

# SPATIAL VARIABILITY OF GOLD AND SILVER MINERALISATION IN THE SEDEFICHE DEPOSIT (THE EASTERN RHODOPES, BULGARIA): A GEOSTATISTICAL APPROACH

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**ABSTRACT.** Gold and silver mineralisation in the *Sedefche* deposit (the Eastern Rhodopes, Bulgaria) was investigated using statistical and geostatistical methods in order to evaluate the spatial variability and distribution of ore grades. The study is based on an integrated exploration database comprising more than 6000 geochemical samples from drill holes and surface workings. Descriptive statistical analysis indicates positively skewed grade distributions with mean values of 0.37 g/t Au and 14.3 g/t Ag. Geological domain modelling was performed using a cut-off grade of 0.3 g/t Au, which delineates the principal mineralised zones. Experimental variograms for gold reveal well-defined spatial continuity and pronounced anisotropy, oriented parallel to the N–NE elongation of the mineralised structures. The spatial structure of Au grades was modelled using a nested spherical variogram model and applied in ordinary kriging estimation, with a maximum correlation range not exceeding 40 m. In contrast, silver grades show weak spatial continuity and were estimated using inverse distance weighting. The results indicate distinct spatial trends and grade zoning within the deposit, reflecting strong structural control on mineralisation. The study demonstrates the applicability of geostatistical modelling for characterising epithermal Au–Ag systems and provides a quantitative framework for mineral resource classification in the *Sedefche* deposit.

**Key words:** gold, silver, geostatistics, variogram analysis.

## ПРОСТРАНСТВЕНА ПРОМЕНЛИВОСТ НА ЗЛАТО-СРЕБЪРНАТА МИНЕРАЛИЗАЦИЯ В НАХОДИЩЕ „СЕДЕФЧЕ“ (ИЗТОЧНИ РОДОПИ) – ГЕОСТАТИСТИЧЕСКИ ПОДХОД

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**РЕЗЮМЕ.** Златно-сребърната минерализация в находище „Седѣфче“ (Източни Родопи, България) е изследвана чрез статистически и геостатистически методи с цел оценка на пространствената променливост и разпределението на рудните съдържания. Изследването се основава на интегрирана база данни от проучвателни работи, включваща над 6000 геохимични проби от сондажи и повърхностни изработки. Описателният статистически анализ показва положително асиметрично разпределение на съдържанията със средни стойности 0.37 g/t Au и 14.3 g/t Ag. Геоложкото домейнно моделиране е извършено при гранично съдържание 0.3 g/t Au, което очертава основните минерализирани зони. Експерименталните вариограми за златото показват добре изразена пространствена непрекъснатост и анизотропия, ориентирана паралелно на протежението на минерализираната структура. Пространствената структура на съдържанията на Au е моделирана чрез вложен сферичен вариограмен модел и използвана при оценка чрез обикновен кригинг, като максималният обхват на пространствената корелация не надвишава 40 м. За разлика от златото, среброто показва слаба пространствена непрекъснатост и е интерполирано чрез метода на обратното претегляне по разстояние. Получените резултати показват ясно изразени пространствени тенденции и зоналност на съдържанията в рамките на находището, обусловени основно от структурния контрол върху минерализацията. Изследването демонстрира приложимостта на геостатистическото моделиране за характеризиране на пространственото разпределение на епитермална Au–Ag минерализация и предоставя количествена основа за моделиране на минерални ресурси в находище „Седѣфче“.

**Ключови думи:** злато, сребро, геостатистика, вариограмен анализ.

## Introduction

Epithermal gold–silver deposits of the Eastern Rhodopes form one of the more productive metallogenic zones in Southeastern Europe. These deposits occur within Oligocene volcanic and volcano-sedimentary sequences associated with sub-volcanic intrusions of the Zvezdel–Pcheloyad and related volcano-plutonic systems (Georgiev, 2012; Popov & Popov, 2022). Fault networks controlled the pathways of ore-bearing fluids and the sites of precious metal deposition. The Ada Tepe, Kupel, Pelevun, and Zvezdel–Pcheloyad ore fields are among the best-studied representatives of this province.

