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MORPHOLOGICAL AND CHEMICAL CHARACTERISTICS OF NATIVE GOLD FROM DETRITAL ENVIRONMENTS: IMPLICATIONS FOR TRANSPORT AND SOURCE PROXIMITY

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Abstract: In this study, an integrated morphological and chemical analysis of native gold from alluvial deposits was conducted in order to determine the relationship between grain morphology, chemical composition, and the distance from the primary gold source. The investigation was carried out using scanning electron microscopy (SEM), whereby the morphology, surface texture, and microstructural characteristics of the gold grains were analyzed, along with their chemical composition (Au, Ag, and Fe). The results indicate significant variability in Au (88.73–99.53 wt.%) and Ag (0.47–9.19 wt.%) contents, whereas Fe is present only in trace amounts. A clear trend of increasing gold fineness with decreasing silver content is observed. Morphologically, the analyzed gold aggregates are predominantly characterized by irregular and angular forms, indicating limited transport and close proximity to the primary source. In addition, grains exhibiting flattened, lamellar, and rounded morphologies are present, which are typical of more distal positions relative to the primary environment. The obtained results confirm that the application of SEM-based morphological and chemical analyses represents a valuable approach for determining transport distance and for assessing the location of primary gold-bearing sources.

Key words: native gold; alluvial deposits; grain morphology; Au–Ag composition; fluvial transport; source distance

INTRODUCTION

Alluvial gold-bearing deposits are formed as a result of the erosion of primary ore occurrences, whereby gold, due to its high specific gravity and chemical stability, accumulates in fluvial systems and may represent a significant economic resource (Yeend et al., 1989).

Under natural conditions, gold most commonly occurs as an alloy with silver, known as an Au–Ag alloy or electrum, in which the ratio between Au and Ag can vary considerably depending on the conditions of mineralization formation (Boyle, 1979).

The chemical composition of native gold is widely used as an indicator in the exploration of gold deposits. Variations in silver content and other elements within gold grains may reflect the nature of the primary mineralization, but may also result from post-depositional processes such as supergene alteration and chemical weathering. Boyle (1979) emphasizes that gold in natural environments is often subjected to selective leaching of silver during weathering processes, leading to the formation of high-fineness gold with reduced Ag content.

Other researchers have also shown that, within fluvial systems, gold particles commonly develop Au-rich rims as a result of selective leaching of Ag, leading to a progressive increase in gold fineness with increasing transport distance (Groen et al., 1990; Chapman et al., 2021). These processes are particularly pronounced under oxidizing conditions and are controlled by the hydrogeochemical characteristics of the environment. As noted by Chapman et al. (2021), alluvial gold deposits reflect a combination of hypogene, supergene, and surface processes, with supergene transformations often enhancing gold fineness through the leaching of Ag. Furthermore, according to Chapman et al. (2021), supergene processes – especially the selective removal of Ag – frequently result in increased gold fineness and the development of pronounced chemical zonation within individual particles.

In recent decades, microgeochemical analysis of gold grains has been widely applied as an important tool in mineral exploration. Chapman et al. (2000) demonstrated that the compositional analysis of alluvial gold grains can aid in identifying primary sources of mineralization, even in regions covered by a thick regolith. According to these authors, the integration of morphological characteristics and chemical composition of the grains represents an effective approach for assessing source proximity and the type of mineralization.

Furthermore, in regolith and soil environments, gold grains may undergo significant supergene alteration. During weathering processes, dissolution of certain elements may occur, accompanied by the development of porous surfaces and the formation of microcavities within the grains. Larizzatti et al. (2008) showed that, in lateritic profiles, gold grains commonly exhibit corrosive textures and porous surfaces, indicative of active supergene processes. These processes can substantially modify the original geochemistry of the grains, particularly through the selective leaching of Ag.

The chemical composition of detrital gold can also provide insights into the genetic nature of the primary mineralization. Knight et al. (1999) demonstrated that the composition of alluvial gold commonly reflects the geochemistry of primary gold veins, and that variations in Ag content can be used to identify different mineralization sources within a given region.

In addition to chemical composition, the morphology of native gold grains represents an important parameter for interpreting transport history and the distance from the primary source of mineralization.

Gold is a highly malleable metal, and as a result, its grains are readily deformed during mechanical collisions with other sedimentary particles. Consequently, during transport, the grains may develop flattened or lamellar morphologies, while prolonged abrasion leads to the rounding of their edges. According to Nono et al. (2021), the morphology of detrital gold can provide direct information on transport history, whereby angular and irregular grains indicate short transport distances, whereas rounded grains are characteristic of longer transport.

Studies have shown that the morphology of gold grains evolves with transport distance: initially, gold exhibits minimal to moderate rounding, but with continued transport, a greater degree of flattening, rounding, and particle folding develops because of the metal's plasticity and the effects of fluvial abrasion (Youngson, 1999; Knight et al., 1999). Additionally, Townley et al. (2003) demonstrated that mechanical abrasion during sediment transport leads to the progressive rounding of grain edges and smoothing of gold grain surfaces, thereby allowing morphology to be used as an indicator of transport distance.

Recent studies increasingly emphasize the need for an integrated approach that combines morphological and chemical data to achieve a better understanding of the genesis and evolution of alluvial gold systems. Such an approach not only allows for the reconstruction of transport history but also has practical applications in guiding exploration activities and identifying potential primary gold sources (Knight et al., 1999a, 1999b; Dumula et al., 2001; McClenaghan, 2001; Youngson et al., 2002; Townley et al., 2003; Nakagawa et al., 2005; Rasmussen et al., 2006; Crawford, 2007; Stefanova et al., 2016, 2018, 2019; Chapman et al., 2010a, 2010b; Moles et al., 2011; Norman et al., 2011; Omang et al., 2015; Gjorgjiev et al, 2024).

GEOLOGICAL SETTING OF THE AREA

The geological structure of the area under exploration comprises rocks of various ages, as illustrated in Figure 1. The Precambrian rocks are represented by marbles and cipolines, as well as muscovite gneisses. The Paleozoic sequence includes cipolines and schists, phyllite-cipolines and marbles, and quartz porphyries. The Triassic and Jurassic formations consist of sandstones, schists, conglomerates, massive and bedded limestones, as well as diabases. Quaternary deposits are represented by tuffs and amphibole andesites. The area is drained by several river systems, including the Konjska Reka river, Matušnica river, Slivka river, and other smaller streams.

