

# Integration of Geostatistics and 3D Geological Modeling for Gold Resource Estimation in Goni prospect, Blue Nile, Sudan: Comparison between Ordinary Kriging (OK) and Simple Kriging (SK)

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**ABSTRACT:** Integrating geostatistics and 3D geological modelling provided a robust framework for gold resource estimation at the Goni prospect. Despite limitations from sparse drilling and a relatively high nugget effect, the validated database and compositing strategy established moderate spatial continuity, confirming structural control of mineralisation within shear-zone quartz veins. Comparative evaluation showed that Simple Kriging inflated tonnage by extrapolating marginal grades, while Ordinary Kriging yielded more conservative, geologically defensible estimates aligned with industry best practice. The 3D geological model constrained mineralisation to realistic domains, minimising grade smearing and enhancing block confidence. Future work should emphasise infill drilling, domain separation, and conditional simulation to reduce uncertainty and strengthen classification. Overall, this study demonstrates that integrating geostatistics with 3D modelling improves accuracy, reduces dilution, and provides a clear framework for reliable resource evaluation in heterogeneous gold deposits.

**Keywords:** 3D geological modelling, gold, geostatistics, ordinary kriging, simple kriging, resource estimation, Sudan.

## INTRODUCTION

Geostatistics has become indispensable in mineral resource estimation, particularly for gold deposits where grade variability and spatial continuity are major challenges. Recent studies emphasise the importance of combining geostatistics with 3D geological modelling to improve accuracy and reliability. Royer and Camara (2025) demonstrated how mineralogical and petrological data, integrated with 3D modelling and geostatistics, produced robust gold resource estimates. Similarly, Zhaxenbayeva *et al.* (2024) applied multiple-point

geostatistics to vein-type gold deposits, showing that 3D geomodeling constrained by geological structures enhances grade continuity and spatial accuracy. The role of implicit 3D modelling in grade estimation was highlighted by Liu *et al.* (2025), who noted that workflows combining geological domaining with geostatistical estimation yield more reliable block models. Brakoa *et al.* (2025) applied geostatistical methods to alluvial gold deposits, reinforcing the value of integrating drilling data with 3D modelling for resource quantification. These

studies collectively confirm that geological modelling provides the structural framework necessary for geostatistical estimation, reducing dilution and improving confidence in resource classification.

Comparisons between ordinary kriging (OK), simple kriging (SK) and other estimation methods remain central to gold resource evaluation. Amadu *et al.* (2022) compared OK with inverse distance weighting (IDW), concluding that OK provided more geologically consistent estimates, particularly in palaeoplacer settings. Similarly, Azmi *et al.* (2020) emphasised the role of OK in modelling grade continuity in the Damanghor gold deposit, where geological domaining was critical to reducing estimation bias.

Emerging approaches have also benchmarked kriging against alternative methods. Zaki *et al.* (2022) introduced machine learning algorithms for highly skewed gold datasets but confirmed that OK and SK remain reliable baselines for resource estimation. Sastry (2025) reinforced this by demonstrating Surpac-based workflows where OK was the default estimator, while SK was selectively applied in domains with well-defined mean grades. These findings highlight that while SK can be useful in stationary domains, OK is generally more robust in heterogeneous gold deposits.

Variogram modelling continues to underpin the reliability of kriging estimates. Darmawan (2025) stressed the importance of variography as the foundation of resource estimation, highlighting how directional variograms aligned with geological structures improve accuracy. In a broader context, Nwaila *et al.* (2025) presented an integrated geodata science workflow for the Merensky Reef, demonstrating how variogram analysis, combined with 3D modelling, enhances the reliability of resource estimation across complex domains. These studies confirm that careful variogram modelling, aligned with geological anisotropy, is essential for defensible resource estimation.

Across these studies, ordinary kriging emerges as the most robust method for heterogeneous gold deposits, particularly when combined with 3D geological modelling and domain-specific variograms. Simple kriging, while useful in stationary domains with well-defined means, is more sensitive to mis-specified parameters and often inflates tonnage by incorporating marginal-grade material (Brakoa *et al.*, 2025; Zaki *et al.*, 2022). The integration of Geostatistics with 3D modelling tools such as Leapfrog and Surpac has become standard practice, enabling precise block modelling and reliable grade estimation (Sastry, 2025).

Ordinary kriging is the primary method for estimating gold grades in sheared mesothermal deposits, as it accommodates local variability. Simple kriging is often unsuitable due to its assumption of a stationary mean, which poorly reflects heterogeneous shear zones. The highly skewed and nuggety mineralisation requires grade capping or transformations to mitigate outlier influence. Anisotropic variograms and restricted search neighbour-

hoods aligned with shear structures enhance model reliability. Thus, ordinary kriging, combined with rigorous grade controls, yields the most geologically defensible estimates (Amadu *et al.*, 2021; 2022; Zaki *et al.*, 2022).

Goni prospect lies about 10 Km east of Qeissan village, South-East Blue Nile state of the Sudan (Figure 1). Qeissan District forms part of the Pan-African Shield and is considered to have significant mineral potential. It is well known as a placer gold prospecting area. Ancient gold mining in the Goni area has extracted mainly from alluvial and eluvial formations derived from quartz veins and meta-volcanic rocks pits for the extraction of gold. Gold mineralisation in the area is associated with sheared quartz veins and stringers. These veins are pyritiferous and display secondary oxide staining, with tourmaline commonly infilling fractures. Textural and mineralogical features are indicative of a genesis related to mesothermal fluid activity within a shear zone environment. Gold-bearing quartz veins in the Goni show promising mineralisation with visible fine gold and trench samples indicating viable grades for exploration. The study in the Goni deposit concerned with the integration of geostatistics and 3D geological modelling, is based on diamond drilling, detailed core analysis and comparison between ordinary and simple kriging for more realistic gold resource estimation.