Mineral resource estimation in epithermal systems requires an accurate characterisation of the spatial distribution and variability of ore grades. Geostatistical methods — variogram analysis and kriging-based interpolation in particular — provide a quantitative framework for this purpose (Matheron, 1963; Isaaks & Srivastava, 1989; Stein, 1999; Wackernagel, 2003). These approaches model the spatial structure of geochemical data explicitly, improving grade estimates and reducing uncertainty in resource evaluations. Geostatistical analysis can also reveal geological controls on mineralisation that are difficult to identify by conventional deterministic methods.

The *Sedefche* deposit, located in the easternmost part of the Zvezdel–Pcheloyad ore field, has been investigated through multiple exploration campaigns spanning several decades. Despite this long history of investigation, the spatial variability of gold and silver grades within the deposit had not previously been subjected to systematic geostatistical analysis. A preliminary three-dimensional geological model of the ore zones at *Sedefche*, together with domain boundary analysis, was presented by Klimentov and Rouskov (2023). The present study builds upon and extends that work, providing a comprehensive statistical and geostatistical evaluation of Au–Ag grade variability, including variogram modelling, spatial anisotropy analysis, and grade estimation by ordinary kriging.

The objective of this study is to characterise the spatial distribution and variability of Au and Ag mineralisation in the *Sedefche* deposit through integrated statistical and geostatistical analysis applied to a unified exploration database. Particular emphasis is placed on the analysis of grade distributions, experimental variogram modelling, the quantification of spatial anisotropy, and the assessment of grade continuity within individual mineralised domains, with the aim of providing a sound geostatistical basis for resource modelling in this epithermal system.

## Geological Setting of the Deposit

### Regional Geological Framework

The *Sedefche* gold-silver deposit is situated immediately north-northwest of the village of Sedefche, within the easternmost sector of the Zvezdel–Pcheloyad ore field. This ore field is genetically and spatially associated with the Zvezdel volcano-plutonic complex and pertains to the Momchilgrad ore sub-region, which is localised within the Momchilgrad Depression (Georgiev, 2012; Popov & Popov, 2022).

The lithostratigraphic sequence of the deposit area comprises two principal complexes (Georgiev, 2012; Sarov et al., 2008). The pre-Tertiary metamorphic basement consists of biotite and two-mica gneisses, amphibolite-biotite gneisses, marbles, and kyanite-garnet-biotite schists (Sarov et al., 2008; Bonev et al., 2010). The overlying Tertiary volcanogenic-sedimentary cover is composed of sedimentary, volcano-sedimentary, and volcanic rocks. Immediately above the metamorphic basement lie Late Eocene organogenic limestones and sandy-clay rocks; locally, the limestones are partially silicified. Acidic to intermediate dykes — rhyolitic, dacitic, and andesitic in composition — represent products of Oligocene volcanic activity and intrude the earlier sequences (Nedyalkov & Mavroudchiev, 1995). The sequence is capped by Quaternary eluvial-deluvial sediments.

### Structural Setting

Four principal fault systems are recognised within the *Sedefche* deposit area. Sub-meridional faults are the most extensively developed and are interpreted to have exerted significant control over hydrothermal metasomatic processes and ore deposition, as evidenced by the N-NE elongation of the gold-silver ore bodies. Sub-latitudinal faults, striking W-NW (280–300°), represent the ore-hosting structures for polymetallic mineralisation in the Zvezdel–Pcheloyad ore field; they also serve as the conduits for a suite of rhyolitic, latitic, and rhyodacitic dykes that define the southern boundary of the ore field. Northwest-trending faults are well expressed as a prominent fault zone between the Asara and Dylgera hills. The zone hosts dykes and metasomatites and can be traced continuously for over 8 km to the Au-polymetallic Obichnik prospect. Northeast-trending faults are the youngest structural elements and are represented by short sinistral strike-slip fractures that cross-cut the hydrothermal metasomatites.