The lithological diversity of the terrain provides multiple potential primary sources for the gold identified in the concentrates. Notably, metamorphic rocks such as phyllites, schists, and gneisses are considered primary sources. Volcanic and subvolcanic rocks also represent potential sources of gold mineralization.

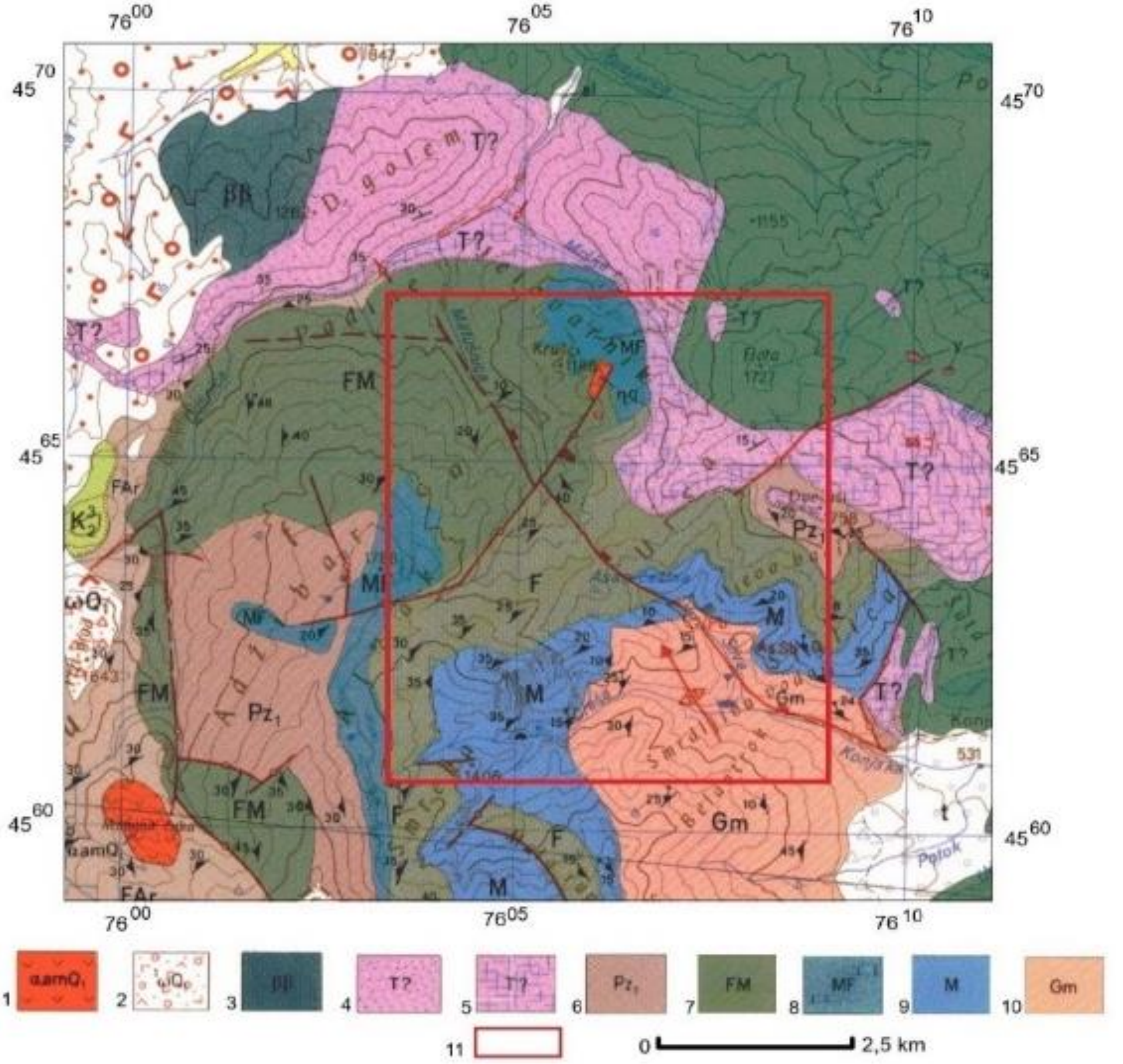

Fig. 1. Geological map of part of the Kožuf area (section of OGK)
1. Amphibole andesite, 2. Agglomeratic brecciated tuff, 3. Diabases, 4. Sandstones, clayey shales and cherts, 5. Bedded and massive limestones, 6. Quartz porphyries, 7.Phyllites, cipolins and marbles, 8. Cipolins and schists, 9. Marbles and cipolins, 10. Muscovite gneiss, 11. Area of interest

METHODOLOGY AND SAMPLING

The fieldwork applied the schlich method. Material was taken from places that were eligible for sampling with the possibility of concentration of heavier minerals (Figure 2). Samples of 15– 20 kg were taken. Then flushing was carried out and the schlich obtained was subjected to further processing. First, magnetic separation of minerals was performed and both fractions were observed under stereomicroscope. The gold aggregates found were manually separated and subjected to further investigation.

The analysis was performed in the electron microscopy laboratory of the University of Štip on a VEGA3 LMU instrument. The standards are TESCAN. Specific operating conditions are: Tension 20 keV; Test method: EDS: Type of analysis: Quantitative X-act: 10 mm^2 (Slicon Drift detector); Maximum resolution: 125 EV; Resolution of MnKα, FKα, CKα according to ISO/TS10798:2011.

One hundred and eighteen gold grains were selected from a collection of 10 samples, and only 40 electron-microprobe analyses were performed.

