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Mineral resource estimation for a placer gold deposit in Cordón Baquedano mining district, Tierra del Fuego, Chile (54°S)

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ABSTRACT

The genesis of gold placer deposits is related to different superficial processes, having varied characteristics and complex mechanisms of mineral concentrations. They are often exploited by medium to small-scale miners, with high geological uncertainty and/or without proper geological characterisation. This represents a difficulty for mineral resource estimation, and usually simpler geometric methods are employed. The Cordón Baquedano Gold Mining District (CBGMD) in southernmost South America has been a source of detrital gold for over a century. Some attempts of industrialised mining occurred but without success. Furthermore, the existing metallogenic models are over 30 years old and do not represent the complexity and variety of the deposits found in the district. This research follows the common practices for mineral inventory estimation to create a resource model for the Mina Nueva Deposit (MND) in the CBGMD. Mineralisation and resource models are proposed by using traditional and geostatistical methods. The results of this study indicate that the gold resources in the MND varies from 8,070 to 10,730 ounces using newly acquired dataset, and from 16,720 to 18,280 ounces for a database that incorporates new and historical information. This illustrates the great complexity and variability of results when estimating mineral resources within placer gold deposits in this area.

HIGHLIGHTS

- Modern resources estimation and categorisation methodologies applied to placer gold deposits
- Estimated gold resources vary from 8,070 to 18,280 ounce depending on the used dataset and methodology
- The study highlights the complexity of estimating mineral resources within placer gold deposits

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1. Introduction

In artisanal and small-scale mining, the exploration, geological characterisation, and resource estimation of mineral deposits are usually precarious or non-existent [1–3]. This can produce an inefficient design and planning of the exploitation of mineral resources and lead to scarce introduction of technologies to optimise the extraction and processing of the ore [1,4,5]. Moreover, this

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situation threatens the sustainability of the business by i) preventing an adequate financing estimation during the initial steps of development; and ii) attaining poor economic, environmental, and social results during the operational stage [6–11].

This problem escalates in the case of placer gold projects due to their inherent/natural characteristics since the mineralisation mechanisms are complex and variable [12–15]. Moreover, in the exploration and evaluation stages of development, usually basic sampling and interpolation methods are used for the estimation of mineral resources and other variables of interest (e.g. gold concentration, sediments particle size distribution, presence of clays, etc.) [16]. Additionally, there is a lack of new technical knowledge regarding exploration and exploitation of this kind of deposits, since they are mostly developed by artisanal and small miners, and a mismanagement of the environmental and social impacts exists due to the scarce inspection of this activity by competent authorities [11,17–19].

Gold placers are a type of mineral deposit whose genesis is related to weathering and erosional processes that allow the mechanical, and sometimes chemical concentration of gold particles in soils or sediments [20,21]. These deposits present different characteristics depending on the origin of the mineralisation, the weathering and erosional processes, and transportation and deposition mechanisms involved in their genesis; and, related to their location in the geomorphological system [13,15]. Moreover, several placer deposits of different types can coexist in the same district or study area, with multiple superimposed mineralisation events. Consequently, their mineralisation is usually erratic and discontinuous, and exploration, resources development and exploitation are difficult [16].

Different classification schemes for placer gold deposits have been proposed in the past. In general, Wells and other researchers identify five main types [15,22]: i) residual placers, when minimum or no transportation of mineralisation is present; ii) eluvial placers, when transportation and concentration processes occur in a solid medium, such as colluvial or moraines; iii) alluvial/fluvial placers, when these processes happen in a medium which is liquid water in continental environments, like in alluvial fans, streams or rivers; iv) beach placers, when transportation and concentration is due to ocean waves effects; and v) aeolic placers, when the media to transport and concentrate is the wind.

Regarding mineral resource estimation, during the past decades the mining industry has evolved from using simple geometrical tools (e.g. triangulations, polygons, etc.) to more robust geostatistical methods that account for the variability of the deposits and their geological identity [23,24]. Nonetheless, for placer gold deposits only a few case studies that use geostatistical tools can be found in the scientific literature [12,25–28].

In the case of Chile, the problems associated with placer gold development described above are even worse, since there have been no industrial exploitations of this kind for the past decades, despite the significant potential of the country to host small and medium size industrialised operations [29–31]. The research project that led to the publication of Jara et al. [29] identified a preliminary potential of five million ounces of gold in placer deposits in the country, enough to sustain a long-term production of around 50 thousand ounces of gold per annum if exploitation triggers new prospecting and exploration activities. However, there is almost no knowledge about prospecting, development, and exploitation of these deposits, so this situation one of the key impediments to the progress of this industry.

This study presents the first attempt to apply traditional geostatistical methods to assess the mineral resources of the Mina Nueva placer gold deposit (MND) in the Cordón Baquedano Gold Mining District (CBGMD), also know as Río del Oro or Tierra del Fuego Gold Mining District, located in the northern part of the Tierra del Fuego Island, Chile (54°S). Section 2 describes the data and methodology used during the work; Section 3 and 4 present the results and discussion of the research, respectively; and Section 5 outlines the main conclusions of the study.

2. Methodology and data

2.1. Characterisation of the study area

2.1.1. Cordón Baquedano gold mining district and the mina nueva deposit

The Cordón Baquedano, also know as Altos del Boquerón or Sierra Balmaceda, is a SW-NE orientation mountain range of low altitude (up to 600 m) located in the northern part of Tierra del Fuego Island [32], in the southernmost region of South America (Figure 1). It is bordered by Bahía Inútil (Useless Bay) to the south, and through the lowlands to the NE before reaching the Strait of Magellan.

In this mountain range there are outcrops of sedimentary rocks from the Mesozoic to Cenozoic, and unconsolidated sediments from the Miocene to Quaternary. These rocks and sediments are part of the Magellan Basin [34–37]. The Basin has had tree main formation tectonic phases: (1)

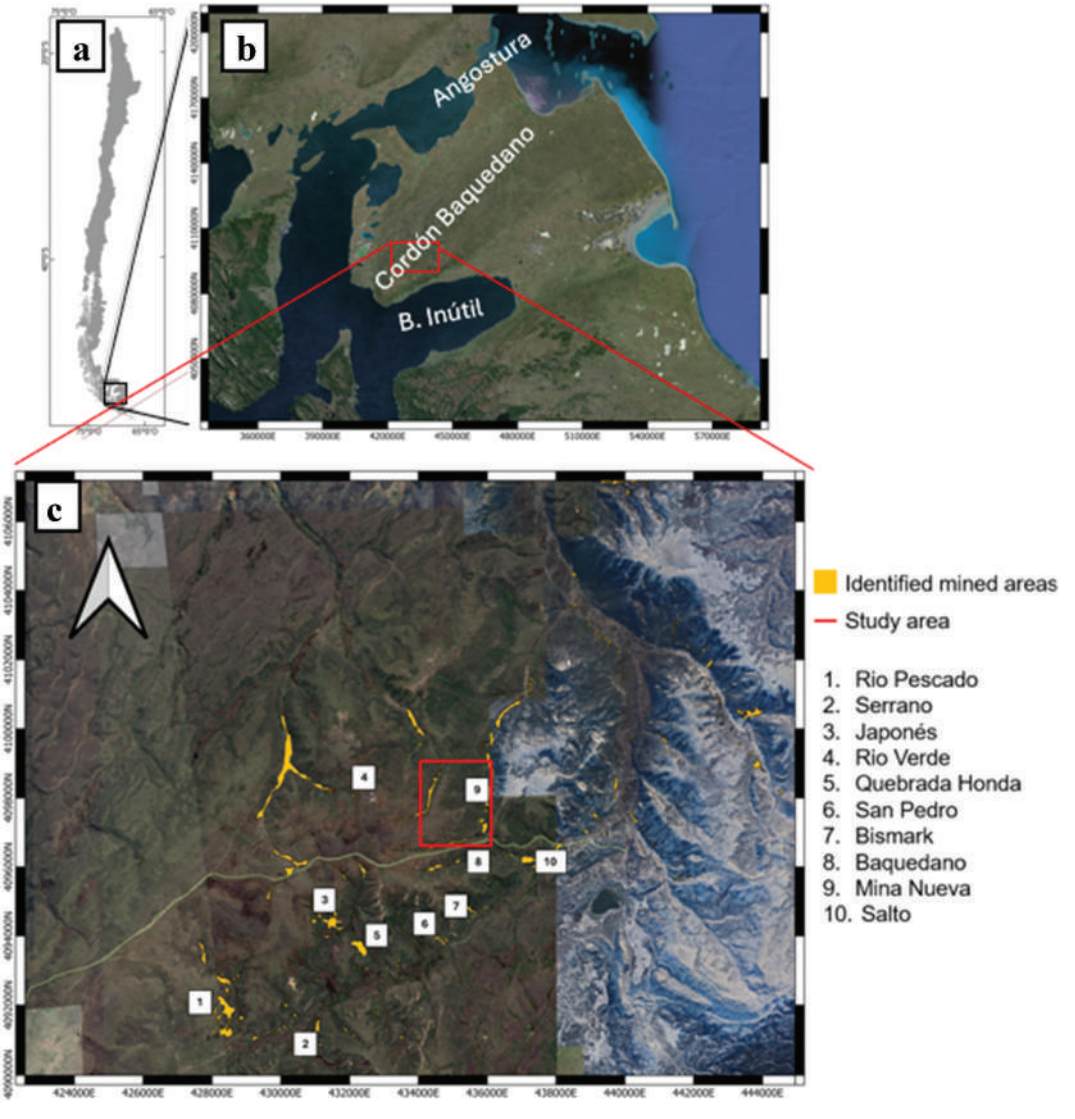


Figure 1. Image of the Cordón Baquedano Mining District with the historical exploited zones (coloured in yellow). The study area is in the red square. Adapted from [33].

extensional during the Jurassic and much of the Cretaceous, with a rift and post-rift basin stage; (2) compressional from the end of the upper Cretaceous to the Palaeogene, with a foreland basin stage; and (3) transpressional during the Neogene and Quaternary, with a foreland basin stage [34,35,37–40]. During the last foreland basin stage, the unconsolidated sediment sequences with a marine and continental origin were developed [35,37,38,41,42]. Then, in the middle to upper Pleistocene-Holocene fluvial, lacustrine, glacial, fluvioglacial and glaciolacustrine sediments have been deposited, shaping the current geomorphology of the Cordón Baquedano range and the surrounding areas [43,44].

The Cordón Baquedano Gold Mining District is a remarkable area for the presence of placer gold deposits that have been exploited since the late 1800s [45–47]. The district experienced a brief period of industrialisation during the last decade of the 19th century and the first decades of the 20th century; a period known as Tierra del Fuego 'Gold Fever' or 'Gold Rush' [48–51]. During the peak of the gold rush in the area (including the Río del Oro, Río Oscar and Río Verde rivers and their tributaries), more than 600 miners, 15 steam dredges and two mechanical shovels were in operation [52]. The average production gold grades reported over that period range from 0.5 to 1.3 grams of gold per cubic metre (g/m^3) [53], and the production from the Tierra del Fuego operations during the first part of the gold rush was around 5,000 kilograms (kg) or 160,750 troy ounces (tOz) [52]; or in average between 180 to 250 kg per year (5,790 to 8,040 tOz) [32]. Additionally, production from placer deposits for the entire Magallanes Region of Chile surpassed the thousand kilograms of gold during several years of the first two decades of the 20th century (Table 1), most of them obtained from the CBGMD [48,54,55]. Moreover, during that period a similar amount of gold is believed to have been extracted and sold without being officially declared in the Chilean custom services [32,48,51,52]. Thus, up-to-date historical placer production from the Magellan Region of Chile could have exceeded two million ounces of gold.

The Tierra del Fuego gold rush associated with large-/industrialised-scale mining and numerous small and artisanal operations ended by the mid 1910s, supposedly due to dredges operational problems, speculative investments and diminishing gold grades [48,49,51]. Nevertheless, exploitation continues until today as artisanal and small-scale mining, with occasional industrialised operations for short periods of time [47,56]. Nowadays, a couple of small-scale industrialised operation and less than 10 miners work in the area, with production grades ranging from 0.1 to 0.4 g/m^3 of gold, with enriched zones giving grades of several grams per cubic metre (C. Soto, personal communication, unreferenced).

