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Artisanal and small-scale gold mining in the Southern Espinhaço Range, Brazil, using time-domain electromagnetic induction: prospecting, efficiency, and environmental aspects

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Abstract

Gold mining has profound ties to the history of Brazilian colonization and still takes place with many communities involved in artisanal and small-scale gold mining. The most relevant gold deposits in the Southern Espinhaço Range are related to the occurrence of shear zones in the region between the cities of Diamantina and Gouveia, Minas Gerais, Brazil. Former colonial-dated gold mines were depleted; however, the use of newer prospecting practices has brought new interest in these areas. In this context, this study assesses the efficiency, environmental impacts, and economic viability of time-domain electromagnetic induction as a gold exploration method for small-scale prospecting in Gouveia county. Additionally, this study provides a characterization of the local gold mineralization and brings awareness to the prospecting community regarding environmental and legal aspects of gold mining. This article presents the results of a field campaign of prospecting efforts in which 114 metallic targets were located, 35 of which were identified as native gold. The gold samples have specific morphology, depth, and weight that suggest a hypogenic origin with a low degree of transport at eluvial levels. From an environmental perspective, the time-domain electromagnetic induction method has presented fewer impacts, related mostly to site-specific remobilization of the soil.

KEYWORDS: artisanal and small-scale gold mining; geophysical prospecting, metal detecting; gold; Southern Espinhaço Range.

INTRODUCTION

Artisanal and small-scale gold mining is ongoing around the world, particularly in developing countries. These activities are mostly informal and, at times, illegal, performed under poor working conditions that oftentimes result in significant environmental impacts. On the other hand, gold mining presents an undeniable role in poverty reduction at a local level, representing a promising economic activity and often the single viable economic possibility for many poverty-stricken communities. The International Institute for Environment and Development estimates that at least 13 million people work directly in artisanal and small-scale gold mining around the world (Hentschel *et al.* 2002). In Brazil, the number of people working directly on small-scale gold mining is around 250,000; however, close to 1.5 million people are dependent on such activities (Hilson and Maconachie 2017). Brazil also takes the lead with the largest small-scale gold mining district, located in the Tapajós River watershed (Lobo *et al.* 2016). Historically, such gold mining practices were significant for the discovery of many deposits around Brazil during colonial times; in contrast, nowadays they have great social and environmental impacts. Hence, there is an ever-growing need for research on such a controversial subject in both academic and governmental spheres regarding prospecting guidelines, new technology, and the regularization of this practice.

With the advent of new technology, very promising tools for artisanal mining are now metal detectors. Such equipment was developed alongside radiotelephony in the late 19th century and was quickly adapted for many diverse applications, such as war engineering, archeology, and mineral prospecting (Connor and Scott 1998). Initially used for amateur gold prospecting, metal detectors developed from 2000 to 2020 have evolved into robust equipment that is easily used with a relatively low cost and high efficiency, which generated major changes in subsurface gold prospecting (Dessertine 2016).

Metal detectors in Brazil have become increasingly popular in the past decades in gold prospecting regions. Many areas considered to be depleted, colonial-time mines, and even brand-new gold occurrences are now being targeted for exploration using this technology. One of these regions is located in the Southern Espinhaço Range (Fig. 1), in Gouveia county, Minas Gerais. This area, despite not presently having large gold mining enterprises, is exploited by small-scale individual prospectors that extract shallow subsurface-level gold utilizing

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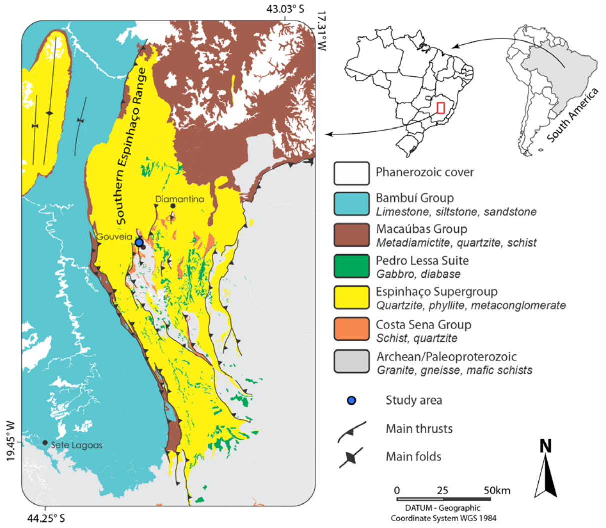

Source: modified from Kuchenbecker (2019).