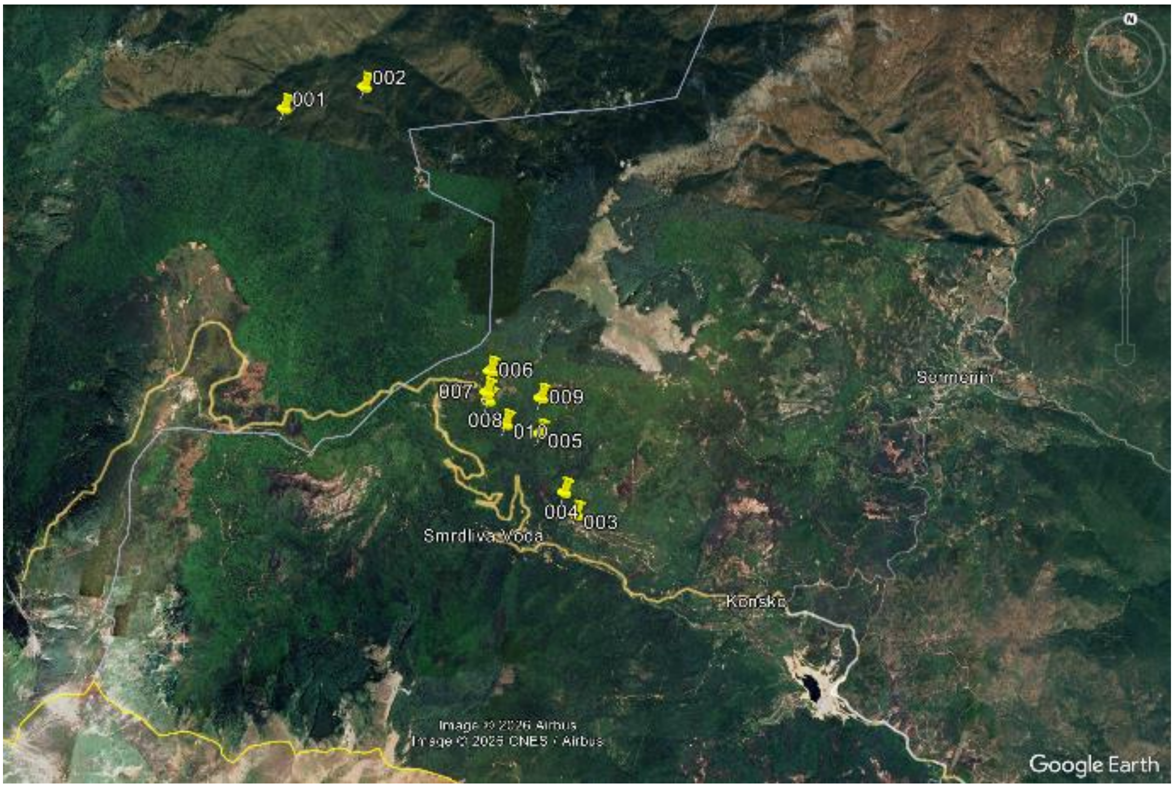

Fig. 2. Location of the testing sites

RESULTS AND DISCUSSION

During the prospecting survey, 10 samples were collected, from which approximately 180 gold aggregates of varying sizes and shapes were identified. In addition to gold, the concentrates contained other metallic minerals, including magnetite and pyrite, with rare occurrences of malachite. Among the non-metallic minerals, quartz, calcite, garnets, muscovite, epidote, and occasionally zircon were observed. Half of the samples were collected from river alluvium, while the remaining samples were taken from soil material adjacent to the river deposits.

The results of chemical and morphological analyses of native gold from alluvial deposits indicate a complex evolution of the gold grains, controlled by a combination of primary source characteristics, mechanical fluvial transport, and supergene processes in the surficial environment. Analysis at the individual grain scale provides valuable data on morphology and surface chemistry, which is particularly important for alluvial gold, as the grain surfaces are most exposed to secondary geochemical processes.

As highlighted by previous studies (Reith et al., 2012; Girard et al., 2021), gold grains may undergo processes of selective dissolution of Au and Ag, as well as the formation of new grains with altered morphology and chemical composition. These surface transformations result from the combined effects of mechanical and supergene geochemical processes, which modify the original structure and composition of the Au–Ag alloys.

Chemical characteristics of native gold

Studies indicate that in primary ore systems, gold most commonly occurs as an Au–Ag alloy, with the Au/Ag ratio being controlled by temperature, pH, redox conditions, and the composition of hydrothermal fluids (Hough et al., 2009). According to this author, epithermal and mesothermal systems often produce gold with higher Ag content compared to orogenic systems.

Our analyses show a predominance of Au with variable Ag contents and localized presence of Fe (Table 1).

The gold content ranges primarily from approximately 88 wt.% to over 99 wt.%. Silver varies from <1 wt.% up to around 9 wt.%. Iron is locally present, reaching values of up to ~9 wt.%.

Table 1

Chemical composition of gold aggregates

Sample No.	Au	Ag	Fe
1.1	89.90	8.21	1.89
1.2	96.29	3.31	0.8
1.3	94.16	3.77	2.06
1.4	94.51	7.3	3.5
2.1	91.71	8.28	–
2.2	97.24	2.76	–
2.3	96.93	3.07	–
3.1	98.01	1.99	–
3.2	88.73	2.47	8.8
4.1	97.53	2.47	–
4.2	96.73	2.77	–
4.3	95.97	4.02	–
4.4	98.51	1.49	–
5.1	90.80	9.19	–
5.2	93.3	2.2	–
5.3	96.39	3.61	–
5.4	93.99	5.86	–
6.1	99.53	0.47	–
6.2	96.69	3.3	–
6.3	95.81	4.29	–
6.4	96.86	3.14	–
7.1	95.96	4.04	–
7.2	98.73	1.27	–
7.3	96.19	2.63	1.18
7.4	96.05	2.87	1.07
8.1	96.78	2.29	0.92
8.2	97.38	2.62	–
8.3	98.5	1.5	–
8.4	97.81	2.19	–

Figure 3 presents a diagram showing the relationship between Au and Ag contents in native gold grains. The diagram reveals a negative correlation between Au and Ag, which is a typical feature of natural Au–Ag alloys (electrum). As the gold content increases, the silver content decreases. In the analyzed samples, most grains contain 95–98 wt.% Au, indicating high- to very high-fineness gold (Zakharova, 1994).

Variations in gold and silver contents are typical for alluvial gold and often suggest that the chemical composition may result from surface modifications of the grains, involving selective depletion or self-purification. During this process, Ag is leached from the Au–Ag alloy during fluvial transport, leading to relative enrichment of the grain rims in Au, forming gold-rich rims (Reith et al., 2012; Fairbrother et al., 2012), particularly on the surface portions of the grains (Groen et al., 1990; Chapman et al., 2010). The grain cores, however, can retain their original composition (Fairbrother et al., 2012; Chapman et al., 2002).