Table 1. Historical production for the Magallanes Region.

Registered Area	Period	Kgs	Reference
Punta Arenas	1903	238.4	Alfaro [55]
Punta Arenas	1904	187.4	Alfaro [55]
Magallanes Region	1904	5,292.7	Earl [48]
Punta Arenas	1905	537.2	Alfaro [55]
Magallanes Region	1905	4,464.8	Earl [48]
Porvenir	1903–1905	70.0	Alfaro [55]
Magallanes Region	1906	1,020.7	Earl [48]
Magallanes Region	1907	3,257.5	Earl [48]
Magallanes Region	1908	1,655.7	Earl [48]
Magallanes Region	1909	2,661.1	Earl [48]
Magallanes Region	1910	1,766.1	Earl [48]
Magallanes Region	1911	969.5	Earl [48]
Magallanes Region	1912	818.1	Earl [48]
Magallanes Region	1913	701.1	Earl [48]
Tierra del Fuego	1934	903.5	Cruz Coke [54]
Tierra del Fuego	1935	7,607.5	Cruz Coke [54]
Tierra del Fuego	1936	47,391.5	Cruz Coke [54]
Tierra del Fuego	1937	114,023.0	Cruz Coke [54]
Tierra del Fuego	1938	105,687.9	Cruz Coke [54]

Several placer gold deposits and production locations have been identified in the CBGMD [32,48,49,51,52], and remnants of placer gold extraction can be easily identified by satellite and aerial photography images, and through field work. Figure 1(c) shows a map identifying placer extraction sites in the district (identified by the name of the creek or stream where they are located), among the most renowned are (from southwest to northeast): Río Pescado, Serrano, Japonés, Río Verde, Quebrada Honda, San Pedro, Bismark, Baquedano, Mina Nueva, and Salto [32,48,49,51,52].

The Mina Nueva Deposit (MND), which is the focus of this research, is located on the SE of the Cordón Baquedano and in the middle of the CBGMD, ~35 km to the east of the Porvenir town, and approximately one kilometre before the bridge over the Río del Oro River on the gravel road that connects Porvenir and Bahía Inútil that cross the CBGMD. The property extends from the Porvenir-Bahía Inútil road approximately for 7 km to the north and 5 km in the EW direction, following the course of the Mina Nueva stream. The stream (and the deposit) can be divided into three main parts: the upper part runs 3 km parallel to the road in an almost EW direction, then turns north for approximately 3,5 km (middle course) before orientating NNE for another 3 km (lower part) until it reaches the Río del Oro River (Figure 1(c)). Through the whole area, which covers the current stream course, the hanging benches and the small tributaries of the Mina Nueva stream, there are remnants of gold extraction. Different sources have reported that artisanal and mechanised operations were developed in this deposit during the last 150 years [32,45,46,51,52,57].

The Mina Nueva Deposit is one of the few deposits in the CBGMD that has received historical, modern, and systematic exploration efforts. By the end of the 1970s a joint venture between Empresa Minera Mantos Blancos (EMABLOS, a subsidiary of Anglo American by that time) and CRA Mining (a New Zealand company specialised in placer gold mining) initiated a regional- and district-scale exploration programme to assess the potential of the CBGMD, with the goal to define a one million ounce of gold resources through the whole district [45,58]. After three exploration campaigns developed during summer seasons between 1979 to 1982, which included 23 churn drill holes and more than 220 pits dug by hand in irregular grids, the company defined 10 prospective areas identified by letters from A to J [57,58]. At that time, the preliminary potential resource of the 10 areas was estimated in more than 30 million bank cubic metres (bcm) with an average grade of 0.45 g/m^3, or nearly 460,000 ounces of in-situ gold, if a cut-off grade of 0.1 g/m^3 was considered [57]. Of the 10 prospective areas, the A and G sectors were selected for further exploration efforts due to their good mineral potential in terms of volume and grades. More than 400 additional pits were excavated in regular grids 50 m × 50 m, 25 m × 25 m and 12,5 m x 12,5 m in a small area within sectors A and G in two summer seasons (1983 and 1984). Additionally, a bulk sampling program was developed, which included 23 linear samples (1,428 bcm) and eight big samples (912 bcm). As a result, the potential resources in sector A, the area in which this research has been developed, were estimated in more than one million bcm with an average grade of 0.93 g/m^3, for a total of more than 31 thousand ounces of in-situ gold [45,58]. Nevertheless, the companies considered these resources to be insufficient to pursue the exploitation stage.

After EMABLOS and CRA endeavour, several artisanal and small miners exploited resources from the MND during the 1990s and 2000s. However, all these operations were short-lived due to the depressed gold market in the 1990s, and technical or economic restrictions.

2.1.2. Proposed geological and mining model

Prior to this study, the geological model proposed for the MND indicated the presence of a continuous mineralised paystreak of fluvio-glacial origin [30,46,57]. In this model there is a ~0.3 m of topsoil with organic material, which in some areas is in contact with an overburden layer of ~2 m thickness and low concentrations of gold. Below the overburden (or the topsoil) there is an enriched level or paystreak that contains the economical portion of the deposit, made up of mainly fluvial material with an average thickness of 2 m. A nonconsolidated bedrock of mainly silt, and no gold concentration, sits below this enriched level (Figure 2(a)) [33,45,58]

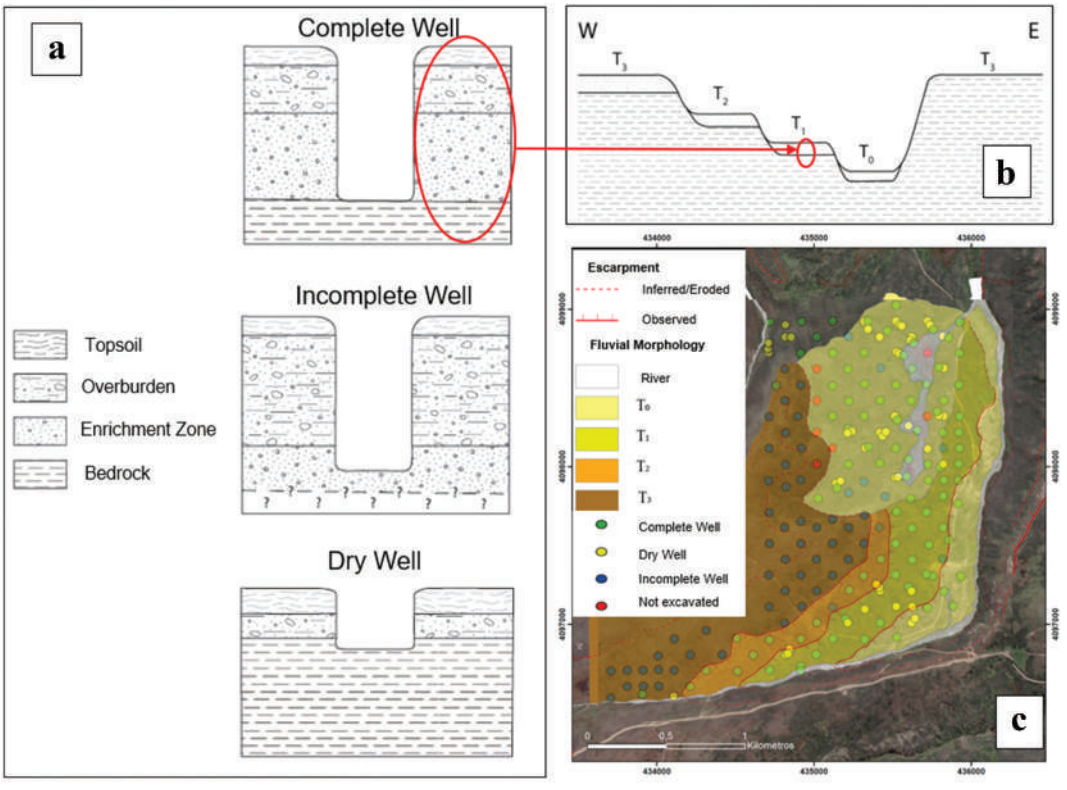


Figure 2. Geological and mining model of the study area. In (a) are shown the mining units as pits in its configuration found in (c). The terraces coloured in (c) are displayed in (b) as a general cross section. The pits that were not excavated (in red) are because of terrain difficulties.

Further studies done recently with public funded sources (Fondef ID21|10351) give complementary information to update and improve the geological model of MND, with proper geomorphological characteristics from the study area. The new model shows that the paystreak is not continuous, existing zones where the topsoil layer is in direct contact with the bedrock, with no enriched level (Figure 2(c)). This may indicate that the mineralisation occurred via multiple channels that left areas without mineralisation. Also, a system of fluvial terraces or benches are identified in the area (T_0 to T_3) , with widths of approximately 100–300 m each [33]. The lower terrace (T_0) is in direct contact with the Mina Nueva stream and is thought to be the flood terrace of the current water channel (Figure 2 (b,c)).

2.2. Exploration and sampling program

The exploration activities that led to the resource assessment presented in this research took place between February and April of 2022. They were conducted by a team of researchers from Pontificia Universidad Católica de Chile and personnel from a small mining company that owns the mining property and the exploration project. Two sampling programs were designed to use them as a data validation of previous works, and to properly model the mineral resources within the upper and middle part of the MND. The first campaign was composed of pits excavated separated by 200 m each across the study area and in a NS-EW orientations (Figure 4(a))The second one was also composed of pits separated by 200 m each across the study area, interlocked with the pits initially excavated (Figure 4(b)). Both programs form a regular sampling grid with a spacing of pits of

approximately 141 m in squares with NE-NW orientations. Some pits were duplicated for control purposes (Figure 1(c))(Figure 2(c)).

All the pits were excavated using a backhoe machine, with approximate dimensions of 2 m × 2 m in the plane. The depth of each pit depended on the depth on which the bedrock was reached or restricted by the excavation limit of the equipment (approximately five metres of depth). Geological data was obtained for each pit, such as material colouration, visual particle size estimation (three sizes: gravels, sand and silt), orebody thickness and anomalous findings. Also, boulders and gravels were selected for further geological investigations. The pits were later filled with the in-excess extracted material due to environmental requirements.

Ten buckets of 20 L were filled with overburden and enriched material. These buckets were washed in the field through a trommel, and depending on the particle size the material was later sent either to a sluice box, a JIG type concentrator or a Knelson (centrifugal) type concentrator. The resulting concentrates were later sent to the mining engineering laboratory at the Pontificia Universidad Católica de Chile for further processing.

The material processed in the laboratory went through a 'Desert Fox' concentrator (spiral wheel concentrator), which separates the light material (such as remaining silicate sands) from the heavier particles. These heavier particles were composed of mainly iron ore particles, heavier non-metal particles and gold. The resulting concentrate from the 'Desert Fox' was contained in 5 ml flasks. A second concentration stage was done using magnets to extract the black sands, leaving a final concentrate. This material was later analysed using magnifying lens to hand-pick the gold from the non-metal heavy particles remaining in this last concentrate. The gold was weighted, and a grade was calculated for each sampled pit. An schematic diagram of the sampling processing method is shown in Figure 3.

