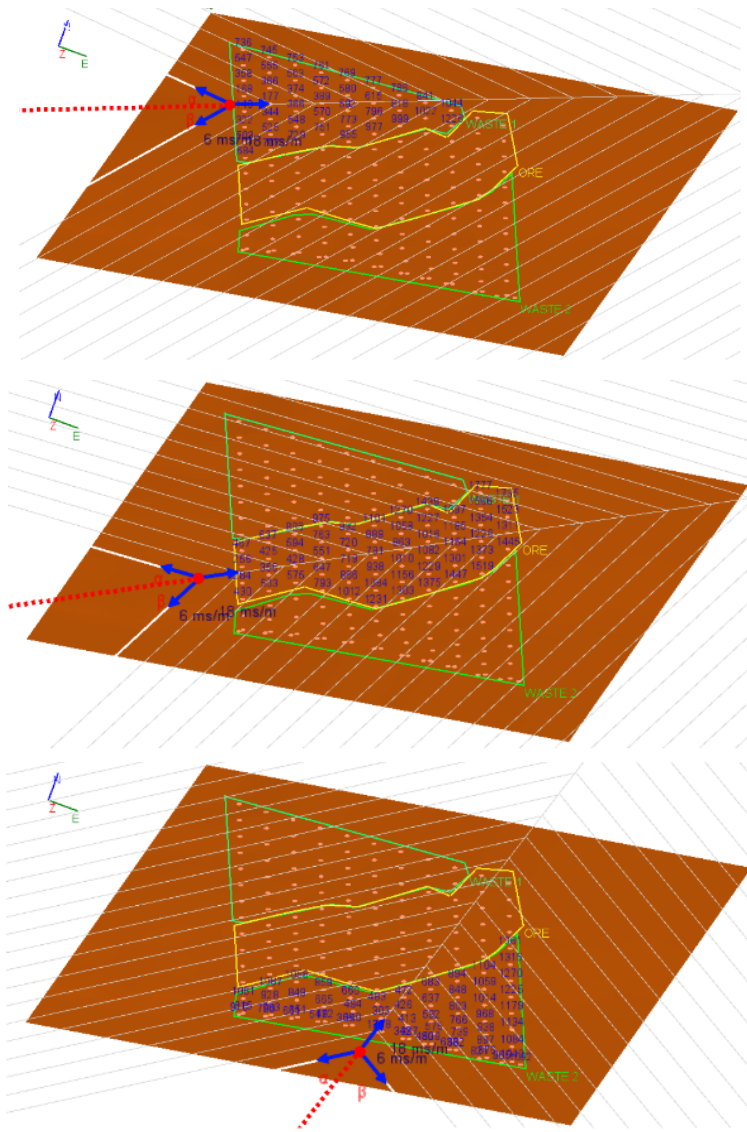
Fig. 13. Different paths (ore/waste) independently sequenced by electronic detonators technology

Connections should be isolated from wet conditions (out of puddles and mud), and all splices must be covered with insulation tape.

Line Tests with the Logger should be continuously performed during the entire tie-up process, with one person observing the current consumption to identify potential leakage sources immediately.

Testing needs to be given sufficient time so that troubleshooting can occur without rushing. Line Test must be performed first, and the current measurement should be less than mA

consuming for the total detonators connected plus the mA allowable leakage provided by the manufacturer.

Communication testing should be performed next. If any missed or duplicate detonators are detected, an investigation must be carried out to correct them if possible.

3.2. Final considerations

This line of research was motivated on the lack of time to apply the conventional methodology and not in economic terms to reduce operational costs. The mine must have enough open exploitation areas to allow waiting the required time for the sampling, its analysis in the laboratory and blasting.

The analysis by the LIBS technique applies to mining samples if previously prepared by reducing the particle size since it is a surface analysis method but offers poor results if the sample is not pulverised. It is recommended to extend this study to analyse the whole spectrum using the pulverised low-grade samples. With this type of sample, only the selected wavelength resulting from the pulverised high-grade samples was studied.

The handheld XRF technique has demonstrated an acceptable accuracy in measuring the content of $\%WO_3$ in samples without preparation, presenting dry conditions due to the storage time of the samples before carrying out the experiments with them. The coefficient of variation between the value obtained and the real one can be used to determine the risk of the decision offered by the tool proposed.

However, the satisfactory results must be verified with the handheld XRF method with the sample presenting humidity conditions to simulate normal operating conditions in the pit.

The risk assumed in the analytical stage can be easily mitigated by a skilled grade control geologist with extensive knowledge of the deposit and a proper sequencing blasting designed using electronic detonator technology.

Achieving a better understanding of the muckpile movement is crucial for the control of the direction throw of the blasted material. This is especially critical for ore dilution and loss control. The above is only possible if electronic detonator technology is implemented in the operation.

Obtaining a truly representative sample from the detritus of a drill hole can be challenging, as there can be significant variability in its composition. A methodology for rapidly obtaining a representative sample from each hole should be developed for each deposit individually. When quantifying an element's content with low grade and high density, a larger sample size and proper homogenisation are required to avoid the nugget effect.