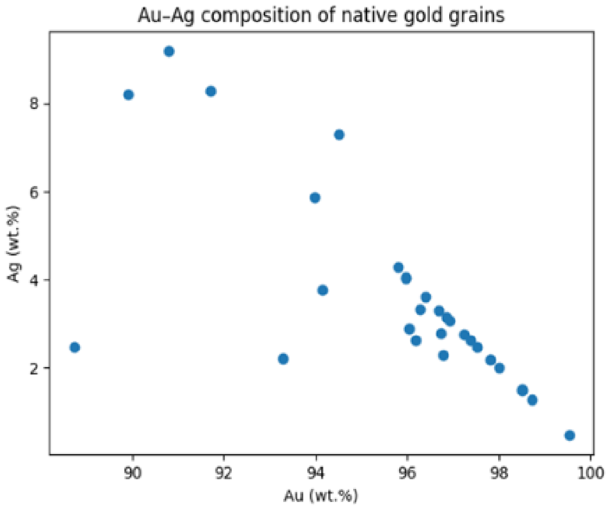

Fig. 3. Au–Ag composition of native gold grains

The wide range of Au–Ag contents may also indicate that the gold originates from heterogeneous primary sources and has been affected by secondary geochemical processes, so that it does not directly reflect the original composition of the source mineralization (Wierchowiec, 2002; Chapman et al., 2002). According to Chapman et al. (2010), such a range in Au–Ag composition reflects the combined influence of primary mineralization and post-depositional processes in the surficial environment, while also indicating transport distance and geochemical gradients.

Recent studies (Chapman et al., 2021) show that these Au-enriched surfaces can reach >99 wt.% Au, even when the primary gold was considerably richer in Ag. These investigations have documented porous textures, microfractures, and secondary Au precipitates resulting from geochemical reactions in oxidizing, shallow environments.

Figure 4 presents a histogram of silver contents in the analyzed gold aggregates. The figure shows that the majority of analyses are clustered in the ~2–4 wt.% Ag range, while a smaller group of samples exhibits higher Ag contents (7–9 wt.%). Very low values (<5 wt.% Ag) indicate very high-fineness gold.

The microchemical characteristics of the Au–Ag alloys in the gold grains from these localities show the presence of silver, without a clear downstream trend in fineness or Ag content. According to Chapman et al. (2011), this may indicate that the dominant mechanisms controlling chemical variation are not simply supergene Ag-leaching processes during transport, but may also reflect the influence of multiple primary sources and the gradual mixing of gold from different origins.

However, other studies have shown that gold fineness and the Ag content of grains can be further modified even during relatively short transport distance or by local supergene processes (Craw et al., 2017). Accordingly, the variability of Ag content in the analyzed grains (Figure 3) can be used as an indicator of the degree of fluvial reworking and the distance from the primary source. Grains with lower Ag content (<2 wt.%) generally indicate longer transport and multiple redepositions, whereas higher Ag contents (5–9 wt.%) may suggest closer proximity to the source mineralization (Chapman et al., 2000, 2003; Hough et al., 2009; Knight et al., 1999; Craw et al., 2017).

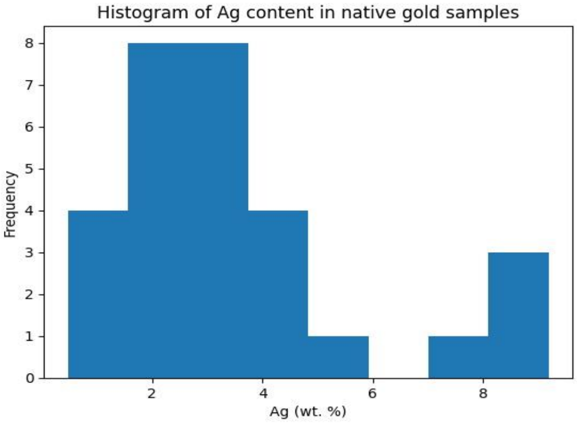

Fig. 4. Histogram of silver contents in gold aggregates

In the examined samples, iron was detected in only a portion of the analyses, while in most cases it was absent. The Au–Fe diagram (Figure 5) shows that Fe does not exhibit a clear correlation with Au. Iron is present in only a few analyses (0.8–3.5 wt%), at low concentrations. Only sample 3.2 shows an atypically high value (8.8 wt.% Fe).

This indicates that Fe is not an intrinsic component of the Au–Ag alloy, but rather represents an inclusional or surface signal, rather than a primary Au–Ag–Fe alloy, most likely originating from iron oxides or mineral particles adhering to the grain surfaces. Larizzatti et al. (2008) demonstrate that in regolith profiles, gold grains are often coated with iron oxide films formed during weathering processes.

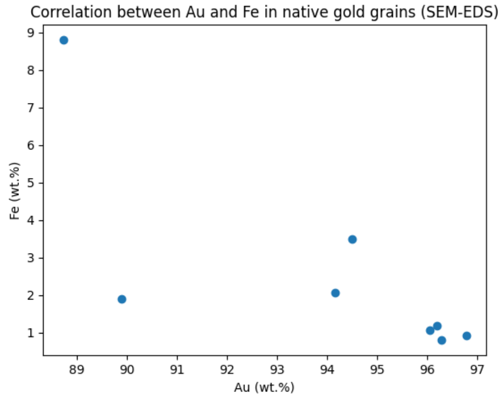

Fig. 5. Correlation diagram between gold and iron contents in native gold grains

A cumulative diagram (Figure 6) was constructed to show the distribution of Ag content in native gold grains from the studied area, with the samples divided into alluvial material (Table 1, samples 1.1 to 4.4) and soil material adjacent to the alluvium (Table 1, samples 5.1 to 8.4). The diagram reveals notable differences between grains obtained from river alluvium and those from soil material.

Gold grains from the river alluvium exhibit a relatively narrower range of Ag content, most commonly between ~1.5 and 8.3 wt.% Ag. The cumulative curve shows a gradual increase in Ag values, indicating a relatively homogeneous population of gold grains with moderate silver content.

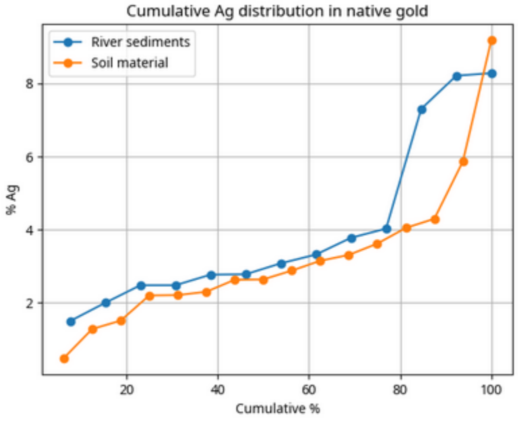

Fig. 6. Cumulative distribution of Ag content in native gold grains from river sediments and soil material.