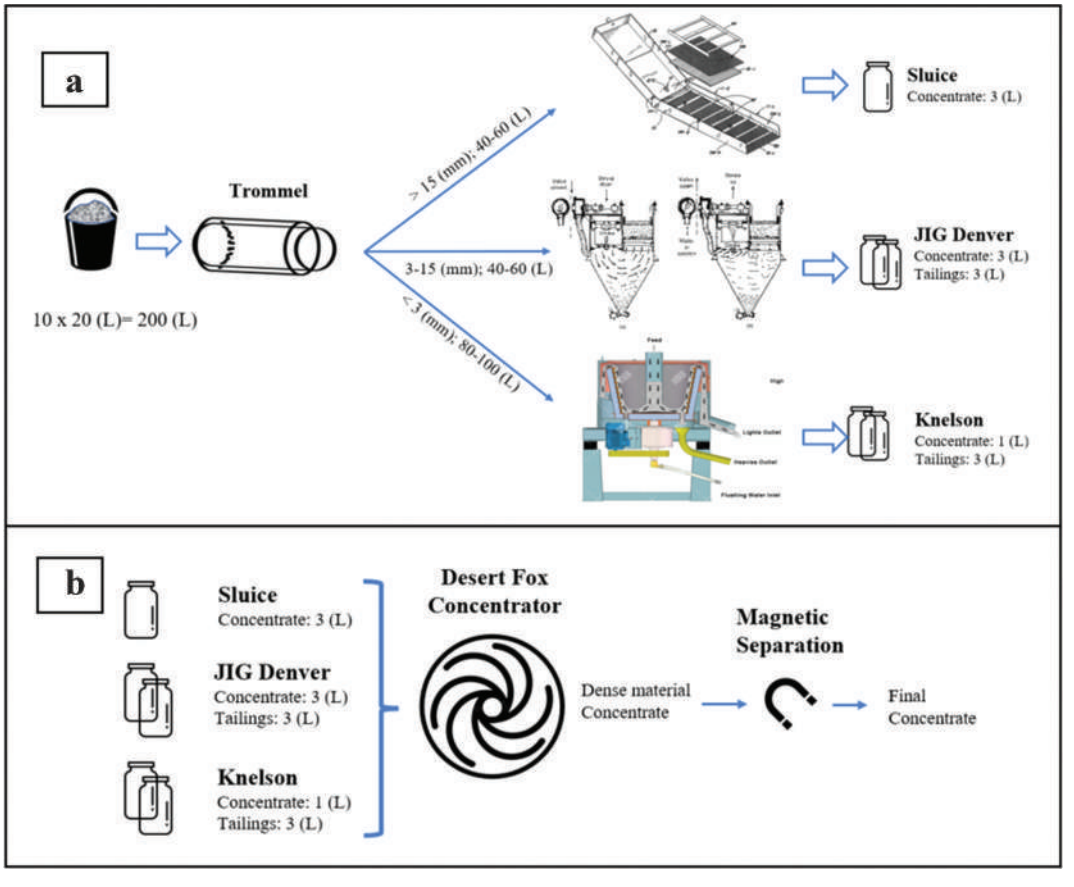


Figure 3. Sample processing diagram. The in-situ processing diagram is shown in (A), while the rest is done in MEL (B).

Additionally, historical reports of exploration campaigns done in the study area by EMABLOS and CRA Mining joint venture are considered in this study. From these reports, 46 historical pits are added to the database (Figure 4(d)).The pits have information about the orebody thickness and gold grade. These measurements were obtained by similar methods, in terms of sampling and processing, to those applied in this research and previously explained [57,58].

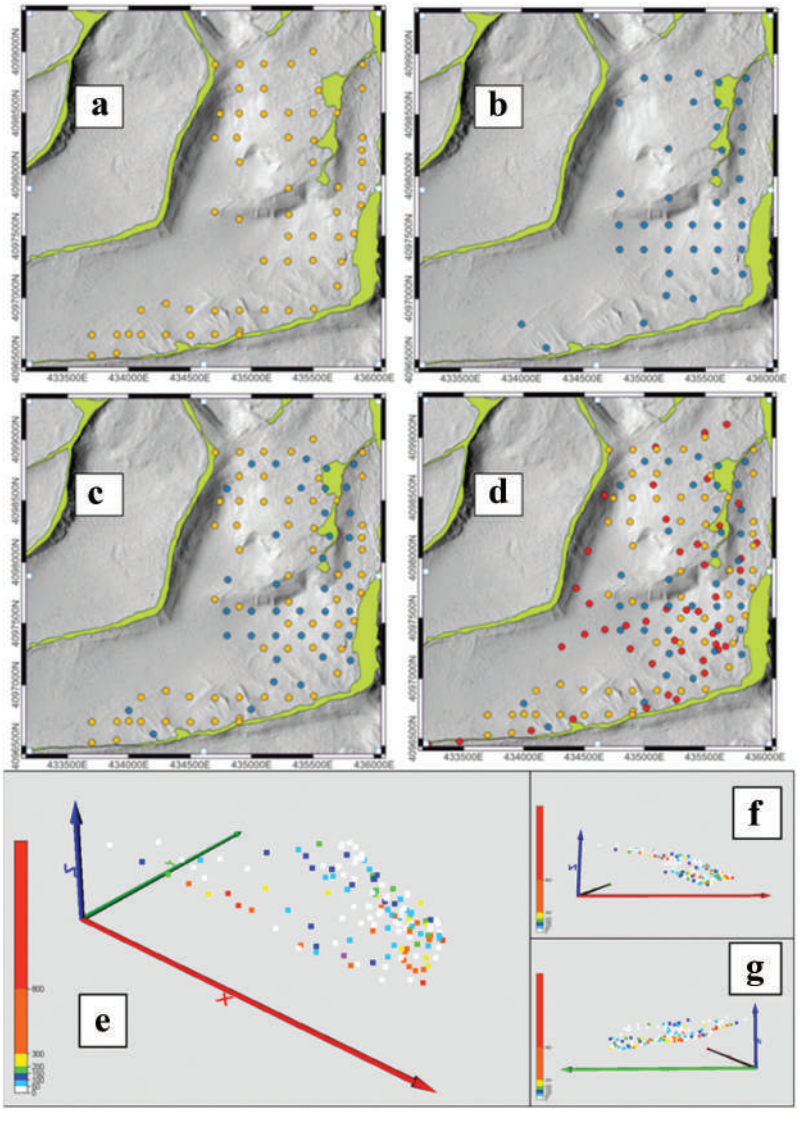


Figure 4. Sampled pits layout. (a) is the 200 m x 200 m spaced grid. (b) is the validation 200 m x 200 m spaced grid. Both grids form a 140 m x 140 m spaced grid (c). In (d) the historical pits are coloured in red along with the grid in (c). (e) 3D perspective view of DB4. (f) 3D E-W view of DB4. (g) 3D N-S view of DB4. All 3D images have an 5x exaggeration in the Z axis.

2.3. Data analysis

The exploration and sampling processing results are compiled as databases in MS Excel (Supplementary Material 1; SM1). A total of 101 pits are analysed for gold grades and the geological characteristics of the pit walls and the sampled materials are described for 158 pits. The variables that are selected for the resource modelling are the gold grade in milligrams of gold per cubic metre (mg/m^3), orebody thickness in metres (m) and particle size visual estimations for gravels, sands, and silt in percentages (%). Some pits (21) have an estimated particle size percentages obtained in laboratory through traditional dry sieving (%). For domaining purposes, the morpho-stratigraphic unit of each pit is also added to the database. For operational convenience, the overburden and enriched level are treated as a single unit.

The databases are separated in four subsets of data for exploratory analysis. The first subset corresponds to DB1, which is the first 200 m × 200 m grid. The second subset is DB2, which is the validation grid of 200 m × 200 m interlocked with DB1. The third subset corresponds to DB3, which includes the pits in DB1 and DB2, and has an approximate spacing between pits of 141 m × 141 m in a NW-SE orientation. Finally, DB4 incorporates the historical data from EMABLOS-CRA Mining joint venture (46 additional pits) to DB3 dataset (Figure 4).

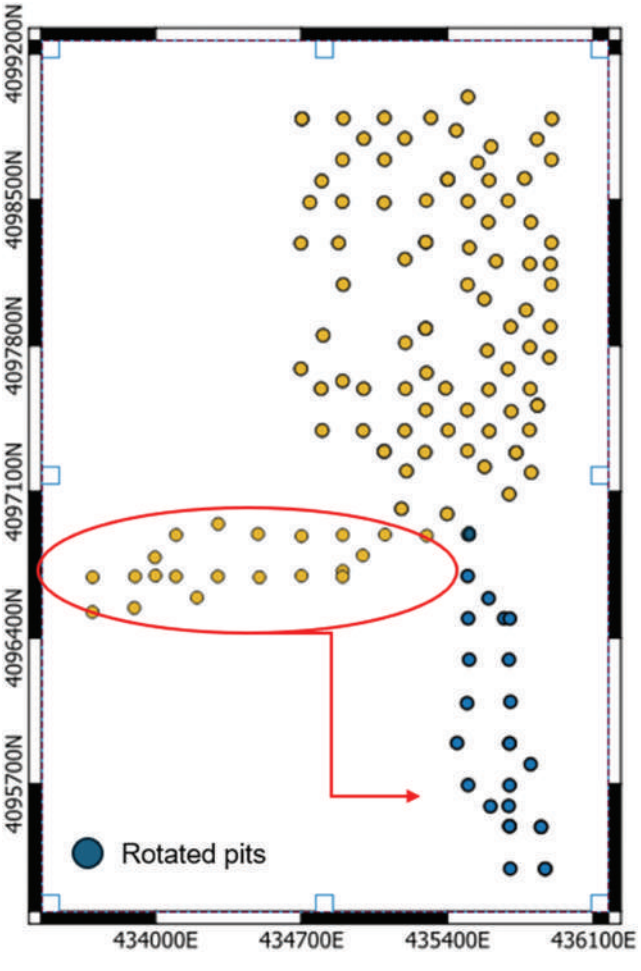


Figure 5. Pit rotation for variogram analysis.

Histograms and scatterplots of gold grades, orebody thickness and particle size distribution are built to analyse the data and assess potential correlations between these variables. Only for the gold grade variable a capping threshold was employed, with a value of 2,000 mg/m^3. Other data that is considered as outliers is supressed.

The spatial variability of the deposit is studied by variogram analysis. Two directions are considered for the study. The first direction is parallel to the active water stream, while the second one is the perpendicular direction to the active channel of the Mina Nueva stream. As the analysis considers the upper and middle part of the stream, and the first one has an orientation from west to east meanwhile the middle portion of the water channel has a south to north direction, a rotation of the pits in the upper part of the deposit is carried out (Figure 5). Since DB1, DB2 and DB3 are composed of regular grids, a 200 m lag distance is considered with 100 m of lag tolerance and a bandwidth of 50 m. For DB4, since the historical pits are irregularly distributed, the mean distance between them is calculated, resulting in a lag distance of 150 m, with a 70 m lag tolerance and a bandwidth of 30 m. The 22.5° azimuth tolerance is applied across all datasets.

Theoretical variograms are obtained using the results of the variogram analysis, accounting for the geological features of the deposit.

2.4. Resource estimation

Three estimation methods are considered in this research, Polygons – Nearest Neighbour (NN), Inverse Distance Weighting (IDW) and Ordinary Kriging (OK). The polygonal method is a geometrical approach to estimate resources via the construction of individual polygons. The value assigned to the polygon comes from the sample that is enclosed inside the polygon. A detailed example of this procedure is shown in Isaaks and Srivastava [59]. This method is commonly used in the estimation of resources in placer deposits due to its simplicity in its application in horizontal oriented deposits [15,16]. Some of the implications of using this method is the overrepresentation of spaced or isolated data. This can be a serious problem if the cut-off grade is higher than the average grade of the deposit, resulting in an overestimation of high-grade volumes and of grades above cut-off [59]. Nonetheless, it can provide a preliminary estimate for the average grade of the deposit [23,59].

In the Inverse Distance Weighting method (IDW), the estimation of a block is carried out by accounting for the distance of each sample to the centre of the block used in the estimation. The reason to do this is to give closer samples a larger influence in the estimation. The power used for calculations is arbitrary but usual values are one, two and three, bigger powers are applied when mineralisation is more erratic or spatially discontinuous [24,59] providing a result closer to polygonal estimation. In this research, powers of two and three are evaluated to see if there is any significant change in the estimation results. This is another method recurrently used in the estimation of placer deposits [16], finding examples in academic literature as in Al-Hassan and AAdjei [25], and Siddig et al. [60], using this method for the resource estimation of gold placer deposits in Ghana and Mali, respectively.

Kriging methods are a range of methodologies to estimate the value of a point or block minimising the error of estimation [23,24,59]. This method is generally accepted across the industry as a more robust interpolation method in comparison to IDW or polygons, being used in all types of deposits. For alluvial/fluvial placer type deposits, due to their heterogeneous nature, kriging could give more compelling results [61]. However, usually it is not considered as an alternative in the primary references for the study and development of placer deposits [15,16]. One of the main advantages of kriging is that it provides a variance or relative error of the estimated variable, thus the estimation confidence can be quantified and classified. In this case, Ordinary Kriging (OK) is used, as this method is robust to trends in the data. Other examples for the use of kriging in resource estimation for placer deposits can be found in Samanta et al. [27], Chatterjee and Bandopadhay [12], Saravanakumar et al. [28] and Al-Hassan and AAdjei [25].