## METHODOLOGY

### Geology

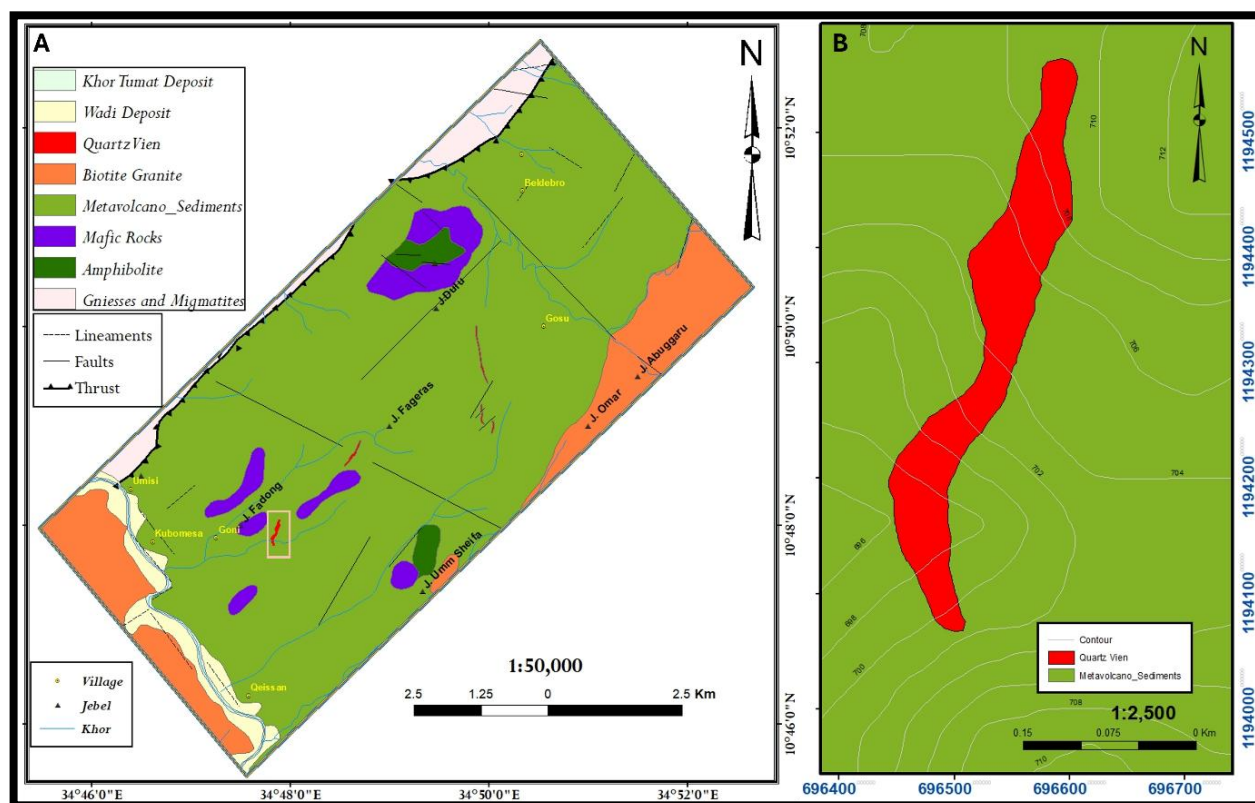
The Qeissan area is composed of Gneisses, amphibolites and a thick volcano sedimentary sequence, tectonic and sedimentary melange and mollasse, altogether representing a suture. These sequences occur as tectonic slices separated by thrusts, megashear zones and strike slip faults. The whole sequence is a result of the accretion of the arc system by continent-arc collision. These rocks were intruded by orogenic and anorogenic plutons (Figure 2A). Toum *et al.* (1992) assumed mineralization type in the Qeissan area is an epithermal gold deposit. Gold-bearing veins are primarily fracture-fill types, with central and oblique shear vein systems trending N-S to N15E and NE, respectively, aligning with the foliation of host lithologies. Gold ore zones display systematic vertical and lateral mineralisation changes, transitioning from brittle to brittle-ductile deformation (Khalil *et al.*, 1993).

Qeissan area, as the gold is found in the quartz veins, veinlets, and stringers, sericite schist, as well as in the basic meta-volcanic rocks (Adde *et al.*, 2007). Goni represents a part of the Qeissan area (Figure 2A).

### Gold mineralization

Goni vein or quartz body is of 1.0 to 1.5 km length and





**Figure 2.** Geology of Goni Prospect.

about 2.5 m width is cutting the volcano-sedimentary sequence of Qeissan belt. The quartz is of various colors iron oxides, pyrite, siderite and fine gold filling cavities. The gold is visible all over this quartz body (Figure 2B). About 6 % of the 53 Goni chip samples assay over 2 g/t Au, with an overall average grade of 0.6 g/t Au. A total of 9 trenches were made at the Goni prospect. The best intersections are by trenches 8 and 9, giving a total of 20 m @ 1.2 g/t Au.

### Drilling

Diamond core drilling was designed and executed in Goni, in order to, fully access the potential of the quartz veins and to confirm the reliability of the gold grades and determine the mineralised zone thickness and gold grade. Diamond cores drilled were fully described, mapped and documented.

Eleven diamond boreholes totalling 729.15 meters in depth were drilled. The borehole collars were marked on profile along the quartz vein body. Boreholes were drilled at angles of 60 degrees with 90 and 165 degrees as azimuth in order to intersect the down depth extensions of the auriferous quartz veins at 30.0 to 60.0 meters below surface. The diamond drill sample recovery good and

above 90%. The core was split at the site using saw blades, with half of the core sent for assay and the other half left in the store. 250 core rock samples were collected, crushed, pulverised and assayed for gold at Rida Laboratory; duplicate samples were sent to a United Arab Emirates Industrial Laboratory for cross check.

### Geomodelling (GM)

Geomodelling or geological modelling is the process of creating a three-dimensional representation of the geology, structures and mineralisation within a specific area, using data from various sources. For the process of geological modelling, several software can be used with drillhole data, logs and assays. Surpac is applied for 3D modelling of an orebody, and Leapfrog is used in 3D geological modelling.

### Estimation

The estimation was carried out using Surpac software, where two estimators were tested and compared; the estimator techniques are Kriging, ordinary (OK) and simple (SK).

## Database and data analysis

Data is collected from Eyat for mining and exploration. This data includes the collars, lithology, survey and assay. The Goni deposit has been explored by drilling 11 Dimond Drill holes, and 250 samples were collected from these locations at different depth intervals. A total of eleven diamond drill holes were well documented. However, only seven were incorporated into the 3D orebody model, as the remaining four have not yet been fully analysed. Boreholes were drilled at irregular spacing, ranging from 33 m to 67.5 m with an average of 54.5 m. This irregularity reduces confidence in resource estimation by creating uneven data distribution and grade uncertainty. Confidence can be improved through closer, regular drilling and geostatistical methods.