In contrast, gold grains extracted from soil material exhibit a wider compositional range, from very low Ag values (~0.47 wt.%) up to approximately 9.2 wt.% Ag. The presence of very low Ag concentrations indicates high-fineness gold, which may result from secondary geochemical processes, such as the selective leaching of silver during weathering and supergene alteration. The steeper slope observed in the upper part of the cumulative curve suggests a more heterogeneous population of gold grains.

A comparison was made between the fineness of gold aggregates from alluvial samples and those from soil samples (Figure 7).

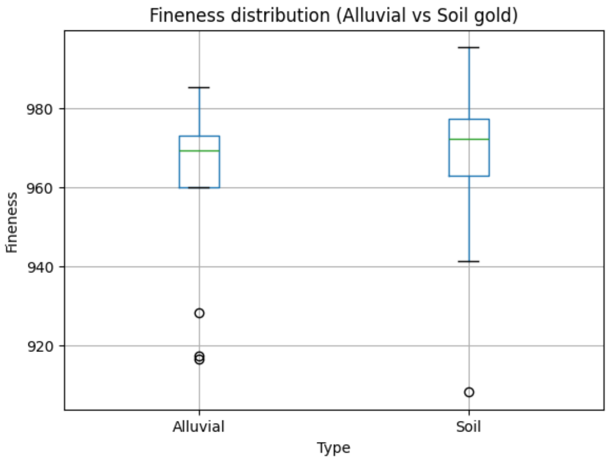

Fig. 7. Distribution of gold fineness in alluvial and soil samples

The calculated fineness values range approximately from 916 to 995, indicating high-fineness native gold. Most grains exhibit fineness between 960 and 980. This range is characteristic of many hydrothermal gold mineralization.

The diagram (Figure 5) shows that alluvial grains have slightly higher Ag content, while soil-derived grains exhibit higher fineness. This difference can be explained by supergene alteration under soil conditions. Boyle (1979) notes that silver can be selectively leached from native gold during weathering processes, resulting in the formation of high-fineness gold. This process leads to the preferential removal of Ag, making the grains relatively enriched in Au.

Such variations in Ag content between gold grains from fluvial sediments and those from soil material can also be interpreted as evidence for multiple gold sources or for differing degrees of post-depositional modification. As previously noted, during transport and weathering processes, silver can be partially removed from gold grains, leading to an increase in gold fineness in secondary environments.

Studies indicate that the observed chemical heterogeneity among grains may reflect either multiple primary gold sources or different transport and depositional histories within the same alluvial system (Chapman et al., 2002; 2011).

Morphological characteristics of native gold

SEM analysis of native gold grains recovered from alluvial river material reveals morphological diversity, which directly reflects the mechanical and chemical evolution of the grains during their transport from the primary source to the depositional environment. Gold morphology is widely recognized as an indicator of transport distance and intensity, as well as post-depositional processes (Knight et al., 1999; Youngson et al., 1999; Hough et al., 2009; Craw et al., 2017).

For the interpretation of results, the grains were classified into those recovered from alluvial samples (Table 2) and those recovered from soil (eluvial) samples (Table 3).

At the studied locality, SEM images reveal significant variability in the morphology of gold grains, ranging from irregular, angular to sub-angular forms, to more rounded and flattened particles with smooth edges (Tables 2 and 3). These differences are directly related to the intensity and duration of fluvial transport (Giusti, 1986; Youngson et al., 1999). The analysis of the grains shows the presence of irregular, angular forms with sharp edges and rough surface textures (Table 2, Figures 1.1, 1.2, 2.1), as well as elongated, irregularly shaped grains with preserved sharp edges and uneven surfaces (Table 2, Figures 4.2 and 4.3). This morphology indicates minimal mechanical abrasion and a short transport distance from the primary source. The lack of rounding and the presence of fresh fracture surfaces are typical of gold that has been liberated from the host rock and deposited near the source (Giusti, 1986; Chapman et al., 2010). These grains generally retain the original shape acquired during primary mineralization, reflecting direct release from the primary source, i.e., a short transport path or proximal zone, with minimal mechanical abrasion.

Some grains exhibit moderate rounding, partially rounded edges, and evidence of plastic deformation (Table 2, Figures 1.3, 1.4, 2.2, and 2.3), or display a complex porous structure with numerous indentations and uneven surfaces (Table 2, Figure

4.4). These features are typical of moderate transport distances, during which the gold gradually deforms due to its high malleability (Knight et al., 1999; Townley et al., 2003). Partial rounding indicates that the grains were transported over distances of several kilometers, but without complete loss of their original morphological characteristics. These features result from a combination of mechanical abrasion and plastic deformation, as well as potential selective leaching of silver (Ag) from the surface. According to Knight et al. (1999), such characteristics are typical for intermediate transport distances. During this stage, microscopic fractures and locally smoothed surfaces often develop, reflecting progressive mechanical modification (Knight et al., 1999; Hérail et al., 1990).

In Table 2, Figures 3.1, 3.2, and 4.1, the grains are predominantly rounded to sub-spherical, with relatively smooth surfaces and no sharp edges. These morphological features are characteristic of long-distance transport, where continuous abrasion and plastic deformation result in significant reduction of the original shape. The observed forms may result from a combination of mechanical wear and chemical processes. Youngson et al. (1999) and Hough et al. (2009) emphasize that such grains serve as indicators of substantial distance from the primary source, often several kilometers along a river system. This morphology is typical of gold transported over long distances, frequently exceeding 10–20 km from the primary source, consistent with both experimental and field observations (Knight et al., 1999; Youngson et al., 2002).

The overall morphological evolution of the analyzed grains indicates a continuum from short to long transport distances, with different forms representing various positions within the depositional system. The combination of angular, deformed, and rounded grains within the same depositional context suggests a mixed source and variable transport history, including contributions from both local and more distant sources, as well as repeated redeposition – a common feature in fluvial gold-bearing systems (Giusti, 1986; Chapman et al., 2010).

However, Hough et al. (2007, cited in Fairbrother et al., 2012) argue that the morphology of grains, particularly those found in stream sediments, is not necessarily diagnostic of source or transport distance, but rather provides evidence of supergene transformations experienced by the grains.

SEM micrographs of gold grains extracted from soil samples reveal pronounced morphological heterogeneity. The grains exhibit irregular shapes, often with uneven contours, indentations, pores/perforations, rough microrelief, and localized flattening. Only a small number of grains are smoother and more rounded. This morphological diversity indicates that the samples do not represent a fully homogeneous population. They comprise a mixture of grains with varying degrees of mechanical and supergene modification, or a complex combination of primary characteristics inherited from the host rock and secondary modifications associated with pedogenic processes. Unlike classic alluvial grains, gold in soil typically exhibits limited mechanical abrasion and short to negligible transport distances.