An anisotropic search neighbourhood strategy is used to account for the anisotropy of the mineralisation from the results of the variogram analysis. This is used for IDW and OK. A typical visual representation of this search strategy is shown in Figure 6. For this research, A is the pit spacing previously discussed and B corresponds to the location of the block. The search radii C and D are based on the range obtained from the variogram analysis. A minimum of three and a maximum of eight samples is considered for the estimation of each block value.

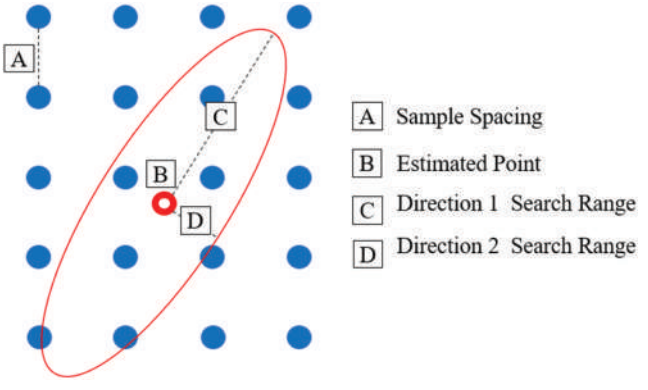


Figure 6. Search strategy diagram.

2.5. Resource model construction

For the delimitation of the resource model, a distance not longer than 100 m from the outer samples is considered. This distance is shortened if there is any external element that could restrict the resource extraction (such as houses, roads, or topographical elements) or the geological characteristics of the terrain suggest a hard limit in the mineralisation. This is defined using QGIS, and 30 × 30 m blocks are considered for the resource model.

Resource models are done for DB3 and DB4. These models contain the estimations for: i) gold grade (mg/m^3) ii) orebody thickness (m) and iii) visual percentages of particle sizes (%) (the latter are not shown in this article for practical purposes). In total six models are calculated. Three models are obtained by using the polygon, ID2 and OK methods with DB3 database. Other three models are generated by using the same methods applied to samples in DB4 dataset. The polygon/NN models are run using the *Voronoi Polygons* option in QGIS software. Later these polygons are discretized in the defined 30 × 30 m blocks. The IDW models are obtained by using Alpha Rho Software. The results are given in a.csv file with the location of the estimated block, its estimated gold grade and orebody thickness, the shortest distance from the samples to the centre of the block and the number of samples used to estimate the block. The OK models are built by using Alpha Rho Software too. The results are given in a.csv file with the same variables in the IDW models but incorporating the variance of the estimated gold grade and orebody thickness. All the models are visually validated in QGIS. The results are compiled in a single.csv file with the estimated values of each variable using all methods for each block. The IDW and OK results are compared and validated via the construction of scatterplots, swath plots and cross validation analysis. For the cross-validation, two methodologies are used to compare results, the first one consisting in scatterplot analysis between the real data and its predicted values to observe the correlation and trend [25,62]; and the other one measuring the root mean square error (RMSE) of the estimations [12,60,63,64]. Finally, a Grade–Volume Curve is constructed for each resource model and potential gold resources are calculated.

2.6. Resource classification

The resource classification is performed using classification guidelines for lode and placer gold deposits [65]. No measured resources are declared due to lack of QA/QC in the process and scarce information to support the variogram analysis. The classification process considers the following criteria: the number of pits from where the samples used to estimate the block are (NH, number of holes); and the distance of the nearest pit to the estimated block (DNDH). If the estimated block is assessed by using more than three pits (NH > 3), and if the nearest pit is closer than 100 m to the block (DNDH <100 m), the block is classified as indicated resource; and if only one of the criteria is met, the block is classified as inferred resource.

3. RESULTS

3.1. Satistical results

The general statistics of gold grades show different results when considering multiple databases. Even though DB1 and DB2 support virtually the same area, with an exception in the south flank of the deposit where DB1 has more pits sampled that DB2 (Figure 4(a,b)), the mean gold grade obtained using each set of data varies from 96 mg/m^3 for DB1 (Figure 7 (a)) to 149 mg/m^3 for DB2 (Figure 7(b)). This may be explained by a high value obtained in one sample of DB2, with a grade of 1525 mg/m^3 (this grade value is within the range of historical high grades of the deposit, and it is located in a zone of high potential accordingly to previous resource estimations); however, the lower quartile, median and upper quartile values for DB2 are consistently higher than those for DB1, suggesting that the impact of this high value cannot completely explain the difference in the average grades. As samples belonging to both datasets were processed in the same facilities and without a predefined order, there is no operational or theoretical explanation for this phenomenon, other than the deposit's grade distribution having a high level of variability and probably a larger number of samples would be necessary to infer the grade distribution with a manageable level of uncertainty.

When historical samples are incorporated into the analysis (i.e. when DB4 is compared with DB3), all the main statistics show higher values either: mean of 173 vs 117 mg/m^3; median of 72 vs 55 mg/m^3; and lower and higher quartiles of 27 and 164 mg/m^3 vs 26 and 123 mg/m^3 (Figure 7(c,d)). This suggest that irregular pits of the 1980s exploration campaigns could had been specifically planned to sample the high-grade zones of the deposit, which are located relatively closer to the current water channel (Figure 4(d)). Declusterisation of the historical samples was performed, but the results do not change significantly. Nevertheless, when comparing DB4 with DB2, these differences are not so relevant. In fact, the lower quartile and median grades for DB4 are lower than those of DB2 (27 and 72 mg/m^3 for DB4 vs 40 and 80 mg/m^3 for DB2), and the higher values of the average grade and the higher quartile in DB4 seems to be more influenced by a number of samples with grades between 300 and 900 mg/m3 than for extremely high-grade samples

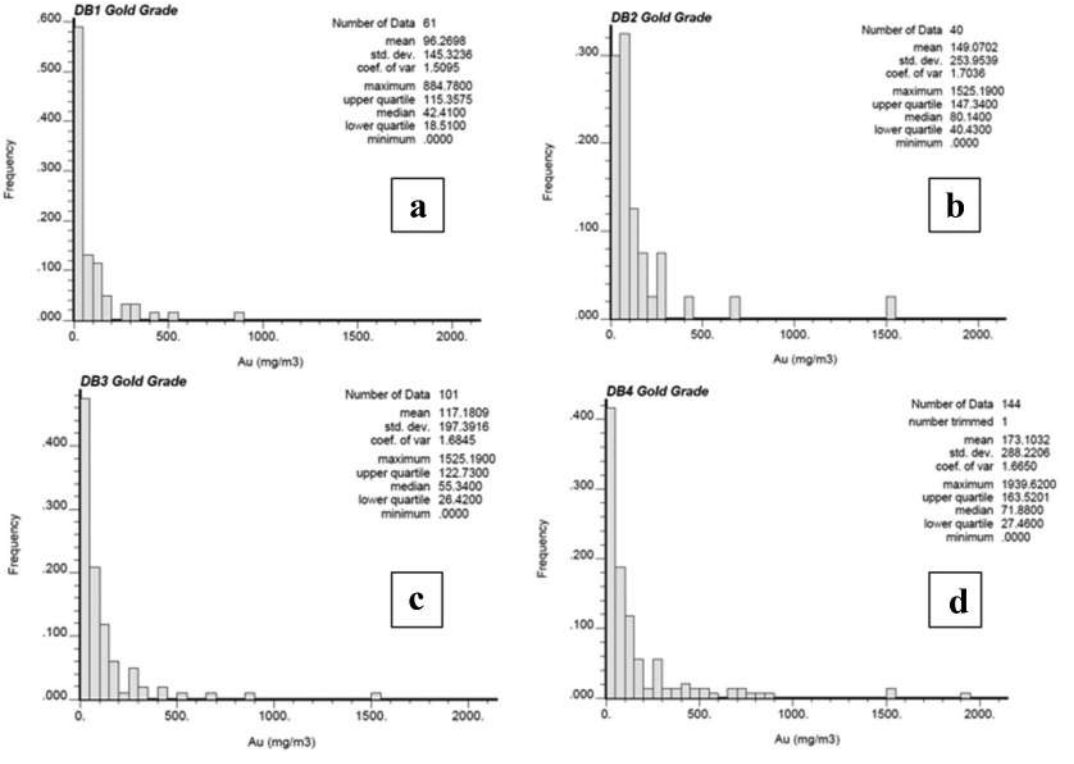


Figure 7. Histogram of gold grade. (a) is the histogram for the DB1 database. (b) is the histogram for the DB2 database. (c) is the histogram for the DB3 database. (d) is the histogram for the DB4 database.

(Figure 7(b,d)). This reinforces the notion that main differences among datasets could be explained primarily by the location of samples within the deposit and not by relevant differences between the sampling and processing procedures applied to obtain the information during different exploration campaigns.

The previously described situation of noticeable differences among grade datasets is not appreciated for the orebody thickness variable (Figure 8). The mean value among DB1 to DB4 varies from 1.8 to 2.2 m with two modes in 1 m and 3.5 m across all datasets (Figure 8). This is consistent with the thickness sampling results, where the zone next to the active water stream (east) is consistently thinner than the opposite (west) side of the deposit where the slope of the terrain also increases.

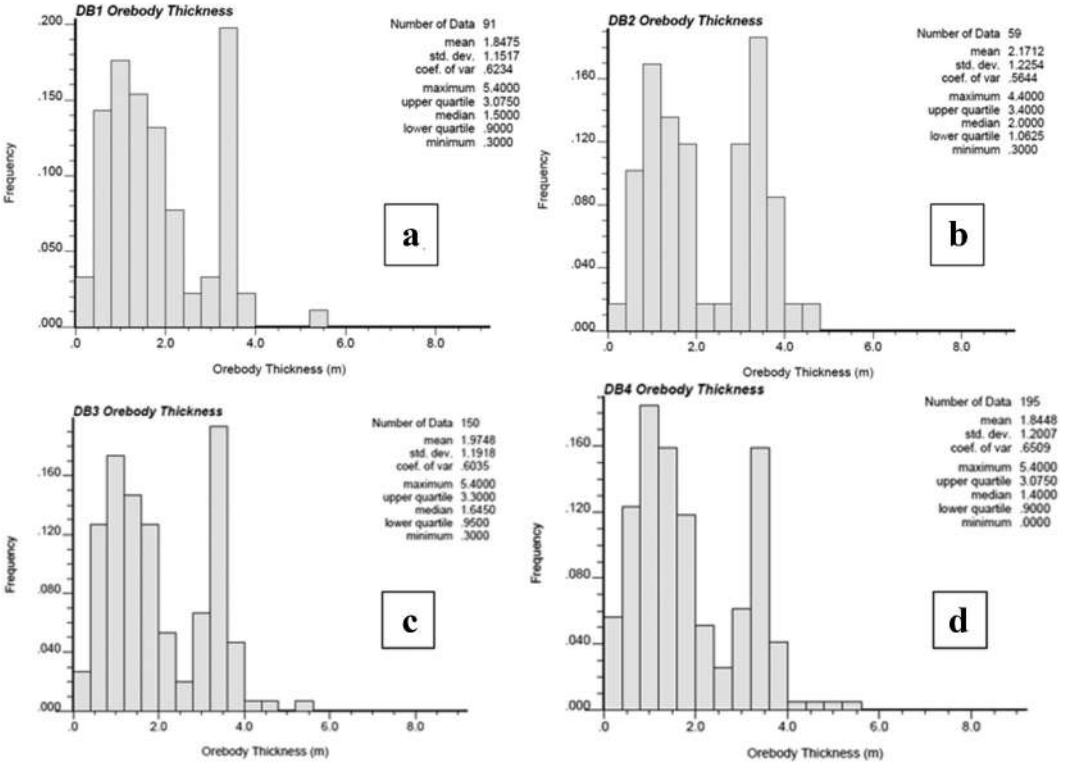


Figure 8. Histogram of the orebody thickness. (a) is the histogram for the DB1 database. (b) is the histogram for the DB2 database. (c) is the histogram for the DB3 database. (d) is the histogram for the DB4 database.