## Cleaning data

The data were cleaned up from any errors before using them in statistical, geo-statistical analysis and reserve estimation. Data cleaning includes data validation, inspecting data, and outlier value analysis. The database was verified in order to detect and repair errors in the records. Selected analytical data from the database were validated with the values from the laboratory's analytical certificates. These validations were checks: (1) for duplicate collar location records overlapping assay intervals, (2) negative assay values, and (3) drillhole depth versus final depth. The validation of the database did not return any significant issues, and there were no errors found in the final database. The analyses are in the opinion that the final drillhole database is adequate to support mineral resource estimation.

## RESULTS AND DISCUSSION

### Distribution and geological implications

The univariate analysis of Au assay data reveals a positively skewed distribution (skewness = 0.53) with a mean (2.46 ppm) significantly higher than the median (1.55 ppm) (Table 1). This asymmetry, visualised in the histogram and supported by a high coefficient of variation (1.09) (Figures 3 to 5), is characteristic of many precious metal deposits (Zaki *et al.*, 2022). The failure of the data to pass normality tests (Kolmogorov-Smirnov, Shapiro-Wilk) is expected and confirms the lognormal or mixed distribution typical of hydrothermal gold mineralisation, where high-grade veins are embedded within a lower-grade envelope (Azmi *et al.*, 2020). The presence of low extreme values (minimum 0.005 ppm) is attributed to samples from barren host rock or values below the detection limit, while erratic high values represent the nugget effect of coarse gold within quartz veins (Brakoa *et*

**Table 1.** Univariate statistical summary of Goni prospect.

Statistics parameter		Au(ppm)
N	Valid	250
	Missing	0
Mean		2.46441
Median		1.55200
Mode		0.005
Minimum		0.005
Maximum		8.800
Range		8.795
Variance		7.268
Std. Deviation		2.696015
Interquartile Range		3.27
Skewness		0.530
coef. of variance		1.09398

*al.*, 2025). This distribution necessitates robust estimation methods that do not assume normality, reinforcing the importance of compositing and top-cut strategies (Darmawan, 2025). The lower determined outliers were removed by applied cutoff of 0.25 ppm, and a top cut of 4.80 ppm, which helps to reshape the skewed distribution to a normal distribution.

### Spatial continuity and structural controls

Semi-variograms provide useful parameters for estimating and understanding spatial variability, including maximum search distance, anisotropy ratios, nugget value, sill value, and range. The spherical semivariogram model fitted to the composited data shows a moderate nugget effect (0.23) and a sill (0.47) reached at a range of 54.5 m (Table 2). The nugget/sill ratio of ~0.49 further suggests moderate spatial continuity, supporting reasonable confidence in resource estimation, though some local variability remains.

This defines the zone of influence for kriging and indicates the average spatial continuity of gold grades. Similar ranges have been observed in vein-type deposits modelled with multiple-point Geostatistics, where anisotropy aligned with structural trends improved continuity modelling (Zhexenbayeva *et al.*, 2024). This range defines the zone of influence for kriging and indicates the average spatial continuity of gold grades within the mineralised domain. To define anisotropy ellipsoid, Variogram maps used many elements (Table 3) and (Figure 6). The anisotropy ellipsoid (major: semi-major ratio = 3.28) reflects strong geometric control on mineralisation, consistent with structurally controlled deposits (Nwaila *et al.*, 2025). Explicit incorporation of anisotropy into search parameters is essential (Table 4), as isotropic interpolation would smooth grades across geological boundaries.

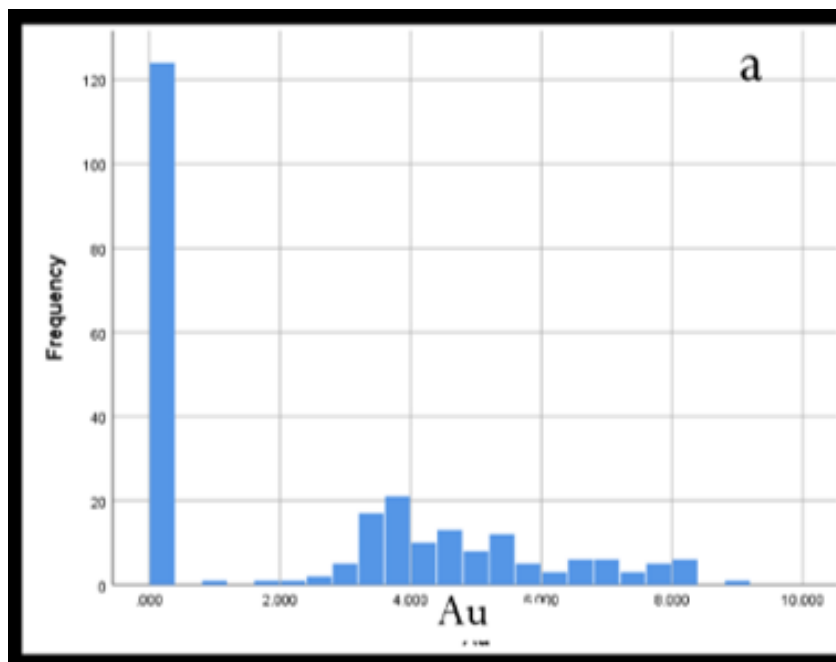


Figure 3. Histogram showing positive skewed distribution of Au, Goni prospect.