Figure 1. Schematic geological map of the Southern Espinhaço Range and adjacent regions showing the study area in Gouveia county, Minas Gerais.

metal detecting equipment. Therefore, this study aimed to study gold prospecting campaigns that employ time-domain electromagnetic induction (EMI) in Gouveia/MG to assess their efficiency, environmental impacts, and economic viability; provide a characterization of the local gold mineralization; and finally bring awareness to the prospecting community regarding environmental and legal aspects of this small-scale gold mining.

GEOLOGICAL SETTING

Regional geology context

The study area is located in the Southern Espinhaço Range in the Araçuaí Belt. The Southern Espinhaço Range extends along the southeastern margin of the São Francisco Craton (Almeida 1977) and hosts the Gouveia granite-gneiss complex and the Pedro Pereira Group, composed of mafic schist and banded iron formations (BIFs), with both geological units dating to the Archean eon. There are also outcrops of metasedimentary rocks from the Costa Sena Group and Espinhaço Supergroup dating to the Proterozoic eon. Subordinately, metabasic rocks occur in association with the Pedro Lessa suite (Knauer 2007).

According to Dossin *et al.* (1990), the most significant gold deposits in the Southern Espinhaço Range coincide with the occurrence of ductile shear zones in association with quartz veins that predominantly occur in mylonitic schists, in which the main conditioning factors of mineralization are physical aspects of the host rock that control the flow of hydrothermal fluids. According to other authors (Abreu 1991), it is less common to find gold mineralizations in association with pelitic metasediment levels, with possible occurrences in hematitic phyllites related to the Espinhaço Supergroup.

Research on fluid inclusions in quartz veins associated with gold mineralizations in this region, conducted by Ronchi *et al.* (1992), suggested that gold precipitation took place due to the mixing of fluids of different compositions (carbonic and aqueous), in which the oxygen fugacity of the mineralizing fluid is close to the conditions of the hematite-magnetite buffer solution. Furthermore, their research suggests that the metal complexing agent would be $AuCl_2$ and that destabilization would occur as a result of the process of progressive fluid dilution. In convergence, studies on fluid inclusions carried out by Freitas (2020) in quartz veins in Serra do Pasmar (20 km southwest of Diamantina, Fig. 1) suggested oxidizing conditions in the field of hematite stability, in addition to transport in the form of chloride complexes, supported by the low salinity of the fluids.

From a geotectonic perspective, the Brasiliano event (490–630 Mya) originated large folds and extensive and numerous ductile shear zones of preferential north-south direction and transported them to the west in the Espinhaço Range (Knauer 2007). The large amount of hydrothermal quartz veins, concordant or discordant with the foliation, developed during this event is associated with, besides gold, hematite, magnetite, rutile, anatase, brookite, and, more rarely, minerals from the groups of crichtonite, euclase, and monazite (Chaves *et al.* 2010).

Based on direct gold dating with radiogenic Helium (^{4}He) by the U/Th –^{4}He method, Cabral *et al.* (2013) suggested an age of 515 ± 55 Mya, relating the gold mineralization of the Diamantina region to the Brasiliano orogenetic event during the Gondwana amalgamation. Furthermore, according to these authors, gold mineralization can be understood as an oxidized variant within the series of orogenic gold deposits.

Local geology context

The exploration study area is located south of Cuiabá village, approximately 6 km northwest of the Gouveia urban area (Fig. 2A). The area is characterized by gentle-slope landscapes on "half dome-like" hillslopes in which rocks of the Gouveia granite complex outcrop. The rocks are composed of quartz, potassium feldspar, plagioclase, muscovite, and biotite; they are mylonitized and homogeneously weathered. The target area of this study is the top portion of a half-dome hillslope with a total area of 0.38 ha.

The region is covered by approximately 3.0 m of eluvial conglomeratic sediments with subangular to angular clasts that are texturally immature, mineralogically mature, and predominantly composed of quartz. Among the clasts, the pebble fraction is predominant, with rare occurrence of larger grain fractions (Fig. 2B). Regarding the matrix, there is a predominantly fine, silty-clay matrix with an orange-ocher color. In the south region of the area, there is a large gully (Fig. 3C) in which the white hue of kaolin can be seen, the result of the weathering of granite rocks. Such geological conditions are favorable for the exploration of native gold with metal detectors, considering the relatively shallow eluvial layer (up to 3 m).