3.2. Variograms

The variograms obtained are not considered as robust enough for any conclusive information regarding the continuity of the mineralisation, specially the variograms for DB1 and DB2 (Figure 9(a,b)). Other plot types, such as correlograms, general relative variograms and madograms are calculated but give similar results. Logarithmic transformation of the data is used to try to obtain more interpretable results without success. The results for DB3 and DB4 datasets show a somewhat regular variogram in the parallel direction of the active stream, with a range between 400–600 m (Figure 9(c,d)). For DB4, the continuity in the perpendicular direction of the active water channel (E-W) is considered to be similar of that for the parallel direction (N-S) (Figure 9(d)). However, this result should not be taken into consideration strictly, since there is no geological explanation that could justify this phenomenon. Therefore, it is considered an artefact.

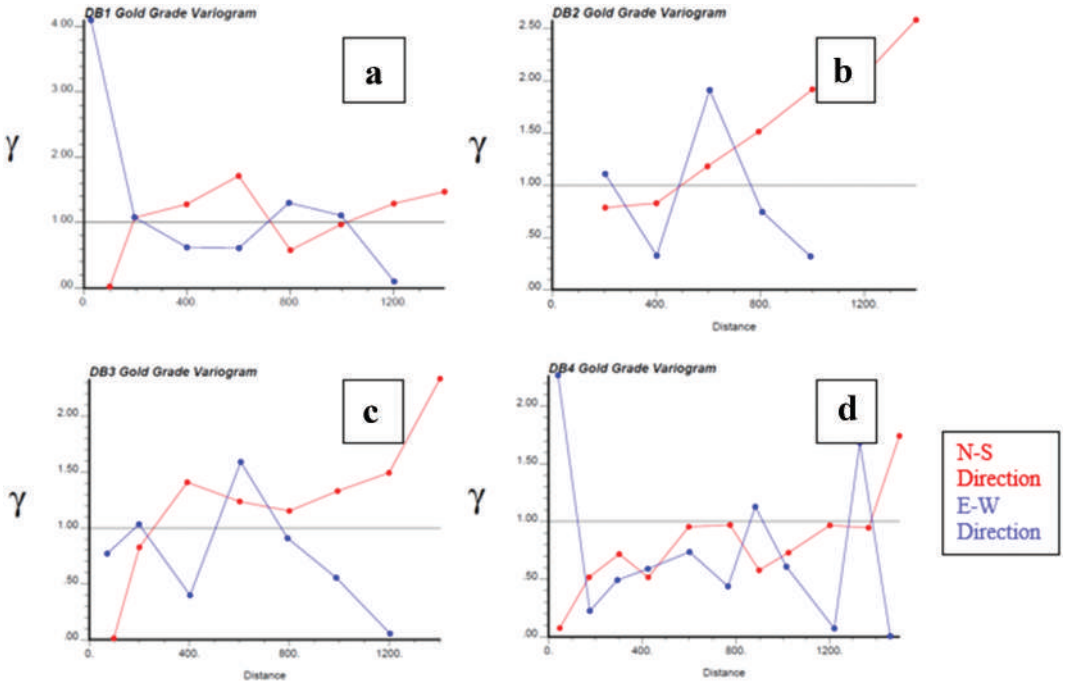


Figure 9. Variograms for the gold grade. (a) is the variogram for the DB1 database. (b) is the variogram for the DB2 database. (c) is the variogram for the DB3 database. (d) is the variogram for the DB4 database. The red coloured variograms are oriented in the N-S direction. The blue coloured variograms are oriented in the E-W direction.

Regarding the orebody thickness variograms, results are consistent across all datasets, indicating that the range for the E-W direction sits between 200–400 m and for the N-S direction the range extends to 800–1000 m, having more continuity than the gold concentration (as expected). These results are consistent with the considered geological model.

Theoretical models for the variograms are obtained by the interpretation of the geological characteristics of the deposit, the use of the information available from the experimental variograms, and the conclusions stated in the reports of historical exploration campaigns [45,57,58]. Using this information, the theoretical variograms for the gold grade and orebody thickness chosen for the estimation process are shown in Table 2 and Figure 10.

Table 2. Theoretical variogram models.

Direction	Variogram Type	Nugget Effect	Range
(N-S)	Spherical	50% of Sill	400 m
(E-O)	Spherical	50% of Sill	200 m

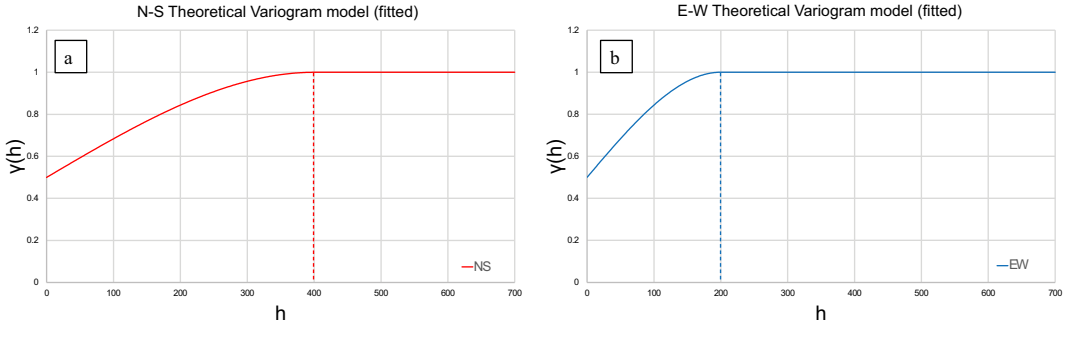


Figure 10. Theoretical variograms. (a) is the N-S theoretical variogram. (b) is the E-W theoretical variogram.

An anisotropic ratio (AR) of 2:1 in favour of the parallel direction to the active stream was considered. The reason for this AR is the experimental range obtained for the N-S direction of 400–600 (m) and the E-W extension (100–300 m) of the fluvial terraces of the deposit (and results from the orebody thickness variograms). A conservative range of 400 (m) in the N-S direction is considered with a mean range of 200 m for the E-W direction. These ranges are also considered for the orebody thickness estimation, as the resulting resource model using an extended N-S range of 1000 m for this variable shows no practical difference. The 50% nugget effect is determined observing the variogram results and analysing the difference in obtained gold grades for duplicated samples.

3.3. Particle size distribution analysis

Regarding the particle size distribution, the visual estimates from the pit walls and the extracted material are compared with the samples sieved in laboratory to evaluate their accuracy of the former, to further use them in the estimation process. Scatterplots for gravels, sands and silt are constructed for 21 samples with both visual estimates and laboratory particle size measurements (Figure 10). Only gravels and silt present a slight correlation of ~ 0.40, and for sands there is almost no statistical correlation (R of −0.1). These results are not robust enough and the visual estimates are no further used in the estimation process, deciding that the particle size distribution of materials within the deposit will be assessed in future studies.

Nonetheless, it is of interest to analyse if the granulometry of materials and gold grades has a relationship whatsoever. Scatterplots of the pits that has laboratory particle size distribution measurements and gold grades are constructed (14 samples) (Figure 11; Figure 12). For gravels a positive correlation is observed ($R = 0.48$), indicating that there may be a positive but not so strong relationship between the percentage of gravels and the quantity of gold in the mineralised materials. For sands and silt the opposite situation

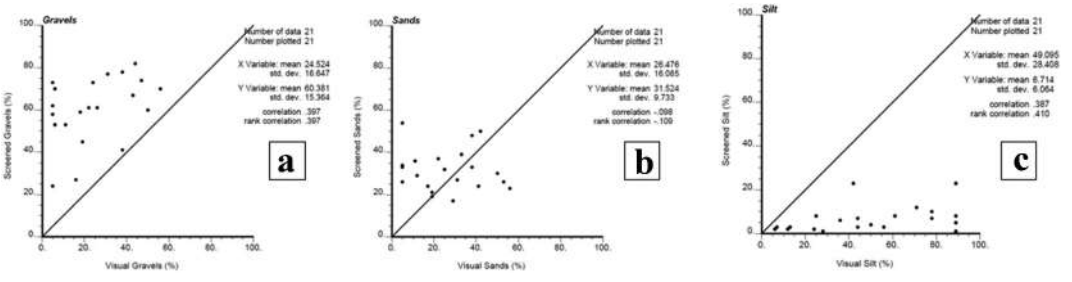


Figure 11. Scatterplot graphs of visual estimates of particle size percentages vs screened values.

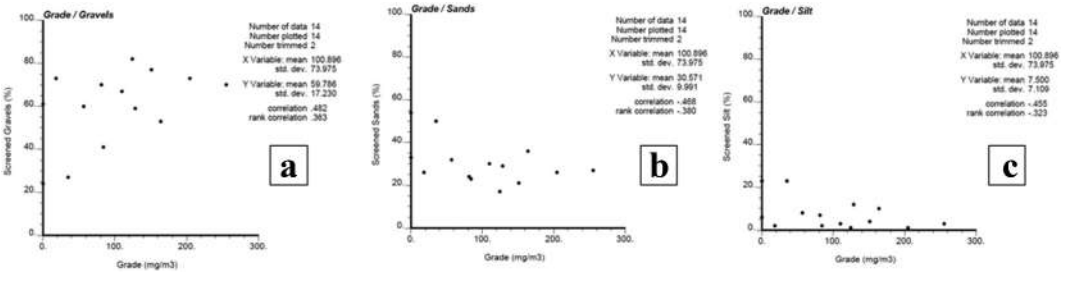


Figure 12. Scatterplot graphs of gold grade vs screened values for particle size percentages.

occurs, with a R of −0.46. This could be expected, since sediments with higher gravel contents are usually associated with or deposited in areas in which the hydrological system changes from high to low energy zones, the same areas in which heavy minerals are concentrated. Then, the same analysis is conducted to test the relationship between gold grades and orebody thickness, but no statistical correlation was found (DB3 $R = -0.14$; DB4 $R = -0.1$).

3.4. Resource model

3.4.1. Estimation results

Six models are obtained using the proposed methodology when applied to the main two defined datasets DB3 and DB4 (Supplementary Material 2; SM2) (Figure 12; Figure 13). The number of wells included in the search was a minimum of 3 and a maximum of 8. An analysis varying the maximum amount of data in ± 2 points was performed, with no significant changes in the estimation results (in all cases with correlations above 0.99, and a maximum average error of less than 12 mg/m^3 when comparing results using a maximum of 6 and 10 data points for DB4 estimation using IDW). A minimum of 3 pits ensured that most of the model area considered was estimated (less than 0.5% of area left unestimated when considering a minimum of 3, 3% of area left unestimated when considering a minimum of 4, and 9% of area left unestimated when considering a minimum of 5 pits, for DB4). In the case of IDW, the analysis with a power of two is presented, as the estimation using a power of three gives practically the same results. For the gold grade estimations, they are consistent to a high degree with the sample data, as seen in the swath plots (Figure 13; Figure 14). DB4 results show generally higher gold concentrations in the same areas where DB3 show better grades, or in some new locations where a few new samples (from this research) are present, as seen in Figure 13 and Figure 14. Two zones with grades above 150 mg/m^3 can be seen in the results from DB4 in which estimations for DB3 are below 100 mg/m^3 (Figure 14(c,d)) (Figure 13.b).

In the case of the orebody thickness, all estimations show similar results across estimation methodologies and datasets. They all present comparable results with similar orebody morphology (Figure 14).