This study has not considered a precise adjustment of the grades of interest in the deposit. Cut-off and grade classification must be defined depending on the strategy of each operation and the commodity's current and forecasted price. FPXRF analyser must to be calibrated to reach the maximum accuracy in the closer range of the cut-off grade so that it can discriminate what is waste from what is ore.

The robustness and performance of the proposed methodology must be validated for each specific deposit and operation, evaluating the impact of its implementation on the economics of the project.

The proposed method has been successfully implemented and tested in Maxam software (RIOBLAST). However, due to its simplicity, it can be effectively used with other software developed by industry competition.

References

[1]   I.C. Runge, Mining economics and strategy. Society for Mining, Metallurgy, and Exploration, Littleton, Colorado (1998).

[2]   R.C.A. Minnitt, Sampling: the impact on costs and decision making. J. S. Afr. I. Min. Metal. **107** (7), 451-462 (2007). https://www.saimm.co.za/Conferences/AnalyticalChallenges/13-Minnitt.pdf

[3]   C. Alvarez-Llamas, PhD thesis, Desarrollo de instrumentación y metodologías innovadoras basadas en libs para el análisis de muestras geológicas y forenses. Oviedo University, Spain (2017).

[4]   C. Alvarez-Llamas, J. Pisonero, N. Bordel, A novel approach for quantitative LIBS fluorine analysis using CaF emission in calcium-free samples. J. Anal.-Atom. Spectrom **32** (1), 162-166 (2017). DOI: https://doi.org/10.1039/C6JA00386A

[5]   M.A. Rey Ronco, PhD thesis, Desarrollo de un método rápido basado en técnicas de activación neutrónica para la determinación del contenido de flúor en muestras de mineral de fluorita. Oviedo University, Spain (2007).

[6]   M.P. Castro García, PhD thesis, Activación neutrónica cíclica para la determinación del contenido en flúor de muestras de mineral de fluorita. Oviedo University, Spain (2016).

[7]   T. Hussain, M.A. Gondal, Laser induced breakdown spectroscopy (LIBS) as a rapid tool for material analysis. J. Phys. Conf. Ser. **439** (1), 012050 (2013). DOI: https://doi.org/10.1088/1742-6596/439/1/012050

[8]   R.K. Glanzman, L.G. Closs, B. Milkereit, Field portable X-ray fluorescence geochemical analysisits contribution to onsite real-time project evaluation, Proceedings of Exploration, Fith International Conference on Mineral Exploration **7**, 291-301 (2007)

[9]   K. Engström, K.H. Esbensen, Optimal grade control sampling practice in open-pit mining – a full-scale blast hole versus reverse circulation variographic experiment. Trans. Inst. Min. Metall. B, **126** (4)176-87 (2017). DOI: https://doi.org/10.1080/03717453.2017.1414104

[10] A. Khan, S. Sapuan, A method for optimal cut-off grade policy in open pit mining operations under uncertain supply. Resour Policy **60**, 178-184 (2019). DOI: https://doi.org/10.1016/j.resourpol.2016.05.005

[11] V. Miranda, P. Couceiro, J. Blazquez, Rioblast: Software de diseño y simulación de voladuras en entorno 3D. IV In Congreso Nacional de Áridos. Madrid, Spain.

[12] https://www-nds.iaea.org/exfor/

[13] https://www.nndc.bnl.gov/nudat2/

[14] https://physics.nist.gov/PhysRefData/ASD/https://oscar.desu.edu/libs/

[15] http://rgeostats.free.fr/, acceso 1/10/22

[16] https://www.w3.org/TR/xml/, acceso 1/11/22

[17] R. Dimitrakopoulos, Conditional simulation algorithms for modelling orebody uncertainty in open pit optimisation. Int. J. Surf. Mining. Reclam. Environ. **12**, 173-179 (1998). DOI: https://doi.org/10.1080/09208118908944041

[18] C.C. Amadu, S. Owusu, G. Foli, B.A. Brako, S.K. Abanyie, Comparison of Ordinary Kriging (OK) and Inverse Distance Weighting (IDW) Methods for the Estimation of a Modified Palaeoplacer Gold Deposit: A Case Study of the Teberebie Gold Deposit, SW Ghana. Malay. J. Geos, **6** (1), 19-28 (2022). DOI: https://doi.org/10.26480/mjg.01.2022.19.28

[19] Y.V. Vasylchuk, C.V. Deutsch, Improved grade control in open pit mines. T. I. Min. Metall. A. **127** (2), 84-91 (2018). DOI: https://doi.org/10.1080/14749009.2017.1363991

[20] J. Domingo, F. Leite, V. Mirada, I. Carrasco, Dilution, ore grade and blast movement calculation model. Proceedings of 11th International Symposium on Rock Fragmentation by Blasting, FRAGBLAST **11**, 71-78 (2015).