METHODOLOGY

Exploration and data processing

The gold exploration campaign discussed here had a total duration of 7 days and encompassed a preliminary

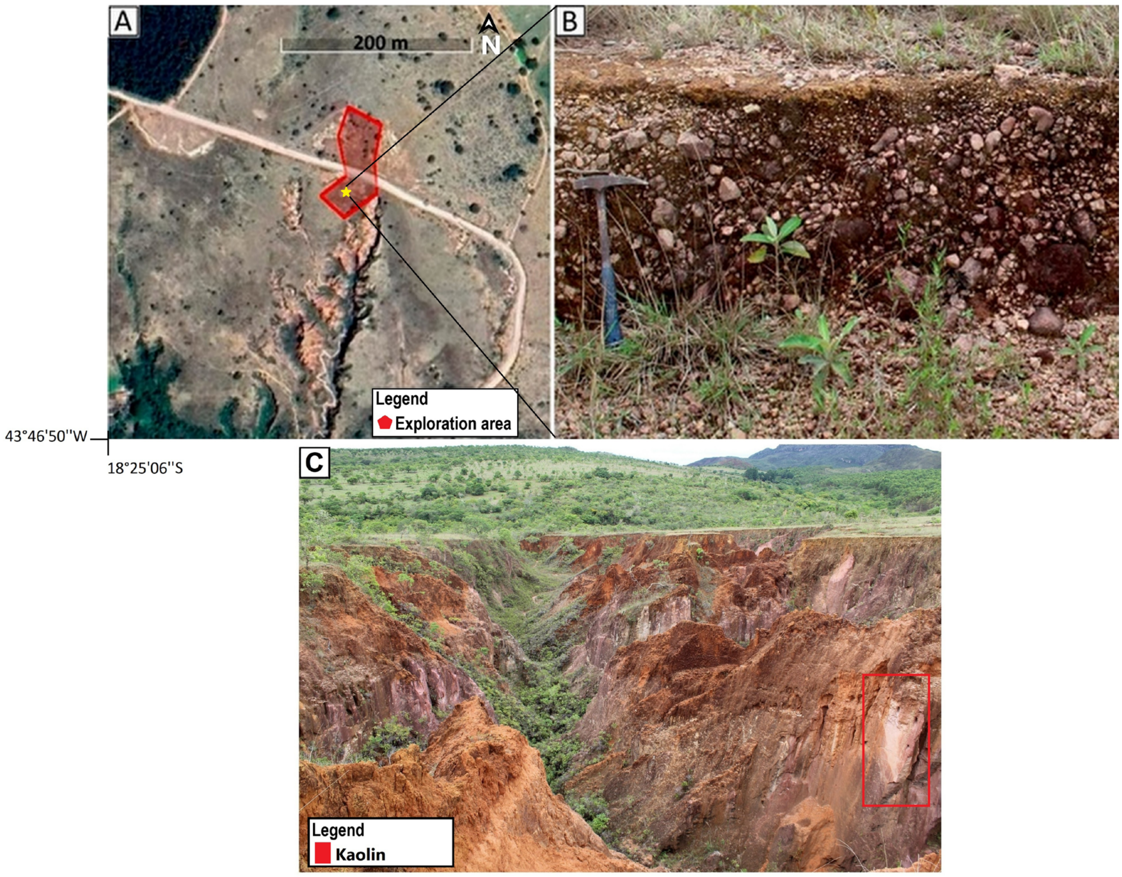

Figure 2. (A) Satellite image of the study area – Google Earth Pro 7.3 (2022). (B) Eluvial level of quartz angular gravels/pebbles. (C) Panoramic view of the adjacent gully (south sight).