It is important to note that no dedicated three-dimensional structural model of the deposit has been constructed to date, a limitation that constrains the precision of the resource model (Dragiev & Dragieva, 2006).

### Ore Body Morphology and Mineralisation

Geological surveys have delineated two primary gold-silver ore bodies within the deposit: the Northern (Central) and the Southern ore bodies (Dragiev & Dragieva, 2006; Klimentov & Rouskov, 2023). The ore bodies lack visible geological boundaries in the field; their boundaries are therefore defined entirely on the basis of assay data from systematically sampled exploration workings.

The Northern ore body is an elongated structure (approximately 400 × 60 m) striking N-NE and hosted within intensely hydrothermally altered pyroclastic rocks and andesites. Its vertical extent reaches approximately 146 m, with elevations ranging from +559.7 m to +413.5 m a.s.l. The ore body is broadly layer-like and pseudo-conformable in shape,

broadly concordant with the basal levels of hydrothermally altered tuffs at or near their contact with organogenic limestones. In its northernmost sectors (north of profile XVII), the ore body progressively dips at 10–15° and cross-cuts multiple stratigraphic levels, reflecting structural rather than purely stratigraphic controls in this portion of the deposit.

The Southern ore body strikes N-S and is hosted within a silica cap overlying the limestone-siliciclastic sequence. The deposit is a typical representative of the low-sulphidation epithermal gold-silver type (Georgiev, 2012). Two broad styles of mineralisation are recognised. Base-metal/low-gold mineralisation with abundant sulphides (pyrite and marcasite) is closely related to the Zvezdel–Pcheloyad intrusive complex, which also hosts the *Pcheloyad* lead-zinc deposit. Gold-silver-bearing silica replacement bodies are partially stratabound and controlled by steep N-S structures; they are interpreted as a later event, potentially related to the younger rhyolite complex south of the deposit. The gold-bearing mineralisation contains abundant sulphosalts, and a significant proportion of the gold is considered refractory in character.

The present geostatistical study focuses on the Central sector of the deposit and is based on a reinterpretation of the available exploration data using an integrated database, as described in the following section.

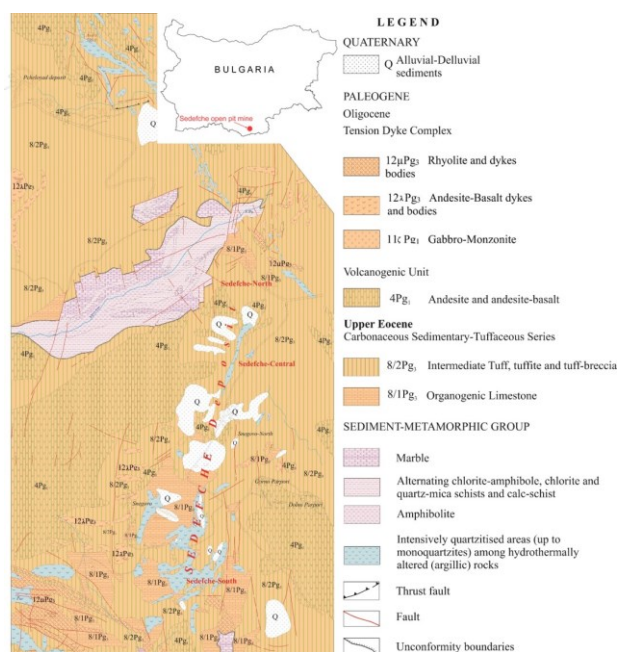


Fig. 1. Geological map in scale 1:50 000 (Cekova, V., 1965)

## Database and Sampling

### Data Sources and Exploration History

The geostatistical study is based on an integrated exploration database compiled from three successive phases of geological investigation in the Central sector of the *Sedefche* deposit. The data were acquired by *Geoinzhenering* JSC and *Gorubso-Kardzhali* JSC in the periods 1984–1993 (132 drill holes totalling 10,878.6 linear metres) and 2004–2005 (82 surface drill holes in 20 profile lines, totalling 2,119.2 linear metres), and subsequently by *Velocity Minerals* Ltd. during the most recent exploration campaign. The dataset encompasses

drill core (DD), reverse circulation (RC), trench, pit (shaft), and channel samples from surface workings.