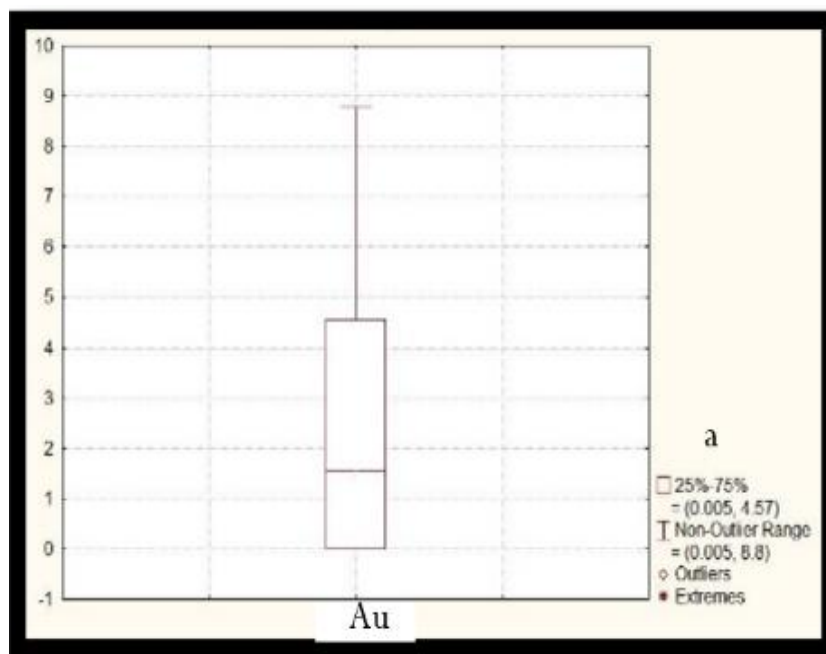


Figure 4. Box-plots showing a symmetric distribution of Au, Goni prospect.

### 3D Geological Model as a Foundation for Estimation

#### 3D Geology

Geological modelling helps to understand and effectively apply the fundamental principles governing geological

bodies, phenomena, and processes (Chen *et al.*, 2021). The 3D geological model, constructed from borehole data and geological mapping, effectively constrains the mineralisation to quartz veins hosted within a metavolcano-sedimentary sequence (quartz-chlorite schist).

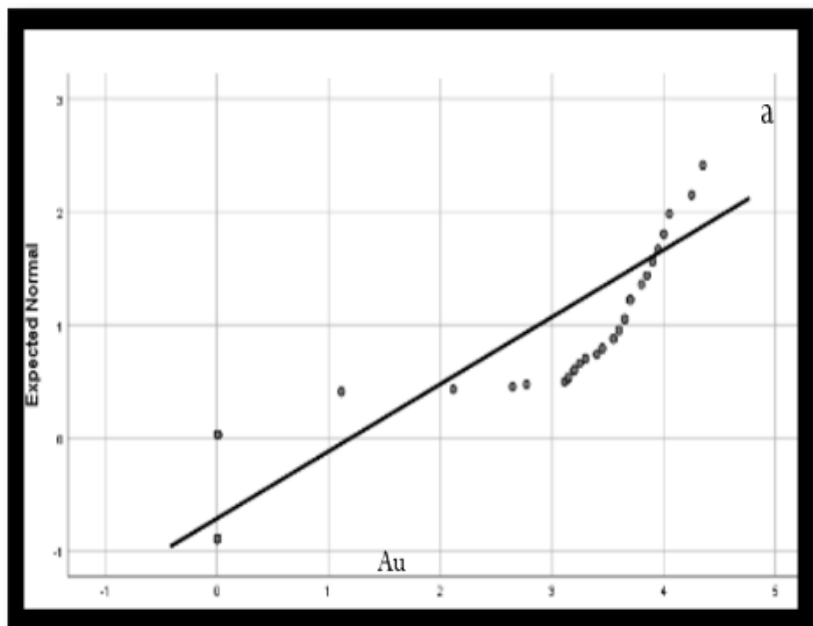


Figure 5. Q-Q plots showing a symmetric distribution of Au, Goni prospect.

Table 2. Variogram model parameters of Goni prospect.

Model Type	Nugget	Sill	Range	Structure
Spherical	0.22872	0.46869	54.553	1

Table 3. Elements used in variogram map.

Plane dip	Dip direction	N. of variogram	Spread angle	Spread limit	lag	Max. distance	N. of samples	N. of boreholes
-60	90	36	30	30	55	263	97	5

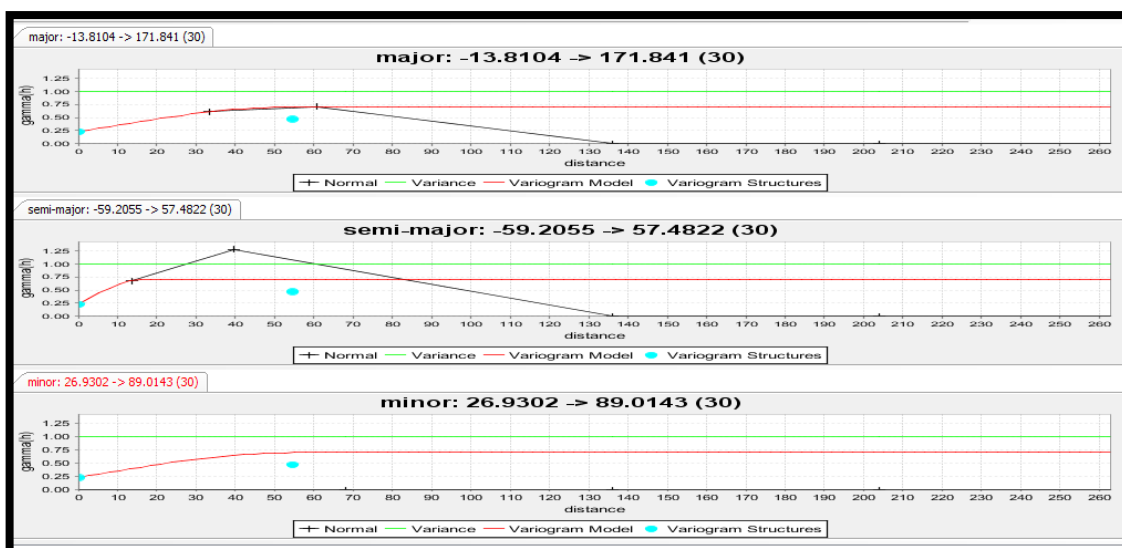
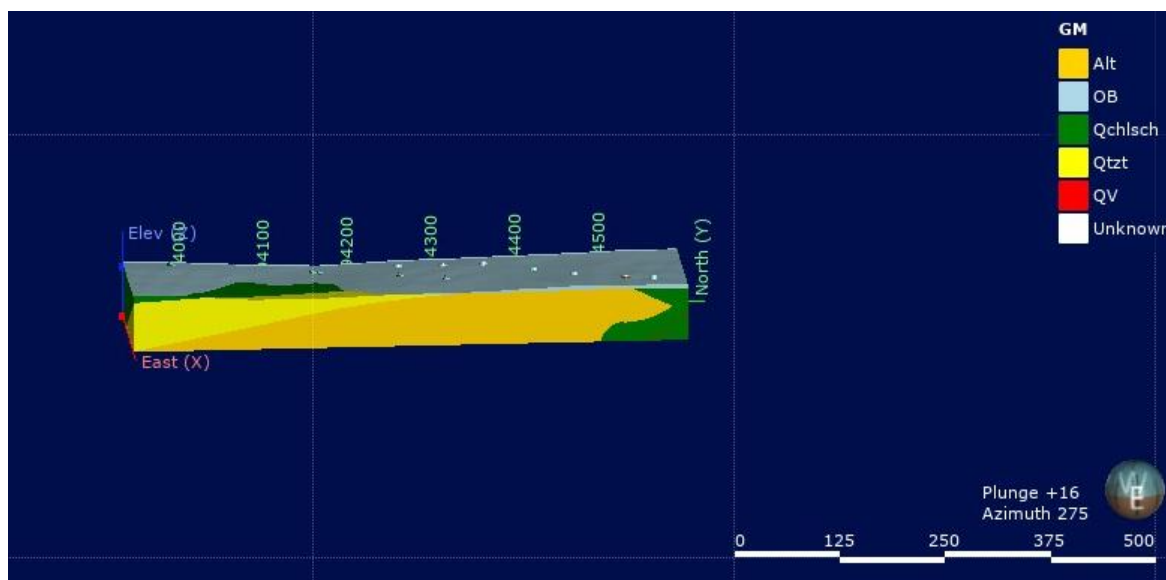