The majority of the grains exhibit irregular shapes, rough surfaces, and uneven edges (Table 3, Figures 7.3, 5.3, 5.4, 8.2, 8.3). These grains often display indentations, protrusions, and preserved microrelief structures. The retention of such irregular morphologies indicates limited mechanical abrasion, which is typically associated with short transport from the primary source. As noted by Nono et al. (2021), angular forms indicate short transport distances, whereas rounded grains suggest longer transport. In other words, angular and irregular grains are characteristic of proximal sedimentary environments, representing eluvial–colluvial accumulation within the soil cover above or near the primary mineralization.

Some of the grains exhibit a flattened or flake-like morphology, with thin edges (Table 3, Figures 5.1, 6.3, 6.4). These morphological features result from plastic deformation of the gold, which, due to its high malleability, easily deforms during transport. Becerra et al. (2022) emphasize that the size and shape of gold particles change during fluvial transport, gradually becoming flattened and rounded. Flattened grains in soil samples likely indicate short to moderate transport distances, where the grains were mechanically modified but not subjected to sufficient transport to achieve complete rounding.

Some of the grains display perforations, cavities, and a porous surface (Table 3, Figures 6.2, 7.1, 7.4, 8.1). These textures are not necessarily solely the result of mechanical transport, but can also be associated with supergene alteration in the soil environment. In a study on gold morphology in a lateritic profile, Larizzatti et al. (2008) report that the surfaces of grains often develop voids and corrosive pits, along with gradual rounding from the bottom to the top of the profile, indicating that the grain surfaces can be modified through dissolution and re-precipitation processes within the regolith.

Table 2.

Morphology of gold grains from alluvial deposits

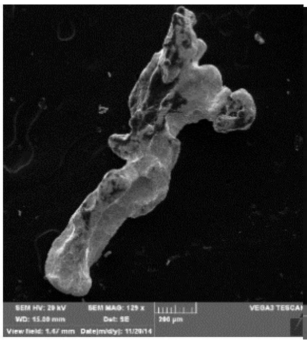

Fig. 1.1. Pronouncedly elongated, irregular, and partially branched shape

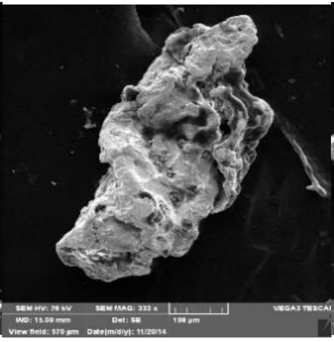

Fig 1.2. Irregular and slightly rounded shape

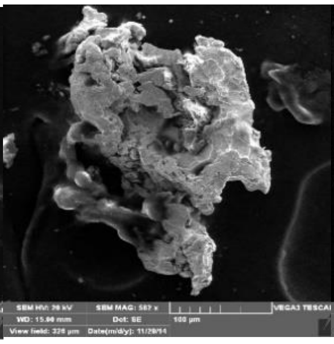

Fig. 1.3. Massive, aggregated, and highly irregular shape

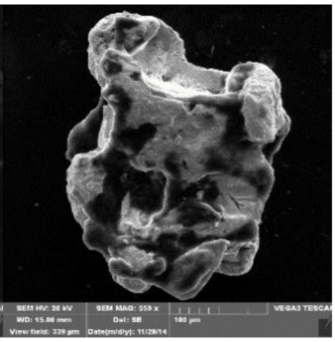

Fig.1.4. Massive, irregular shape with slight rounding

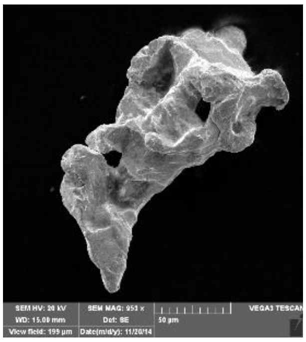

Fig. 2.1. Irregular, elongated, and slightly rounded shape

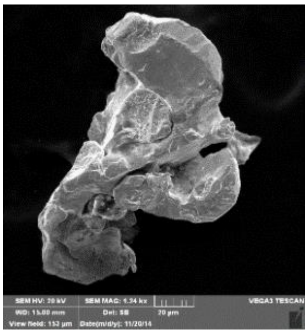

Fig. 2.2. Massive, irregular, and slightly rounded shape

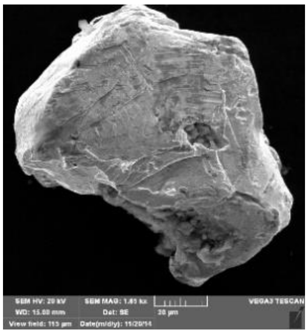

Fig. 2.3. Compact, massive, and slightly rounded shape, relatively smooth surface