The database of *Gorubso-Kardzhali* JSC (which incorporates the *Geoinzhenering* JSC data) contains records from 122 drill holes, 45 trenches, 41 pits, and 86 surface trenches for the Central sector. The *Velocity Minerals* Ltd. dataset comprises 81 core holes (including 3 duplicate holes) with a total length of 5,582 m and 52 reverse-circulation holes totalling 2,088 m (the latter being infill holes drilled by *Gorubso-Kardzhali* JSC following the completion of the *Velocity Minerals* block model). The combined, integrated database contains a total of 133 drill holes (81 DD and 52 RC), as reported in Klimentov and Rouskov (2023).

### Database Compilation and Verification

Data from the three exploration phases were compiled into a unified database and processed in Datamine Studio RM software. Prior to statistical analysis and geostatistical modelling, the database was subjected to a systematic verification and validation procedure to identify inconsistencies, duplicate entries, and anomalous or erroneous values. Collar, survey, lithology, and assay tables were cross-checked for completeness and internal consistency.

The grade data for Au and Ag show strongly right-skewed (positively skewed) frequency distributions, a characteristic feature of precious metal deposits in which high-grade assay intervals occur as a relatively rare but volumetrically significant population within a background of low-grade or sub-economic material. The skewness coefficients for Au (217.13) and Ag (158.49) confirm the extreme positive skewness of both distributions. The combined dataset contains 6,410 Au assay intervals and 6,833 Ag assay intervals.

### Compositing

The raw assay intervals in the *Gorubso-Kardzhali* JSC dataset exhibit variable sample lengths, with the most frequent lengths being 1 m (2,432 samples) and 2 m (1,789 samples), and a further prominent population at 1.6 m (1,483 samples). The *Velocity Minerals* Ltd. data are dominated by 1 m samples (5,271 samples) with a subordinate population at 1.2 m (772 samples). To eliminate the bias introduced by irregular sample support lengths and to ensure uniform data support for geostatistical analysis, all assay intervals within the mineralised domains were regularised to a uniform composite length of 1 m prior to variogram computation and kriging estimation.

## Variogram Analysis

### Methodology

Variogram analysis was conducted to characterise the spatial continuity and anisotropy of Au and Ag grades within the mineralised domains of the *Sedefche* deposit. Experimental semi-variograms were computed from the 1 m composited dataset, separately for each principal domain, in order to capture domain-specific spatial structures consistent with the stationarity assumptions required for ordinary kriging. Variograms were calculated at angular increments of 10°, and a contour map of variogram dispersion values derived from the experimental variograms was constructed to identify the principal directions of anisotropy (Fig. 2).

Down-hole (linear) variograms were examined as a first step. Although down-hole variograms are commonly the most

reliable indicator of the nugget effect because they are computed from the most closely spaced sample pairs, no interpretable spatial structure was recovered from the down-hole variograms in the present dataset, likely reflecting the irregular drill-hole orientations relative to the principal directions of grade continuity. Directional variograms were therefore relied upon exclusively for model fitting.

### Directional Variograms and Spatial Anisotropy

Directional experimental variograms computed for Au grades reveal clear anisotropic behaviour. The contour map of experimental variogram dispersion (Fig. 2) shows that the maximum spatial continuity is oriented parallel to the principal elongation of the mineralised structure, consistent with the dominant sub-meridional (N–NE) structural trend identified in the geological setting. The minimum continuity direction is perpendicular to the ore zone elongation, indicating that grade variability is greatest across the ore bodies.