Figure 6. Experimental variogram and variogram modeling of Au, Goni prospect.

**Table 4.** Results of anisotropy parameters.

Plunge	Bearing	Dip	Major: semi-major	Major: minor
-13.81035	171.84095	62.2	3.278325	1



**Figure 7.** 3D geological modeling of Goni prospect. Alt = alteration, OB = overburden, Qchlsch = quartz chlorite schist, Qtzt = quartzite, QV = quartz vein.

### 3D geological object modelling

1. The methodology that was followed for 3D geological object modelling involved the following steps: Geoscience data acquisition and compilation: The study area data include a 1:2000 scale geological map (Figure 2), 11 borehole logs, lithological information, metavolcano-sediments (quartz chlorite schist), quartzites, quartz vein and alteration zone as a result of hydrothermal invasion and recently overburden, which is composed of clay, Landsat (OLI8) and pallasar images and DEM. Geological, topographical and gold assay data are quantified and standardised in the same 3D coordinate system.
2. Geoscience information interpretation and extraction: This is efficient and effective for deriving information from a number of geosciences data on the basis of geology and an ore deposit model.
3. Virtual section and virtual borehole construction are based on geological information, which is controlled from sparse borehole data by applying leapfrog software (Figures 7 and 8).

### 3D modelling of orebody

Orebody modelling is a reflection of the geological and

geometrical reality of an ore deposit (Roy and Sarkar, 2014). To create a 3D orebody model using Surpac software version 6.6.2 from GEOVIA, several steps were followed as listed below:

**Geological database creation:** Creation of the database is based on the raw data, which was obtained from the boreholes. four tables were imported into the database, containing different data. The imported tables are collar, survey, geology and assay in csv format.

**Ore sectioning and solid model generation:** Borehole assay data over 0.25 ppm are selected and digitised to create ore outlines in string format. These data were cleaned: removing overlaps, duplicates, spikes, and triangulated within and between section segments to build a 3D ore model (Figure 9). The model is then validated and used for visualisation, volume estimation, and geological database integration. Calculated volumes of solid objects (e.g., Trisolation1, True Solid) are compiled and verified (Table 5).

**Topographic surface (DTM):** XYZ data from a 10 m DEM are converted to string format and used to generate a digital terrain model (DTM), which is a representation of elevation data to represent the terrain of the Goni prospect.

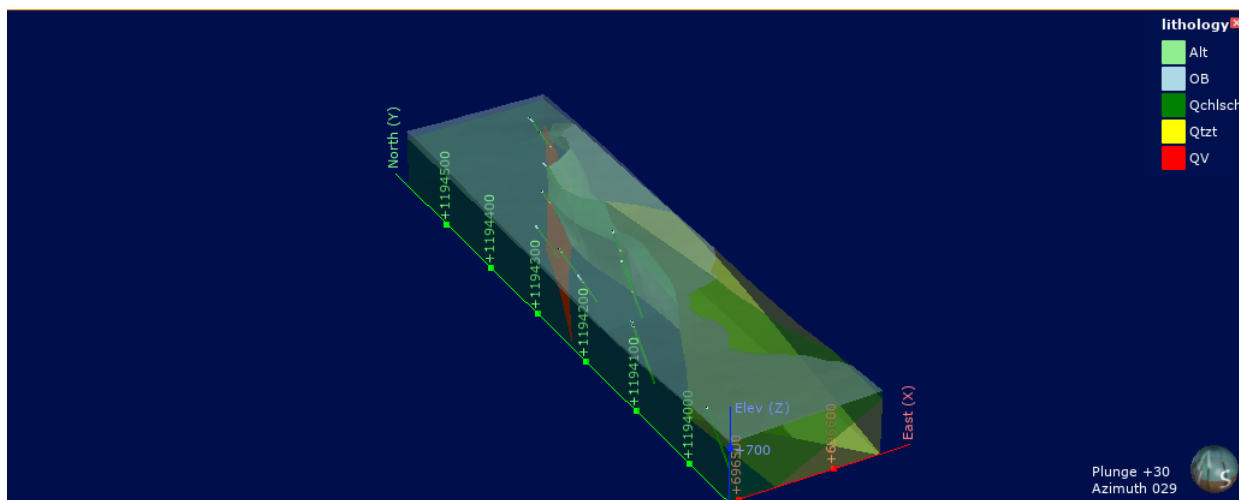


Figure 8. 3D geological modeling with transparency, looking (azi.029, plunge+30).