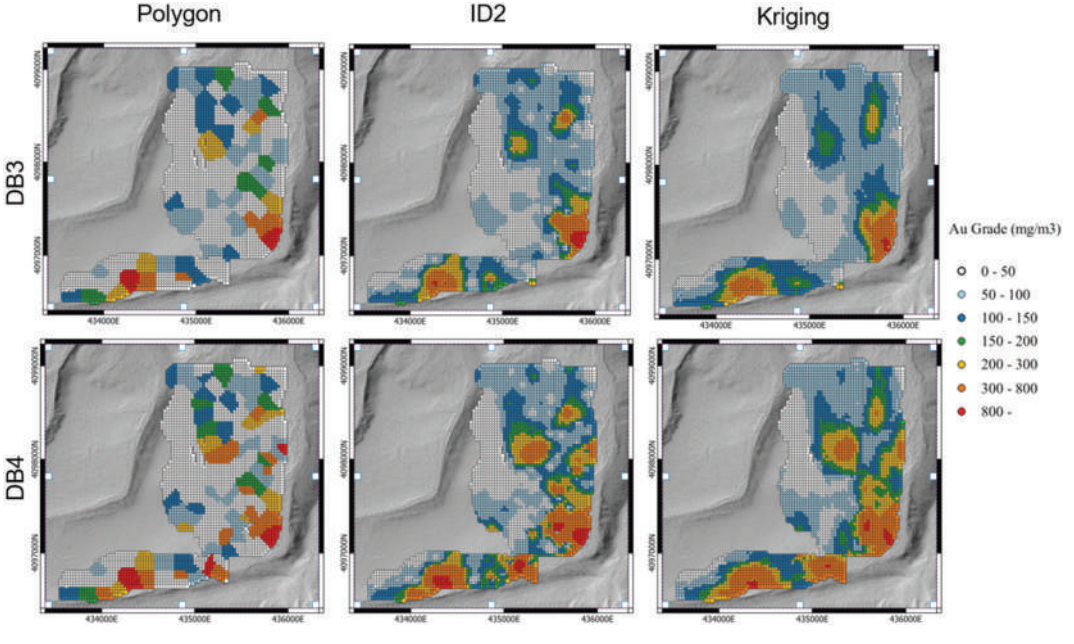


Figure 13. Gold grade distribution model for DB3 and DB4 databases using polygon, ID2 and OK methods.

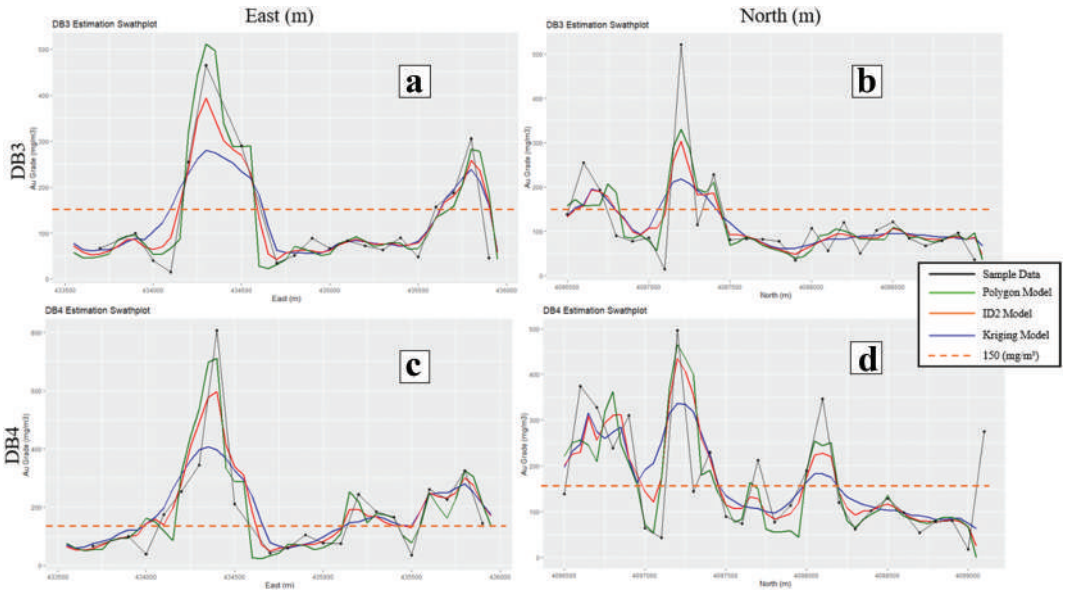


Figure 14. Gold grade distribution swath plots. (a) East swath plot for DB3. (b) North swath plot for DB3. (c) East swath plot for DB4. (d) North swath plot for DB4.DB4.The discontinuous red line indicates a grade of 150 (mg/m^3).

3.4.2. Model comparison

Four models are compared, using the ID2 and OK results, since they are considered to better represent the morphology and grades of the deposits over polygon/NN models. For the DB3 models, the gold grade distribution of the OK and ID2 models are very similar, as shown in the histogram (Figure 15(a); Figure 16(a)). Both models have a mean of 111 mg/m^3, though the ID2 model has a somewhat higher standard deviation (136 mg/m^3 vs 108 mg/m^3). Again, DB4 model histograms (Figure 15(b); Figure 16(b)) show similar average grades of ~167 mg/m^3. This represents a 51% increase in grades when compared to the results obtained using DB3 dataset. In this case, the ID2 model has a larger standard deviation (206 mg/m^3 vs 159 mg/m^3) too.

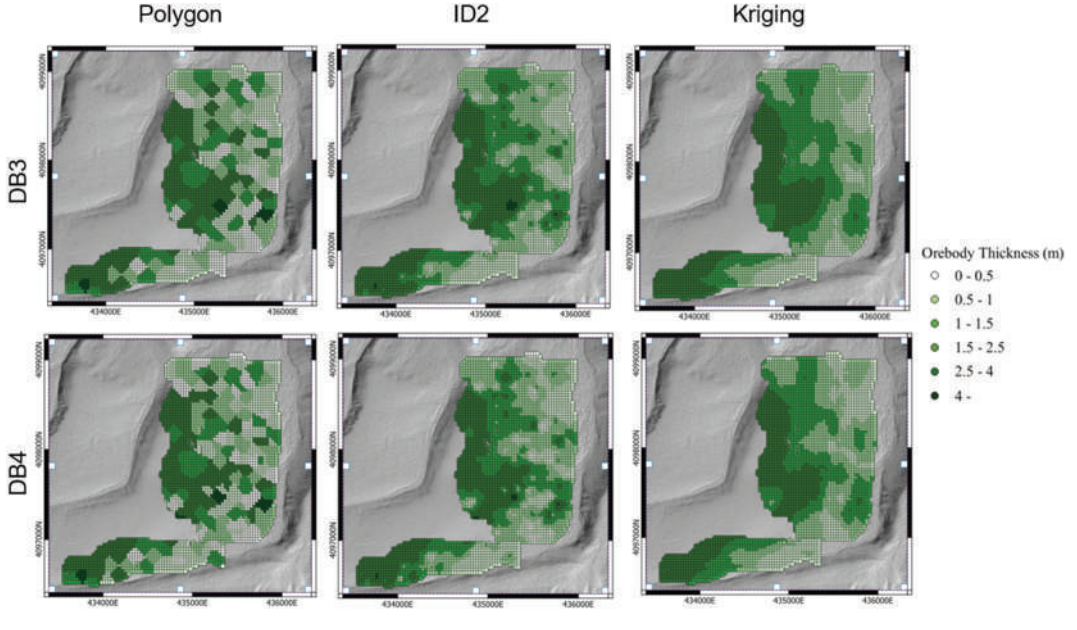


Figure 15. Orebody thickness model for DB3 and DB4 databases using polygon, ID2 and OK methods.

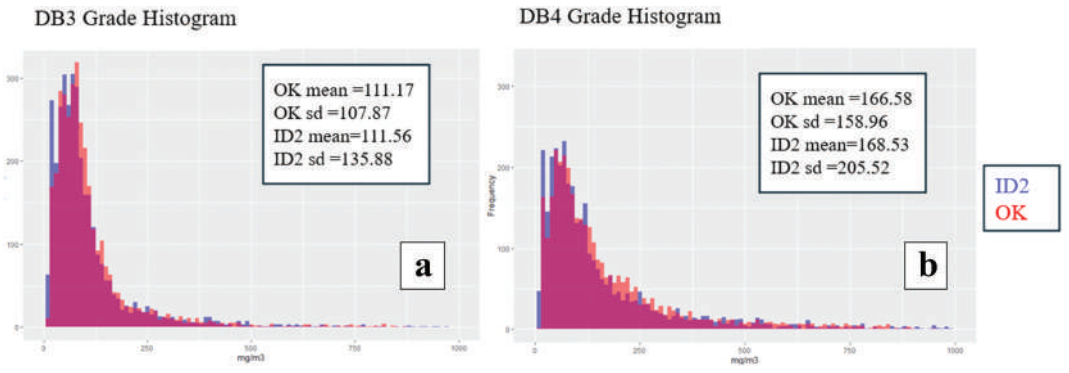


Figure 16. Gold grade estimated value histograms for DB3 (A) and DB4 (B) databases. OK and ID2 results are shown.

Looking at the scatterplots between block estimation grades, ID2 and OK models each one gives similar results, with all correlations between models over 0.90 (Figure 16; Figure 17). In the first one (gold grade using DB3), ID2 estimate more blocks with higher gold concentrations, mainly due to the nature of the method and to the tendency of OK to smooth the estimation results. The gold grade estimation using DB4 give a slightly poorer grade correlation ($R = 0.91$), but still over 90% (Figure 16(C); Figure 17(c)). For the orebody thickness, the statistical correlation is high and similar for both datasets ($R = 0.953$ for DB3 and $R = 0.946$ for DB4), and both have similar dispersion measurements (Figure 16(b,d); Figure 17(b,d)).

When comparing DB3 and DB4 datasets with the same estimation methodology, the results in terms of orebody thickness show a R coefficient above 0.95, and a high consistency between the results obtained using the new dataset and the one including historical pits (Figure 17(b,d); Figure 18(b,d)). The gold grade results show more disparity, specially for the ID2 models, where the R is of 0.72, whereas for the OK models the R is of 0.78 (Figure 18(a,c)). The scatterplots reflect the difference in the datasets, where DB4 sampled a higher-grade population, which is evident in the blocks estimated as low grades when using DB3. Although the results for grades are not as consistent as in the case of the orebody thickness, they indicate that both new and historical campaigns identified similar zones except in the case of a couple of high-grade areas indicated previously.

3.4.3. Cross validation

The result from the cross validation indicates low correlation between the real and predicted values for the samples, as expected, given the huge variability of the gold grade values. For DB3 kriging has an R of 0.13, while polygon and ID2 methods have an R of 0.18 and 0.23 respectively. For DB4 these values change to 0.27, 0.24 and 0.25 respectively. In the case of RMSE results, for DB3 kriging has an RMSE of 199.15 mg/m^3, the lowest among estimation methods, as expected, while polygon and ID2 have RMSE´s of 242.21 mg/m^3 and 206.56 mg/m^3, respectively. For DB4, these values increase considerably. The RMSE of kriging is 356.31 mg/m^3, 474.01 mg/m^3 for polygon and 369.83 mg/m^3 for ID2.

In the case of the orebody thickness, the results of the cross-validation analysis show a larger gap between the obtained correlation coefficient of the polygon method from ID2 and OK. For DB3 the polygon method has an R of 0.41, while ID2 and OK have R of 0.55 and 0.58 respectively. For DB4 the polygon method has an R of 0.41, while ID2 and OK have R of 0.51 and 0.51 respectively. This not only shows an increase in the gap among estimation methods, but also that the statistical correlation is higher. The RMSE results for DB3 are 1.26 m for the polygon method, 1.00 m for ID2