Directional variograms for ore body 1 were computed in the azimuth range 80–170°, capturing both the direction of maximum continuity (approximately azimuth 170°, parallel to the ore body long axis) and the direction of minimum continuity (approximately azimuth 80°, perpendicular to the long axis). The experimental variograms (Fig. 3) clearly document this anisotropy: the correlation length (range) in the direction of maximum continuity significantly exceeds that in the perpendicular direction. The anisotropy is oriented in the plane of the mineralised zone, consistent with the structural control on mineralisation.

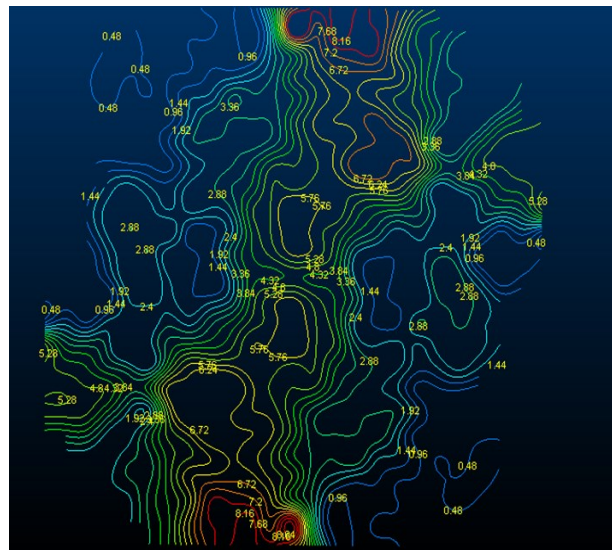


Fig. 2. Contour map of experimental variogram dispersion (azimuth vs. dip)

For silver, experimental variograms computed in all tested directions failed to yield a stable, interpretable spatial structure. The absence of a well-defined variogram model for Ag reflects the more heterogeneous and poorly spatially correlated distribution of silver grades within the deposit. This behaviour may be attributed to variations in the mineralogical associations of silver (sulphosalts, native silver) relative to the more spatially coherent gold distribution, or to the influence of multiple hydrothermal stages with differing Ag/Au ratios. For this reason, no variogram model was fitted for Ag, and silver grades were estimated using the inverse distance weighting (IDW) method.

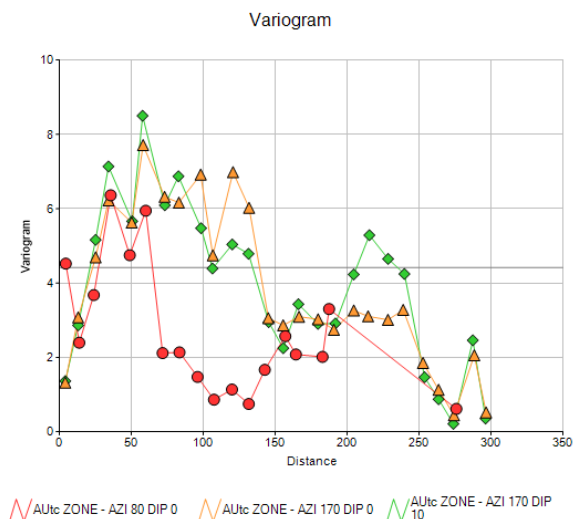


Fig. 3. Directional experimental variograms for ore body 1 at azimuth 80/170

### Variogram Model

The experimental variograms for Au in ore body 1 were modelled using a nested spherical variogram model with a triple (three nested components) structure (Fig. 4), following the approach described in Matheron (1963) and Wackernagel (2003). The nested model is composed of a nugget component and two nested spherical structures, which together adequately reproduce the observed spatial continuity at both short and long ranges. The anisotropy of the model is oriented in the plane of the mineralised zone.