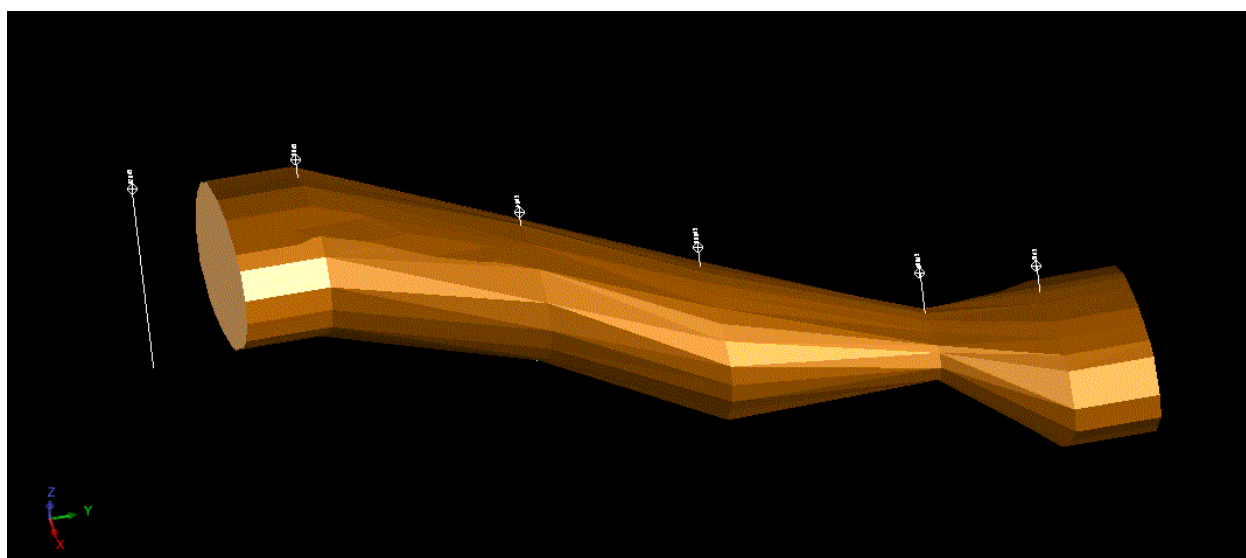


Figure 9. Shows solid model of Goni prospect with boreholes.

Table 5. Solid modelling orebodies report.

Minimum			Maximum			Area	Volume
X	Y	Z	X	Y	Z	(m <sup>2</sup> )	(m <sup>3</sup> )
696498.5	1194328.5	657.7	696656.6	1194577.1	706.6	42843	403936

This surface is applied to truncate the ore model, aligning it with actual topography.

**Block modelling:** Block modelling divides solid ore into customised block units for better resource evaluation. It determines ore deposit volume, compares with the solid

model, and estimates block grade using compositing techniques. The factors that determine the size of the block are mainly to reflect the changing characteristics of the ore body. If the block size is too large or too small, the sample evaluation result will be average, and it cannot accurately reflect the characteristics of grade changes. The size of

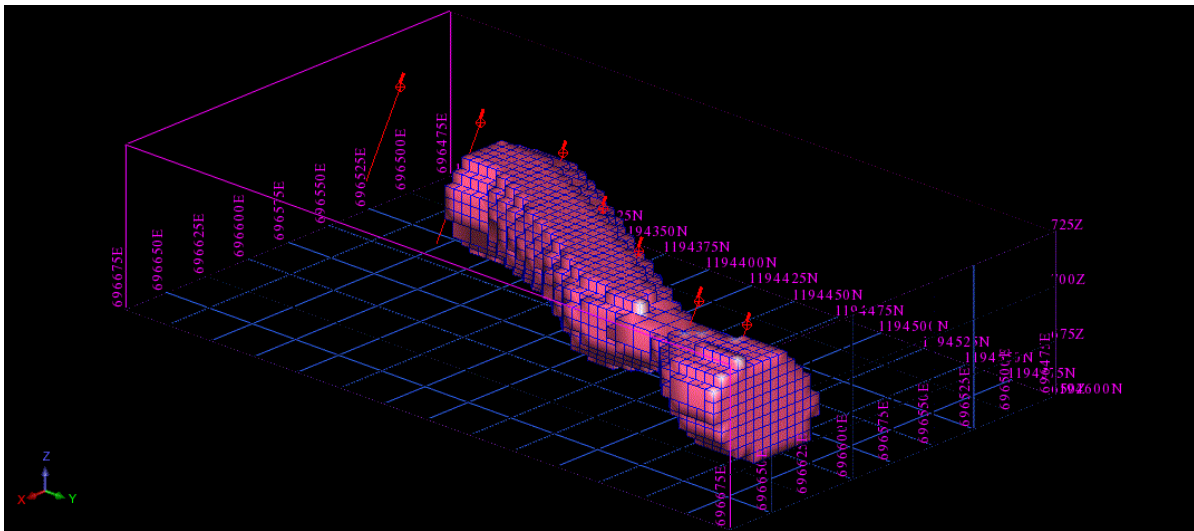


Figure 10. Constrained 3D modeling of orebody, Goni prospect.

these blocks is selected based on several factors, such as the drill hole spacing, mining method (bench height), and ore deposit geological settings. The optimal block size for estimation is mainly a function of drillhole spacing, and is one-half of the drillhole spacing or larger. If the deposit has consistent mineralisation and a low nugget, a quarter of the drillhole spacing may be acceptable. 3D coordinates spatially define the model extents. Block modelling has been done with a block size of 5 m x 5 m x 5 m. Then the block model is constrained according to the extent of the ore deposit, and the volume of the block model is calculated (Figure 10).

**Create composite:** Composite is an even representation of sample grades based on sample length to eliminate the bias. From a simple statistic of data length, the mode is 1.5m. The frequency of the sample lengths (Figure 11) shows the dominant sample interval, which is selected as the composite length. Figure 12 showed plot of the sample grades against the sample lengths; there are no remarkable patterns. Snowden (2009) reported that the data can be composited to longer lengths than the sample interval, because the variance becomes lower and the variography smooth and also reduces the amount of data available to work with. Based on that, the appropriate length is 2 m.