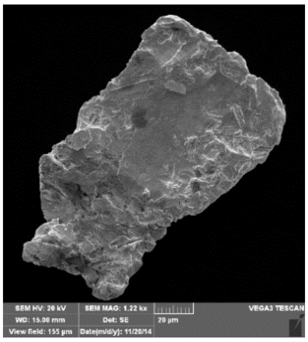

Fig. 3.1. Flattened, massive, irregular, and slightly rounded shape

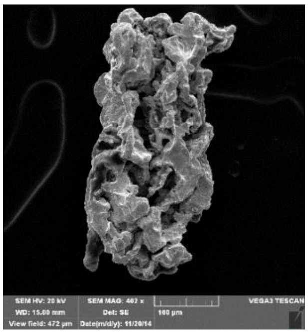

Fig. 3.2. Pronouncedly massive, irregular, and porous aggregate shape

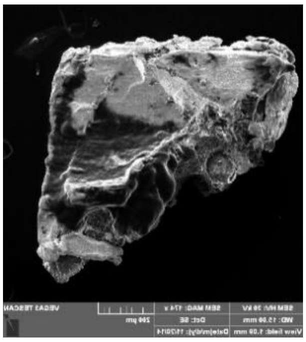

Fig. 4.1. Irregular and moderately rounded shape

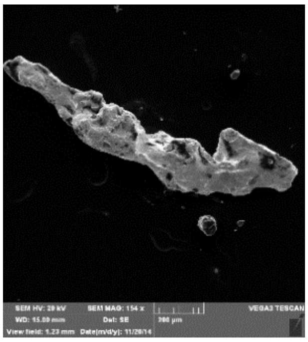

Fig. 4.2. Elongated grain with rounded edges

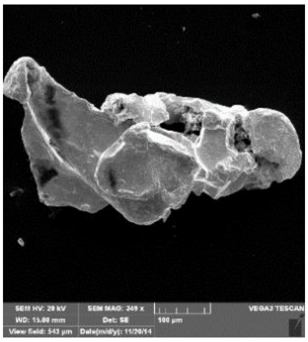

Fig. 4.3. Elongated and moderately rounded shape with smooth surfaces

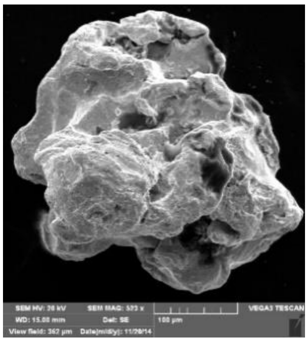

Fig. 4.4. Massive and irregular shape with weakly developed rounding

Table 3.

Morphology of gold grains from soil samples

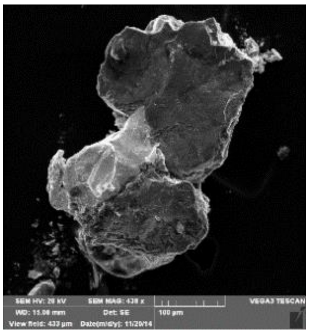

Fig. 5.1. Irregular, massive, and partially flattened shape with moderate rounding

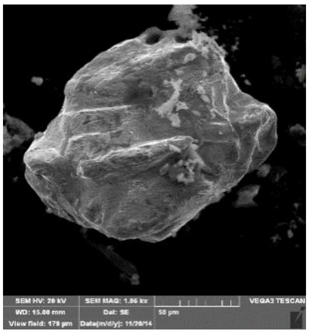

Fig. 5.2. Grain with massive, compact, and rounded shape

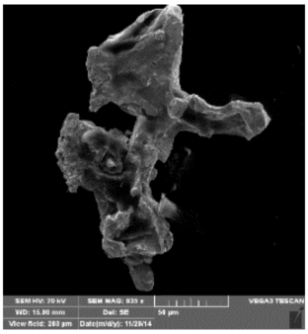

Fig. 5.3. Irregular, branched, and skeletal shape with complex geometry

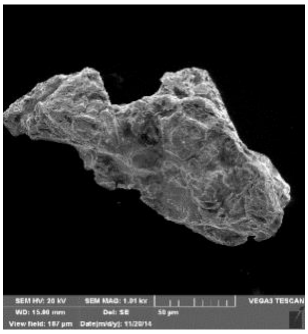

Fig. 5.4. Massive, irregular, and slightly rounded shape

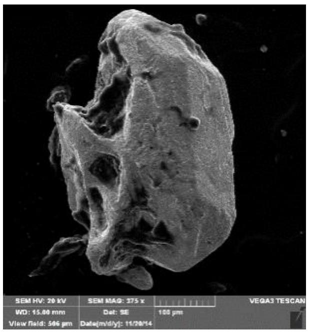

Fig. 6.1. Elongated, partially flattened, and moderately rounded shape with local caverns

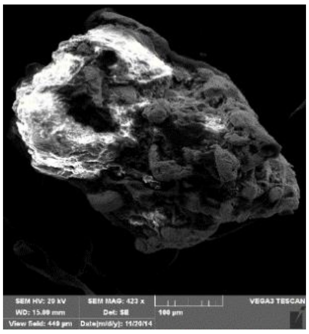

Fig. 6.2. Massive, irregular, and aggregate shape with pronounced surface heterogeneity

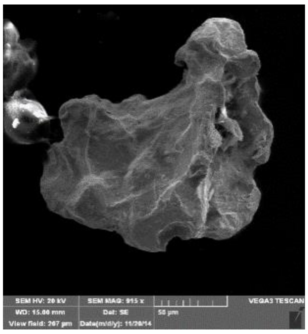

Fig. 6.3. Irregular, partially flattened, and rounded shape

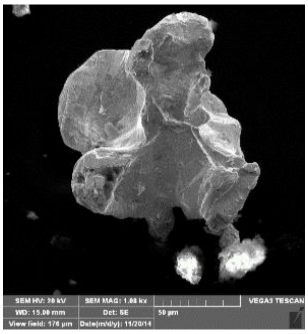

Fig. 6.4. Irregular, massive, and partially flattened shape with moderate rounding

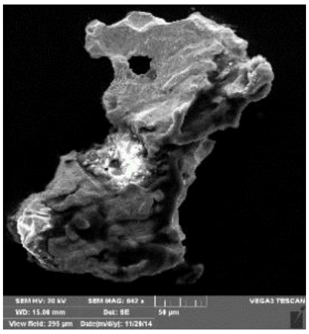

Fig. 7.1. Irregular, angular to morphology with micro-depressions and porous zones