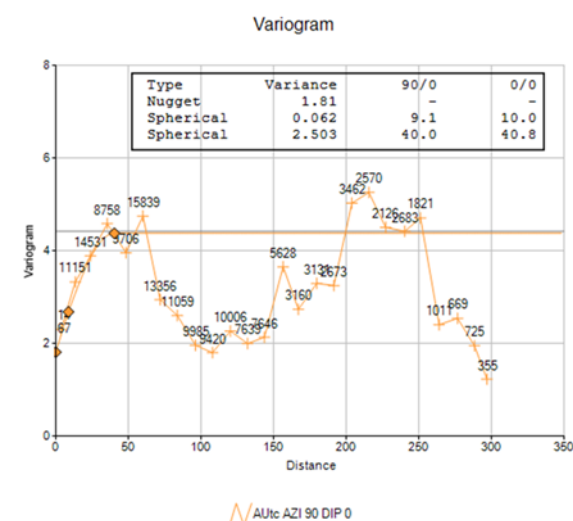


Fig. 4. Fitted spherical variogram model

The fitted variogram model defines a maximum correlation range not exceeding 40 m, consistent with the relatively short spatial continuity typical of structurally controlled, low-sulphidation epithermal mineralisation (Klimentov & Rouskov, 2023). The nugget-to-sill ratio reflects a moderate nugget effect, indicative of both small-scale grade variability below the 1 m composite support length and measurement uncertainty. The variogram model parameters were used directly to define the search ellipsoid orientations and semi-axes for the subsequent ordinary kriging estimation. This ensures geometric consistency between the estimation and the modelled spatial structure of Au grades.

### Geological Domain Modelling

Geological domain modelling — including wireframe construction of ore body boundaries, boundary analysis at the 0.3 g/t Au cut-off grade, and the three-dimensional characterisation of the spatial distribution of Au grades within the *Sedefche* deposit — was presented in detail by Klimentov and Rouskov (2023).

The three domains used in the present geostatistical study are: ore body 1 (the principal mineralised zone, N–NE elongated, approximately 700 m long and up to 170 m wide, with a vertical extent of 146 m), ore body 2 (a smaller body situated to the west of ore body 1), and zone 3 (the aggregate of 12 minor domains peripheral to the two main bodies).

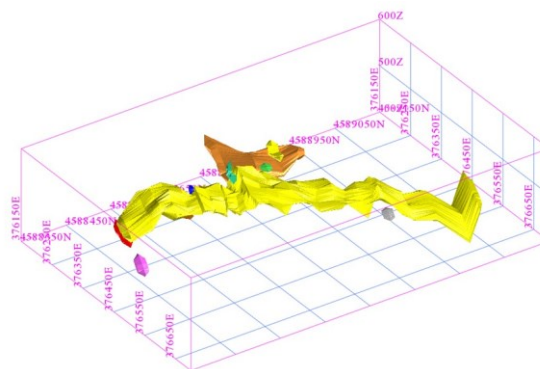


Fig. 5. Isometric view of all 14 domains after Klimentov & Rouskov (2023)

### Results and Discussion

#### Grade Distribution and Statistical Character of the Mineralisation

The combined exploration database shows grade distributions characteristic of low-sulphidation epithermal precious metal deposits. Both Au and Ag are strongly right-skewed, with skewness coefficients of 217 and 158 respectively: the bulk of the sample population is sub-economic, while a small proportion of high-grade intervals contributes disproportionately to total metal content. The arithmetic mean of 0.37 g/t Au is an order of magnitude higher than the median of 0.03 g/t Au, which reflects this skewness and shows why grade capping and compositing are necessary before geostatistical analysis.

The skewed distributions also have important implications for variogram modelling: the presence of extreme high-grade values (up to 34.83 g/t Au) inflates the variance of the raw data and can distort experimental variograms, particularly at short lag distances, producing artificially elevated nugget estimates. The application of a grade cap of 12 g/t Au for ore body 1 (and 7 g/t Au for domains 2 and 3) prior to variogram computation was therefore essential to obtain stable experimental variograms that accurately represent the spatial continuity of typical ore-grade intervals, rather than reflecting the erratic behaviour of rare extreme values.