Downhole drill compositing has been done with a fixed length of 2 m composite length, with a minimum percentage of samples to be included as 75% and a multiple zone selection method for the ore zone. A total of 250 raw samples were collected, of which 132 were composited, yielding a combined value of 192.24 for the ore zone. The statistical analysis of these composites shows a mean grade of 1.46, with values ranging from 0.05 to 3.00 and a range of 2.95. The variance (0.284) and

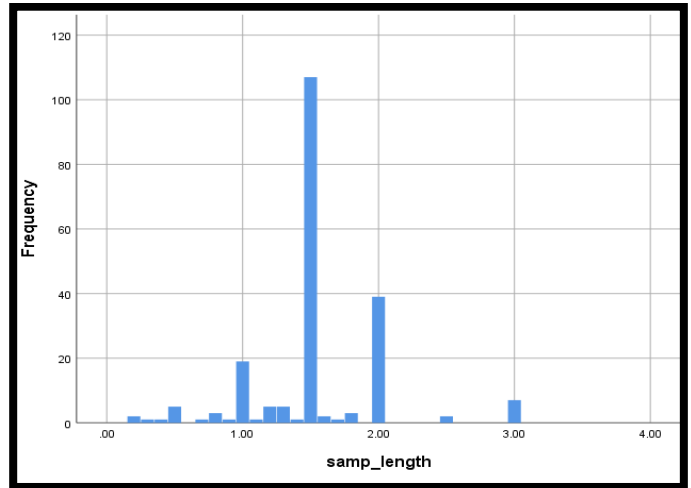


Figure 11. Composite length selection.

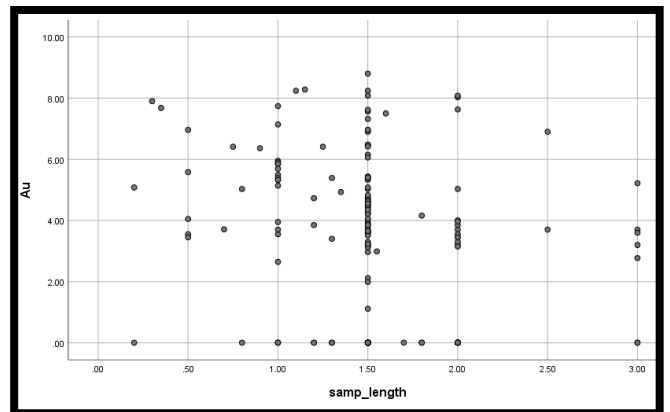
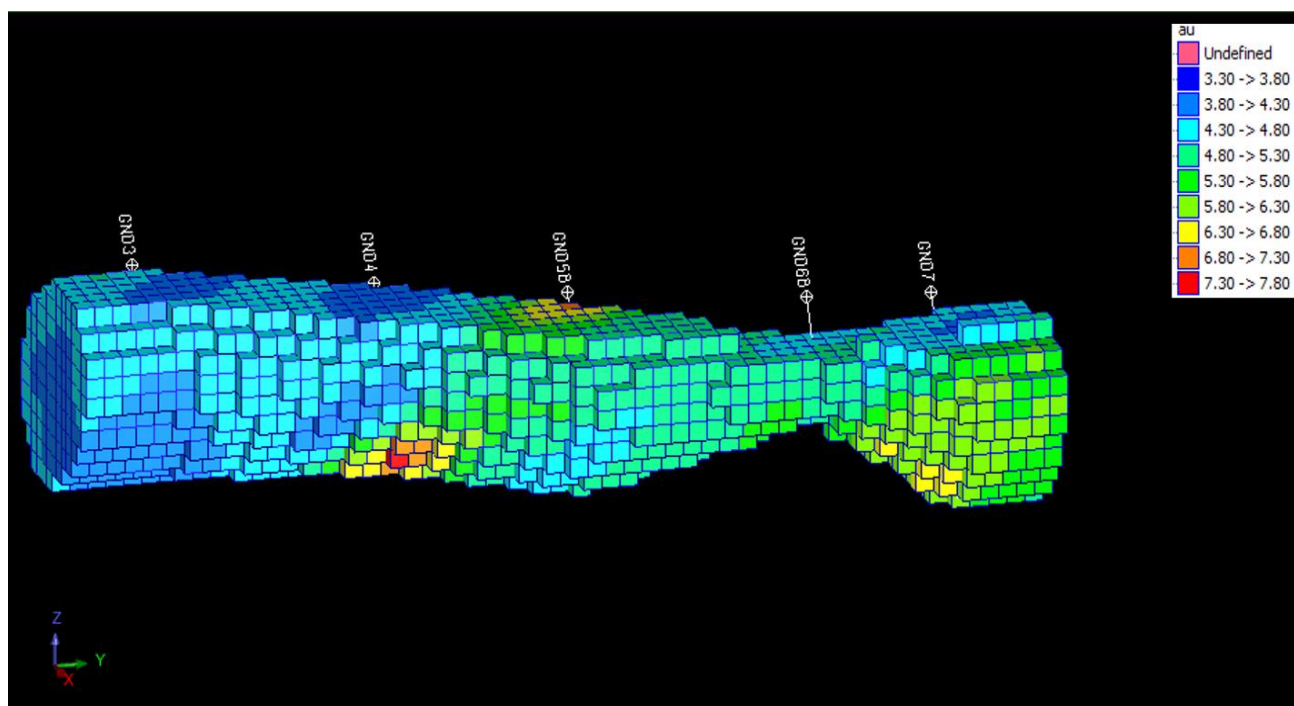


Figure 12. shows plot of the grades (Au) against the sample lengths.



**Figure 13.** Block model of the gold deposit with ordinary kriging estimator.

standard deviation (0.533) indicate moderate variability, while the coefficient of variation (0.37) suggests relatively consistent grade distribution within the ore zone. The compositing string is used in statistical analysis of data and geostatistical analysis.

The generation of a solid ore model (>0.25 ppm Au) provides a hard boundary for resource estimation, ensuring that interpolation occurs only within geologically justified volumes. This practice is fundamental to minimising the volume-variance effect and preventing the smearing of grades into barren wall rock (Rossi and Deutsch, 2014; Royer and Camara, 2025). Similar approaches in Surpac workflows emphasise the importance of geological domaining before block modelling (Sastry, 2025). The difference between the solid model volume (403,936 m<sup>3</sup>) and the final block model volumes highlights the volumetric discretion introduced during block estimation and the application of a top-cut or grade threshold (Liu *et al.*, 2025).

### Comparative evaluation of kriging methods and resource classification

Kriging is an interpolation technique, a fundamental method in the estimation of mineral resources. The effectiveness of kriging depends on the correct input of parameters that describe the semi-variogram model.

Practically, many decisions are required to make a kriging estimate, such as kriging type, search parameters and data selection (Deutsch *et al.*, 2014). Grade estimation of Au for a particular block has been done using the techniques of Kriging (Figures 13 and 14), ordinary (OK) and simple (SK) (Tables 6 and 7).