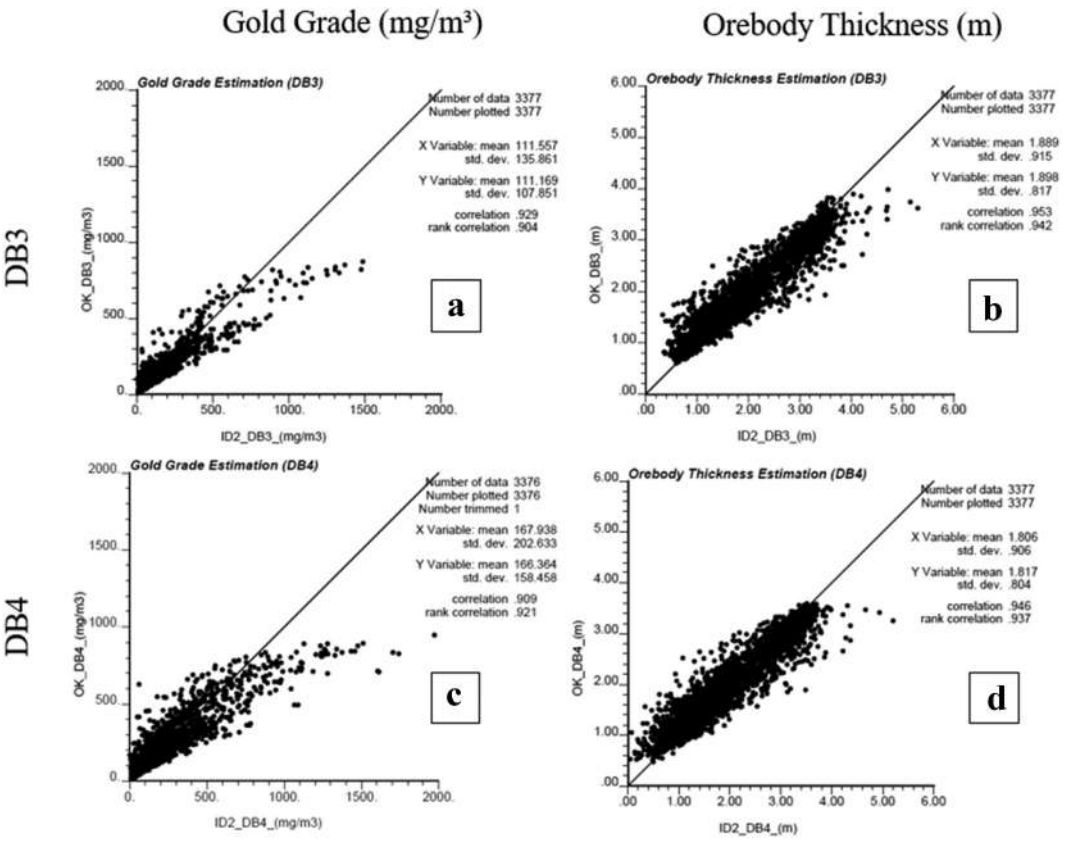


Figure 17. Scatterplots of OK vs ID2 results. (a) is the gold grade scatterplot using DB3. (b) is the orebody thickness scatterplot using DB3. (c) is the gold grade scatterplot using DB4. (d) is the orebody thickness scatterplot using DB4.

and 0.98 m for OK. In the case of DB4, these results change to 1.28 m, 1.07 m and 1.06 m respectively; there is no major difference in the RMSE results between DB3 and DB4.

Looking at the resulting resources, there are noticeable differences in the amounts of total in-situ gold from DB3 to DB4. Using an estimated 150 mg/m^3 cut-off grade, for DB3 the tOz of gold obtained ranges from 8,073 to 10,731 tOz (Table 3, Figure 18(a); Figure 19 (a)). For DB4, these values go up considerably, ranging from 16,720 to 18,276 tOz (Table 4, Figure 18(b); Figure 19(b)). This represents a variation of over 100% in some cases. The results for the considered cut-off grade between models for DB4 have less differences than those for DB3, but for higher cut-offs DB4 shows more disparity in its results. The OK and ID2 methods report similar amount of tOz of gold up to a cut-off of 300 mg/m^3, while the polygon method reports lower amounts of tOz for low cut-offs (<50 mg/m^3) in comparison to the other methods. The opposite situation can be seen for higher cut-offs, where the polygon results are considerably higher that the other methods. Nonetheless, in both cases OK is the model that have more conservative results for tOz of gold for the considered cut-off, and due to its characteristics may be the model that provides the most robust results. The ID2 model sits in between, but closer to OK results.

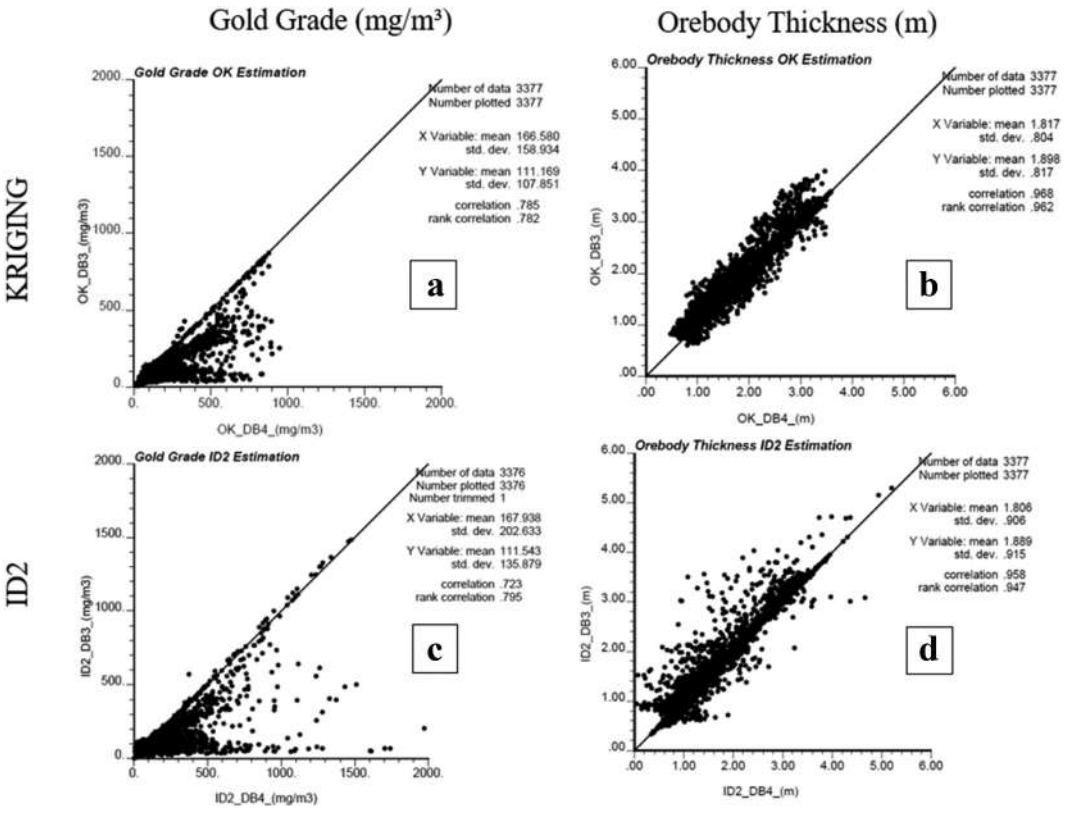


Figure 18. Scatterplots of DB3 vs DB4 results. (A) is the gold grade scatterplot using OK. (B) is the orebody thickness scatterplot using OK. (C) is the gold grade scatterplot using ID2. (D) is the orebody thickness scatterplot using ID2.

3.5. Resource classification

Considering a cut-off grade of 150 mg/m^3 and the classification methodology previously described, the indicated resources are above 80% of the total gold resources in all the cases considered in the analysis (Table 5). The dataset including the historical samples (DB4) shows a subtle increase in indicated resources, consistent with the higher number of pits. Also, the indicated resources have a considerable higher average grade, with ID2 having the greatest disparity between indicated and inferred grades. This situation is expected since sampling efforts are devoted to most promissory zones of the deposit.

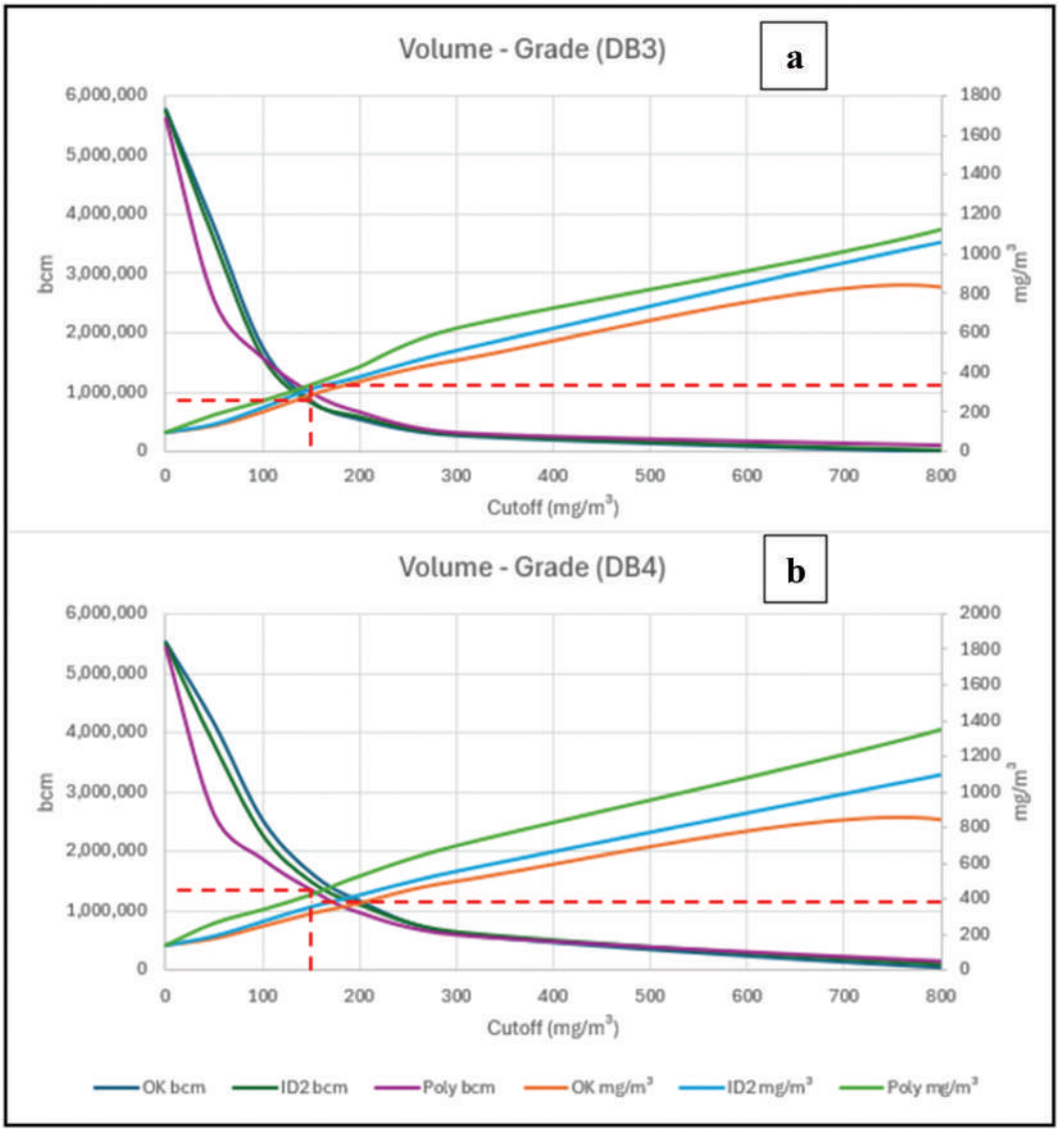


Figure 19. Grade-Volume curves of each method using DB3 and DB4. The discontinued red line indicates volume and mean grade for a cutoff grade of 150 mg/m^3.

Table 3. Estimated resources by method using DB3.

	Kriging (DB3)			ID2 (DB3)			Polygons (DB3)		
Cut Grade (mg/m3)	bcm	Mean Grade (mg/m3)	Au (tOz)	bcm	Mean Grade (mg/m3)	Au (tOz)	bcm	Mean Grade (mg/m3)	Au (tOz)
0	5,768,173	100	18,572	5,742,609	99	18,222	5,616,900	99	17,782
50	3,794,420	134	16,386	3,569,528	140	16,079	2,541,582	187	15,278
100	1,768,115	203	11,548	1,599,587	224	11,509	1,572,291	257	13,007
150	**867,873**	**289**	**8,073**	**832,627**	**319**	**8,546**	**983,214**	**339**	**10,731**
200	557,236	356	6,377	593,421	380	7,248	655,290	429	9,032
300	284,720	463	4,243	300,344	513	4,952	305,460	624	6,124
800	11,837	831	316	33,958	1061	1,161	93,600	1121	3,375
1000	0	0	0	18,597	1208	722	34,560	1525	1,695

Table 4. Estimated resources by method using DB4.