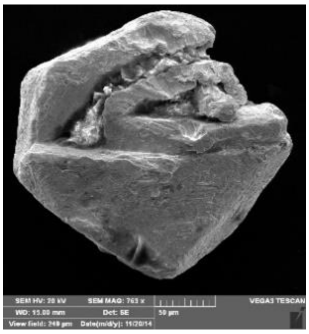

Fig. 7.2. Compact grain, massive, blocky shape and relatively smooth surfaces

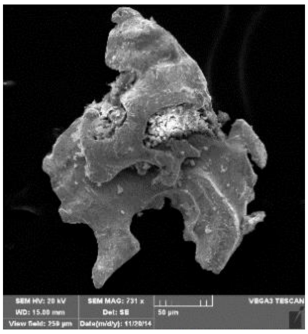

Fig. 7.3. Irregular, branched morphology

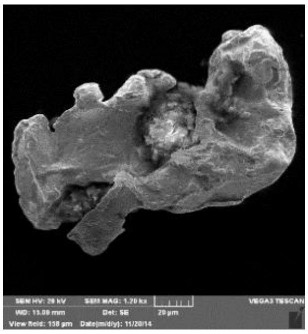

Fig. 7.4. Irregular morphology with rounded edges

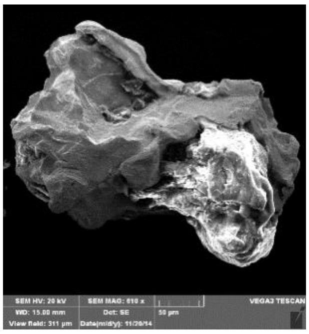

Fig. 8.1. Complex, irregular morphology

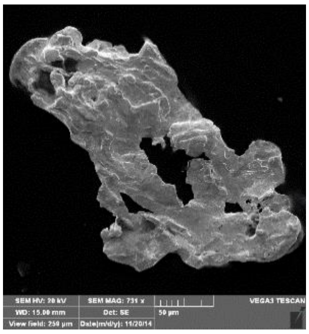

Fig. 8.2. Flattened grain with well-developed cavities and irregular edges

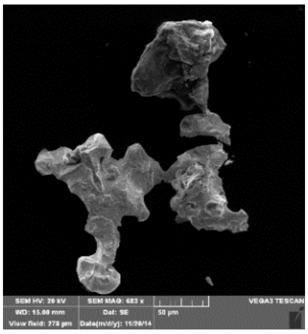

Fig. 8.3. Grains with irregular shape and limited rounding

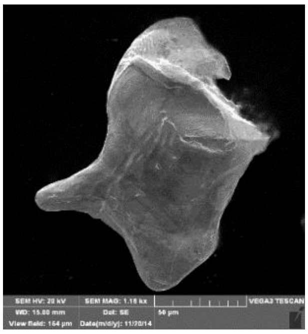

Fig. 8.4. Rounded grain with smooth surface and pronounced plastic deformation

Compared to the other grains, a few particles exhibit smoother surfaces and relatively simpler shapes (Table 3, Figures 5.2, 6.1, 7.2, 8.4). The edges of these grains are more rounded, and the surfaces are relatively polished. These features are typical of grains that reflect the direct influence of transport distance on morphological evolution. However, since these grains were recovered from soil samples, they most likely represent recycled grains that were previously modified during earlier sediment transport and subsequently incorporated into the soil cover (Craw, 1992). This is also supported by the findings of Youngson & Craw (1996), who indicate that the presence of gold grains in soil samples can result from sedimentary recycling, whereby gold initially accumulates in fluvial or alluvial sediments and is later remobilized and incorporated into younger sediments or the soil cover through erosion and denudation processes.

Overall, the morphological characteristics of the native gold grains (Table 3) indicate that the majority of the particles underwent short to moderate transport, which is typical for eluvial or proximal colluvial soil environments. The presence of irregular shapes, rough surfaces, and limited rounding suggests that the primary source of mineralization is likely located relatively close to the sampling sites.

CONCLUSION

The chemical analysis of native gold indicates a predominance of high-purity Au–Ag alloys with considerable variability in silver content. This range (<1 to ~9 wt.% Ag) reflects the combined influence of primary mineralization, mixing from multiple sources, and secondary supergene processes.

Grains with higher Ag content and lower fineness suggest shorter transport distances and closer proximity to the source, whereas grains with low Ag content and high fineness are indicative of longer transport, during which selective leaching of Ag occurs and enrichment in Au is achieved.

The absence of a gradual change in the chemical or mineralogical composition of the material along the river or stream flow, as well as the differences between alluvial and soil samples, indicates that in addition to transport, local geochemical conditions and post-depositional processes play a significant role.

Overall, variations in the Au–Ag composition serve as a reliable indicator of transport distance and the degree of fluvial reworking, while simultaneously reflecting the complex evolution of the grains and the contribution of multiple gold sources.

Morphological analysis of gold grains from alluvial sediments indicates the presence of a wide spectrum of forms — from angular and minimally abraded to well-rounded and sub-spherical. These forms reflect a variable transport history, ranging from short to prolonged fluvial transport. The presence of angular grains with sharp edges points to a proximal source and minimal mechanical abrasion, whereas rounded forms are indicative of longer transport and intensive mechanical and chemical modification. The combination of different morphological types within the same depositional context suggests a mixed source and the potential for resedimentation.

The morphology of SEM-observed grains from soil samples is predominantly irregular, perforated, and locally flattened, with limited rounding in most particles. Overall, the morphological characteristics of the native gold grains indicate that the majority of particles exhibit restricted rounding and irregular shapes, typical of short to moderate transport distances. This suggests that the primary source of mineralization is likely located relatively close to the sampling site, whereas the smoother grains may represent a previously transported and recycled population.

Based on the geological framework of the study area, potential primary sources of native gold include metamorphic rocks (phyllites, schists, gneisses) as well as volcanic and subvolcanic intrusions (quartz porphyries, diabases, andesites). These rocks may host hydrothermal Au–Ag mineralizations, which, through erosion and transport into fluvial sediments, become the source of placer gold.

Overall, the combination of morphology, chemical composition, and geological sources provides a clear understanding of the complex interactions between primary mineralization, transport, and post-depositional geochemical processes, confirming the presence of multiple sources and varying transport distances for native gold within the study area.

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Резиме

МОРФОЛОШКИ И ХЕМИСКИ КАРАКТЕРИСТИКИ НА САМОРОДНОТО ЗЛАТО ОД НАНОСНИ СРЕДИНИ: ИМПЛИКАЦИИ ЗА ТРАНСПОРТОТ И БЛИЗИНАТА НА ИЗВОРОТ

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Клучни зборови: самородно злато; наносни наслаги; скенинрачка електронска микроскопија (SEM); морфологија на зрна; Au–Ag состав; флувијален транспорт; растојание од примарниот извор

Во оваа студија е извршена интегрирана морфолошка и хемиска анализа на самородно злато од наносни наслаги со цел да се утврди врската помеѓу формата на зрната, нивниот хемиски состав и оддалеченоста од примарниот златоносен извор. Истражувањето е спроведено со примена на скенирачка електронска микроскопија (SEM), при што се анализирани морфологијата, површинската текстура и микроструктурните карактеристики на златните зрна, како и нивниот хемиски состав (Au, Ag и Fe).

Резултатите покажуваат значителна варијабилност во содржината на Au (88.73–99.53 wt.%) и Ag (0.47–9.19 wt.%), железото е многу малку застапено. Јасен е трендот на зголемување на чистотата на златото со намалување на

содржината на сребро. Според морфологијата анализираните златни агрегати се карактеризираат со неправилна и аголна морфологија, што укажува на ограничен транспорт и близина на примарниот извор. Присутни се и зрна кои покажуваат сплескани, ламеларни и заоблени форми, типични за дистални делови од примарната средина. Добиените резутати потврдуваат дека примената на морфолошката анализа базирана на SEM и на хемиска анализа е значајна за одредување на должината на транспортот и за процена на локацијата на примарните златоносни извори.