High Au grades are not confined to a single lithological unit. Elevated mean values occur in quartzites (1.30 g/t), silicified rocks (1.08 g/t), clay-altered tuffs (0.97 g/t), and pyritic tuffs (0.45 g/t), but also in unmineralised country-rock lithologies at sub-economic concentrations. This distribution across rock types suggests that gold deposition was controlled primarily by

structural permeability — the fault network that channelled hydrothermal fluids — rather than by lithological controls alone.

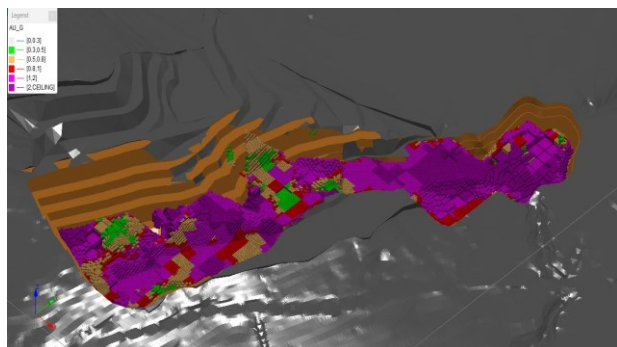
### Contrasting Spatial Behaviour of Gold and Silver

A notable finding of this study is the markedly different spatial behaviour of gold and silver within the same deposit. While Au grades exhibit well-defined spatial continuity with a fitted variogram model and a correlation range of up to 40 m, Ag grades show no recoverable spatial structure: the experimental variograms for silver in all tested directions failed to stabilise at a sill value, precluding the fitting of a reliable variogram model.

This contrast between Au and Ag spatial behaviour likely reflects fundamental differences in the mineralogical controls and depositional history of the two metals. Gold in low-sulphidation epithermal systems is typically concentrated in discrete silicified zones and quartz vein corridors whose geometry is closely governed by the structural framework, resulting in spatially organised grade distributions that are amenable to geostatistical analysis. Silver, in contrast, is often hosted in a wider variety of sulphosalt and sulphide minerals, which may be distributed more heterogeneously and may have precipitated during multiple hydrothermal pulses at varying temperatures, resulting in a more dispersed and spatially uncorrelated distribution. The gold-bearing mineralisation at *Sedefche* has been noted to contain abundant sulphosalts with a significant refractory gold component, suggesting a geochemically complex system in which different precipitation episodes may have generated Au- and Ag-rich assemblages with distinct spatial footprints.

From a practical perspective, the inability to model Ag spatial continuity means that inverse distance weighting (IDW), rather than kriging, is the more appropriate estimation method for silver. IDW provides a smooth interpolant that honours the data values at sample locations without requiring assumptions about the spatial correlation structure, making it more robust when no reliable variogram can be established. The resulting Ag estimates should therefore be interpreted with greater uncertainty than the Au kriging estimates, and any resource classification based on Ag grades alone would require a more conservative approach.

Taken together, the statistical and geostatistical results give a quantitative account of the spatial organisation of Au–Ag mineralisation at *Sedefche* that is consistent with the geological setting. The strong anisotropy of gold grades (Fig. 6), oriented parallel to the N–NE fault system, confirms structural control on mineralisation: auriferous fluids were channelled along favourably oriented, permeable fault zones. The short correlation range ( $\leq 40$  m) shows that grade continuity is limited even within these corridors. This reflects the episodic character of hydrothermal precipitation at the local scale.



chemical precipitation conditions along different structural pathways.

(7) The geostatistical approach applied here demonstrates that spatial analysis of grade variability can yield quantitative insights into the geological controls of epithermal mineralisation that complement and extend traditional geological mapping and logging. The short variogram range, the anisotropy orientation, and the domain-specific grade statistics together define a spatial model of the deposit that can directly inform the design of future exploration programmes. Building a three-dimensional structural model of the deposit is the most important outstanding step for improving the accuracy of grade estimation at *Sedefche*.

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