	Kriging (DB4)			ID2 (DB4)			Polygons (DB4)		
Cut Grade (mg/m3)	bcm	Mean Grade (mg/m3)	Au (tOz)	bcm	Mean Grade (mg/m3)	Au (tOz)	bcm	Mean Grade (mg/m3)	Au (tOz)
0	5,523,926	144	25,498	5,488,310	144	25,367	5,423,031	139	24,312
50	4,150,090	180	24,046	3,790,598	195	23,711	2,607,156	263	22,035
100	2,525,448	249	20,246	2,266,709	277	20,180	1,861,569	339	20,280
150	**1,632,759**	**319**	**16,720**	**1,481,635**	**359**	**17,110**	**1,342,494**	**423**	**18,276**
200	1,162,799	377	14,106	1,094,395	425	14,965	960,264	527	16,278
300	611,751	500	9,830	631,615	558	11,327	584,532	698	13,124
800	38,771	844	1,052	91,405	1098	3,228	144,738	1350	6,283
1000	0	0	0	45,326	1300	1,896	77,634	1760	4,394

Table 5. Resource classification for the Mina Nueva Deposit.

	DB3		DB4	
Cutoff 150 mg/m^3	ID2	OK	ID2	OK
Indicated volume (bcm)	667,415	696,420	1,279,544	1,437,534
Indicated ave. grade (mg/m^3)	336.1	299.7	368.0	323.0
Indicated Ounces (tOz)	**7,214**	**6,712**	**15,140**	**14,930**
	84%	**83%**	**88%**	**89%**
Inferred volume (bcm)	165,212	171,453	202,091	195,226
Inferred ave. grade (mg/m^3)	250.7	247.0	303.2	285.1
Inferred Ounces (tOz)	**1,332**	**1,362**	**1,970**	**1,790**
	16%	**17%**	**12%**	**11%**
Total Volume (bcm)	832,627	867,873	1,481,635	1,632,759
Average Grade (mg/m^3)	319.2	289.3	359.2	318.5
Total Ounces (tOz)	**8,546**	**8,073**	**17,110**	**16,720**

4. DISCUSSIONS

The resources estimation process for placer gold mines is particularly difficult due to the usual lack of knowledge of the geology of the deposit, the sparsely distributed information of its main characteristics, and the natural variability of the mineralisation. This study presents the process and results obtained for the mineral resource estimation of the Mina Nueva Deposit, which is located in the globally significant but mostly unknown Cordón Baquedano Gold Mining District, Tierra del Fuego, southernmost South America.

This study uses a new geomorphological model of the Mina Nueva Deposit [33], the information gathered from 101 new samples obtained from recently pitting works in a ~ 140 × 140 m grid, and the recovery of data for 45 historical excavations that are irregularly distributed among the deposit. Even though the total number of samples could seem small ($n = 146$), in terms of spatial density compares reasonably well with the few other resource estimation studies devoted to this kind of deposits that have been published in the scientific literature. For example, in their study of the Goodnews Bay marine platinum placer, Chatterjee and Bandopadhay [12] uses a dataset with 470 samples with an average distance among them of 500 m. When studying other marine placer deposit, but this time of gold mineralisation in Nome, Samanta et al. [27] use 497 samples for an area similar to that comprised by the MND; and for the same beach placer deposit (Nome), Saravanakumar et al. [28] consider different spacing among samples, going from 100 m × 100 m to 25 m × 25 m, to determinate optimal sample size and spacing among pits. In addition, Nkrumah et al. [26] examine 324 samples in a 200 m × 50 m grid to estimate a fluvio-alluvial placer gold deposit in Ghana, and Siddig et al. [60] utilise 112 pits spaced 50 m each other to calculate the gold resources of a deposit in Mali.

In terms of samples' grade distribution, the results for the MND are similar to those of the case studies cited in the previous paragraph. The average grade for the two datasets of the MND are 117 and 173 mg/m^3, and the standard deviations (SD) are 197 and 288 mg/m^3 (DB3 and DB4, respectively). In comparison, the mean grades of the named placer deposits are between 193 and 811 mg/m^3, and their grade SD goes from 237 to 1751 mg/m^3 [12,26–28]. It is noticeable that in most cases the SD is 1.5 to 2.2 times the mean grade, as in the MND, remarking the high variability of mineralisation in placer deposits. Moreover, in all cases the grade distribution is positively skewed, with a high percentage of samples with low to very low values (usually below 100 mg/m^3), and a few ones showing grades over the mean of the deposit.

Regarding gravel or paystreak thickness, only the study of the Kwabeng placer in Ghana considers its estimation [26]; the other ones assume a fixed value for the entire deposit. Again, the characteristics of the datasets are alike. Both this study and the Kwabeng show a slightly, positively skewed log-normal distribution with potentially two frequency peaks. Average thickness for MND is 1.97 m for DB3 and 1.84 m for DB4; and in the case of Kwabeng deposit, it is 2.5 m. In all cases, SDs of the thickness data are lower than the mean thickness values.

Anisotropy and variogram ranges remain a big concern for this study, particularly for gold grade variable. Although variogram analysis has been applied to placer deposits and anisotropy is commonly assumed when planning sampling campaigns through rectangular grids with longer spacing along the main orientation of sedimentary processes [15,16,26], usually resource estimation studies apply traditional methodologies in this kind of deposits [15,16]; in particular, inverse distance weighting methods in recent years [25,26,60], or even more simple approaches as triangulations and polygons [15,16]. Anisotropy has been identified for gold placer deposits before [25], but the lack of sufficient data and relatively poor variogram results obtained in this study led to define the anisotropic ratio and variogram ranges mainly by geological and variographic analysis interpretation. This has been a common practice in other mining fields, such as petroleum geostatistics [66]. Additionally, in many gold placer deposits the nugget effect for gold grades ranges from 26% to more than 70% of the sill [27,28,60]. The nugget effect of 50% considered in this study was obtained via duplicated samples and variogram results, and sits in between values reported for other placer deposits studied by the aforementioned scientific articles.

Of the analysis performed, which considered declustering under different conditions and analysis of near samples belonging to different campaigns, no statistical result is consistent enough to strictly justify the use of the historical data along with the results of the 2022 campaign. The average grade of the historical data is somewhat higher than the results of the newer campaign, and the resulting gold resources considering the additional information increases the estimated in-situ gold. This could be explained mainly because of the spatial bias in the distribution of additional samples considered in historical campaigns. These samples were taken mainly in known mineralised areas and do not represent the central and southern zones of the study area. This kind of bias is common during the first stages of mineral exploration, when efforts are focused on probing geological potential in highly prospective areas. Thus, including these additional data must be only done for comparative purposes, and it is expected that the resulting resources could not properly represent the actual materials of the prospective area. The difference in gold grades for both campaigns could had also been affected by different sample practices and processing methods, but historical information regarding this issue is scarce [57]. Nevertheless, it is important to remark that thickness data and thickness estimation results between datasets are highly consistent, given additional support to the decision to include the historical samples in the study.

Correlations between the gold grade and certain particle sizes are observed; this is a phenomenon not described in the scientific literature reviewed for this research. For the gravels fraction, a positive correlation coefficient is noted. The opposite scenario occurs with sand and silt fractions, which is expected given the compositional nature of the particle size proportions. This may be a result of the combination of various mechanisms related to transport and concentration of gold mineralisation in these deposits. Another possible explanation for this situation is the dilution

of samples with material from the bedrock, which is made-up mainly of sand/silt and has no gold content [46]. The use of a backhoe excavator reduces selectivity and in some cases contamination of the sample with bedrock material may occur, lowering the gold grade in the sample and increasing the percentage of sand and silt present in it. This underlines the relevance of QA/QC protocols when capturing information during sampling campaigns, and the usefulness of hand dug sampling processes in placer gold resource characterisation despite its higher costs.

Regarding the obtained resource models, it can be seen via cross-validation that both OK and ID2 give slightly better results when compared to the polygonal model, since the later presents conditional bias. Nonetheless, all models show low correlation between real and estimated grades for samples. This may happen due to the gold variability and sparsity of samples or because the mineralisation ranges do not properly correlate to the geological model; this phenomenon has been described in other studies that refer to resource estimation of placer deposits [27]. Despite this issue, there is a good correlation between block estimates by ID2 and OK, a result that supports the conclusion reached by Al-Hassan and AAdjei [25], that ID2 method could be used for simplicity when estimating mineral resources in placer deposits. Additionally, a cross-validation analysis was made for the orebody thickness using OK and real samples values, where the R obtained is over 0.50. This indicates that although the parameters used do not give robust results for the gold concentration, they are more suitable for characterising the morpho stratigraphical behaviour of the deposit, which is more continuous than gold grades.

Finally, in terms of the resource classification the authors do not find any other study that has applied established criteria to categorise the resources in the obtained block models. Thus, to the authors knowledge, this is a first attempt to apply standard classification methodologies to placer gold systems. However, it is important to remark that the available information is not sufficient to establish measured and indicated resources under internationally recognised resources and reserves codes within the MND.

Summarizing, the results obtained in this study are indicative of the potential of the MND even though they should be taken carefully. More information is probably necessary to delimit and obtain overall volumes and grade distributions for the deposit, as stated by EMABLOS. In its study of optimal sampling grid in a small part of the project's property, they found that a spacing of 100 m between samples is adequate for long-term estimations but even a 25×25 m grid is requested to clearly delimitate the orebody and to obtain reliable short-term block grades [57]. Additionally, more samples and better QA/QC protocols are needed to improve the classification process and to incorporate resources in the measured category.

5. Conclusions

This paper illustrates the research regarding the resource estimation of a placer gold deposit in Mina Nueva Sector, Cordón Baquedano, Tierra del Fuego Island (54°S). The Cordón Baquedano Gold Mining District has been known historically for its placer gold mining, which is still in production at small and artisanal scale. Previous studies have been reviewed, the methodologies applied, and the results and shortcomings are presented.

The geological model for this type of deposit consists in a series of non-continuous sedimentological units above a sedimentary bedrock, with one unit containing the main gold mineralisation. The knowledge regarding the mechanisms that mineralised the orebody are improved, but still further studies are necessary to better understand the deposit to enhance the estimation process. For example, more sampling is necessary to better delimited the orebody.

The main variables considered for this study are gold grades, particle size distributions and orebody thickness. No correlation is found between gold grade and orebody thickness. However, in the case of particle size distribution and gold grades a possible correlation is noted, but further studies are necessary since a small number of samples have laboratory particle size analyses.

The variogram results are not sufficient to establish any reasonable mineralisation range and anisotropy. Nevertheless, the geological model is used as a supporting reference to define the parameters of the theoretical variograms. This is a limitation that can be assessed by using data in a denser sampling grid. Further spacing of 50 m × 50 m and 25 m × 25 m may give more trustable results, as historical works suggest. This may help reducing the variability in the variogram analysis, obtaining a better estimation model in return. The variograms considered are spherical with a nugget effect of 50% of sill and a range of 400 m in the direction of the stream flow and 200 m perpendicular to it, which is in accordance with the common knowledge that mineralisation continuity is higher in that orientation.

Three estimation mechanisms are used: Polygons, Inverse Distance Weighting (ID2) and Ordinary Kriging (OK). The variables modelled are gold grade and orebody thickness. A total of six models are built using new and historical datasets. All models are consistent in having better grades and lower thickness in the eastern side of the deposit (nearby to the water stream), while the western side has overall lower grades and higher thickness. While all models give similar results as seen in the swath plot and scatterplot analysis, the cross validation indicates low correlation between real and estimated samples (less than 0.3). It is important to understand if this result is due to the inherent variability of the deposit, or because the parameters employed are not suitable for its modelling.

The resulting gold resources vary depending on the dataset used for this purpose. For a cut-off gold grade of 150 mg/m^3, the new samples alone give a resource that range from 8,070 to 10,730 ounces of in-situ gold, while for the same cut-off grade the results are between 16,720 to 18,280 ounces of gold when historical pits are added to the information gathered during recent exploration campaigns. Possible explanations for this phenomenon are discussed, including a spatially biased sampling of the historical campaigns, or differences in the sampling and sample processing methods.

Finally, a classification of the estimated mineral resources was done. This is a first attempt in the scientific literature, up to the authors knowledge, to apply established categorisation methodologies to placer gold deposits; and it is a good example of how industry best practices could be used in small-scale mining projects. Nevertheless, more information of the MND is needed to comply with international reporting codes.

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Disclosure statement

JJJ is a shareholder in the company that owns the Mina Nueva Deposit. No other potential conflicts of interest are reported by the authors.

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Data availability statement

The four datasets used in the research are available as supplementary material to this publication (SM1). The resulting block models (six resource estimations) are also available as supplementary material (SM2). All other information is available upon request to the corresponding author.

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