The comparative analysis of Ordinary Kriging (OK) and Simple Kriging (SK) yielded significantly different resource statements (Table 8). SK produced a larger tonnage (1.12 Mt at 3.50 g/t Au) by extrapolating grades into lower-grade zones (0.25–2.75 g/t Au), while OK, which estimates the local mean within each search neighbourhood, yielded a more conservative estimate (0.58 Mt at 4.71 g/t Au), effectively truncating lower-grade material (Table 9). Similar findings have been reported in Ghana, where OK provided more geologically consistent estimates than IDW or SK in palaeoplacer deposits (Amadu *et al.*, 2022; Brakoa *et al.*, 2025). SK's reliance on a global mean is problematic in skewed datasets, as confirmed by comparative studies (Mpanza, 2015; Zaki *et al.*, 2022). OK, by estimating local means, aligns more closely with the vein-dominated nature of the Goni deposit and industry best practices (Godoy and Dimitrakopoulos, 2004; Deutsch and Deutsch, 2015). The total contained metal difference (OK: 2.74 t Au; SK: 3.93 t Au) underscores the impact of methodological choice, with OK presenting a lower-risk, higher-grade scenario suitable for early-stage reporting.

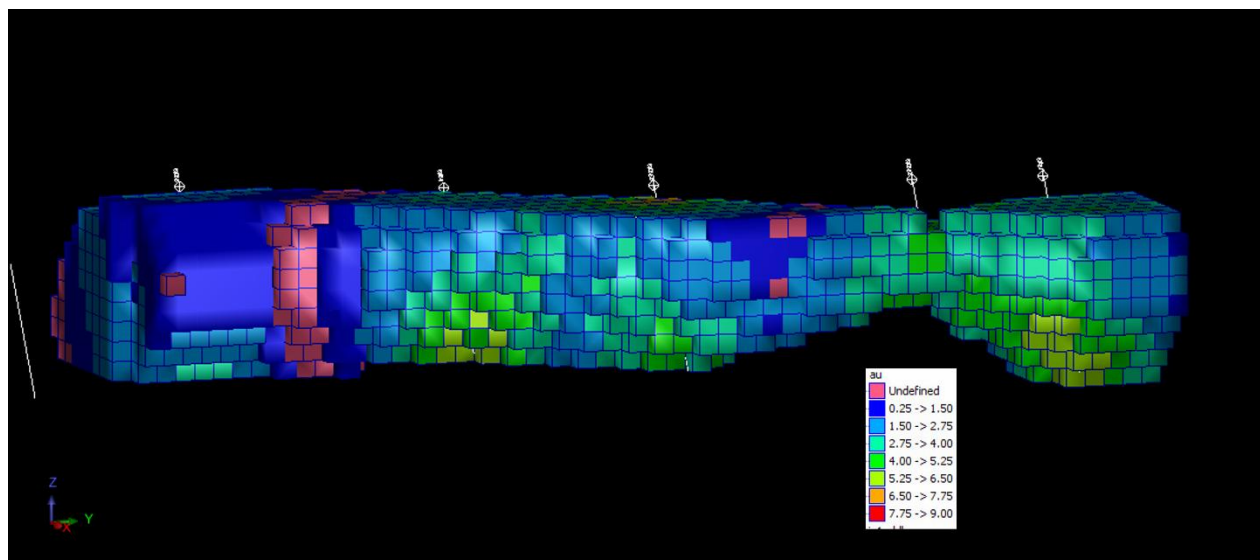


Figure 14. Block model of the gold deposit with simple kriging estimator.

Table 6. OK estimates of Goni prospect.

Gold (au)	Volume	Tonnes	Au g/t	Gold (t)
2.75 -> 4.0	98625	246563	3.50	0.86
4.0 -> 5.25	51000	127500	4.69	0.60
5.25 -> 6.5	56625	141563	5.82	0.82
6.5 -> 7.75	25125	62813	6.81	0.43
7.75 -> 9.0	1125	2813	7.84	0.02
Grand Total	232500	581250	4.71	2.74

Table 7. SK estimates of Goni prospect.

Gold (au)	Volume	Tonnes	Au g/t	Gold (t)
0.25 -> 1.5	45625	53753	1.22	0.07
1.5 -> 2.75	144375	302734	2.16	0.65
2.75 -> 4.0	112125	370148	3.34	1.24
4.0 -> 5.25	59875	273008	4.59	1.25
5.25 -> 6.5	19250	110276	5.75	0.63
6.5 -> 7.75	1750	11899	6.81	0.08
Grand Total	383000	1121817	3.50	3.93

Table 8. Comparison between OK and SK estimates of Goni prospect.

Grade Range	OK gold (t)	SK gold (t)
0.25-1.5	-	0.07
1.5-2.75	-	0.65
2.75-4.0	0.86	1.24
4.0-5.25	0.6	1.25
5.25-6.5	0.82	0.63
6.5-7.75	0.43	0.08
7.75-9.0	0.02	-
Total	2.74	3.93

**Table 9.** Compare OK and SK estimates of Goni prospect.

Estimation method	Volume	Tonnes	Au g/t	Gold (t)
OK	232500	581250	4.71	2.74
SK	383000	1121817	3.50	3.93

## Conclusion

Integrating geostatistics and 3D geological modelling provided a robust framework for gold resource estimation at the Goni prospect. Despite limitations from sparse drilling and a relatively high nugget effect, the validated database and compositing strategy established moderate spatial continuity, confirming structural control of mineralisation within shear-zone quartz veins. Comparative evaluation showed that Simple Kriging inflated tonnage by extrapolating marginal grades, while Ordinary Kriging yielded more conservative, geologically defensible estimates aligned with industry best practice. The 3D geological model constrained mineralisation to realistic domains, minimising grade smearing and enhancing block confidence. Future work should emphasise infill drilling, domain separation, and conditional simulation to reduce uncertainty and strengthen classification. Overall, this study demonstrates that integrating geostatistics with 3D modelling improves accuracy, reduces dilution, and provides a clear framework for reliable resource evaluation in heterogeneous gold deposits. These findings are consistent with recent advances in integrated geostatistical workflows, defining a coherent exploration target and providing a clear framework for future evaluation.

## CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

## ACKNOWLEDGEMENTS

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