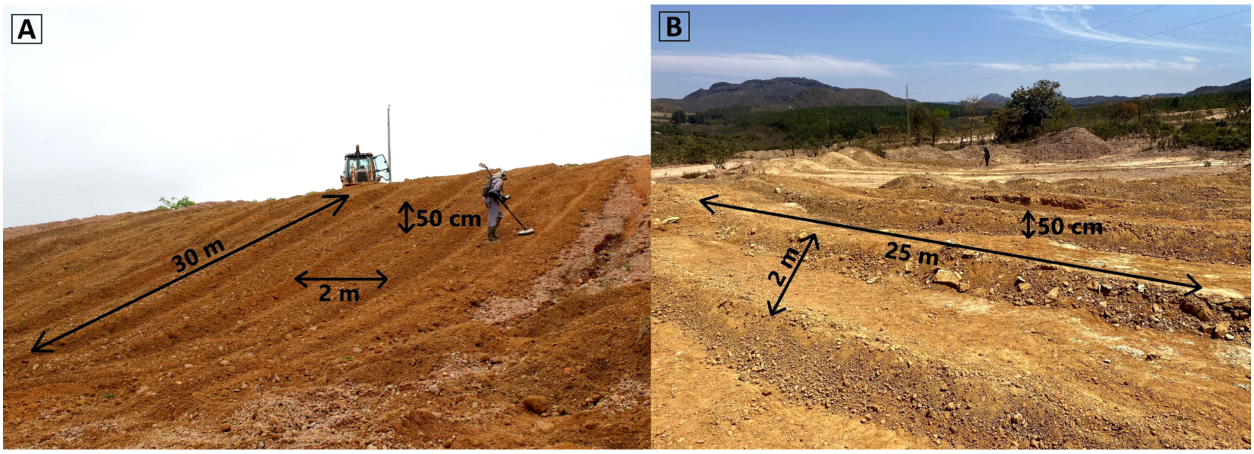

Figure 3. (A) and (B) Open rows excavated with the aid of mechanical scarification for metal prospecting at the eluvial gravel level, row dimensions 2 m × 0.5 m × 25–30 m.

reconnaissance of the area, terrain preparation (2 days), exploration (3 days), and finally row closure and soil compaction (2 days). The exploration stage was further subdivided into three parts, corresponding to each prospecting day. There was no difference in any variable on each prospecting day: same duration, area, and depth. This subdivision of the prospecting stage was carried out to emphasize the decrease in metallic targets found as a function of prospecting days. The terrain preparation comprised selection of row placement (length, width, and depth) followed by systematic excavation of 12 rows that were 2.0 m wide, 0.50 m deep, and 20–30 m long (Figs. 3A and 3B). It is noteworthy to emphasize that the device depth investigation increases with the volume of the metal target until its maximum reach. Therefore, smaller metal targets are only found at shallow depths (less than 1 m), making the stage of terrain preparation fundamental to improve accuracy of the gold finds.

For such excavation, a Case backhoe model 580M was used. In the subsequent exploration days, the freshly excavated rows were randomly surveyed by two high-resolution Minelab metal detectors, model GPZ 7000. This type of metal detector is widely used among individual professional gold prospectors, considering its investigation depth (up to two meters), accuracy regarding small metallic targets (from

2 mm), and relatively affordable price (same price as a standard car). We only found gold targets in the rows given that the shallow eluvium blanket was already intensely surveyed. The metallic targets were manually extracted using a pickaxe. The final stage consisted of the closure of the excavated rows and the compaction of the eluvial materials to minimize related environmental impacts. Following the field campaign stage, the gathered data were logged into spreadsheets. The processing of the data used descriptive statistics, a sample Pearson correlation coefficient (r), and a hypothesis test to assess its significance.

In this study, a 10% significance level was adopted, that is, alpha = 0.10. This level was selected based on the existing relationship between type I (alpha) and type II (beta) and for consistency with the sample size (Kim 2015). Therefore, all p-values lower than 0.10 will lead to the conclusion of the significance of the correlation coefficient. The R software™ version 4.0.3 was used to perform the analyses.

Operation principles: EMI devices

EMI sensors have been used for the detection of metallic objects since the 19th century and are currently considered a mature technology (Mlambo *et al.* 2018). The term "metal detectors" is commonly used to refer to EMI devices that are low-frequency inductive systems composed of a search head containing one or more coils carrying a time-varying electric current. These can be subdivided into frequency-domain and time-domain systems (Bruschini 2002). This study will focus on the time-domain systems.

Field research using time-domain electromagnetic detection consists of a transmitter coil that generates a pulsating primary magnetic field that induces eddy currents in any nearby metallic objects. The decay of these currents with time generates a secondary magnetic field with a specific rate of decay that is determined by the object's characteristics (size, shape, and composition) (Telford *et al.* 1990). Measurement of the decay of this secondary field (the transient response) therefore provides the metallic location of the target once read through the receiving coil (Fig. 4A) (Bruschini 2002).

Traditional metal detectors are not commonly power-efficient. For this reason, in this study we opted to use the GPZ 7000 gold detector (Fig. 4B), which is a high-sensitivity, high-resolution, constant-current time-domain metal detector suitable for gold detection. This device emits a sonorous alert when it detects any metallic object in the subsurface. Expert metal prospectors can differentiate metals based on their sound characteristics; basically, two sound categories are informally classified: one, the target should be gold, silver, aluminum, or copper; the other, the target should be iron or steel alloys. This is expected due to the values of their electrical conductivities. Besides, this metal detector can also map their finds with a GPS and a PC mapper; however, this study did not map their finds given that this kind of prospection is not formally legalized with the regulatory agency and is not the purpose to harm local miners.

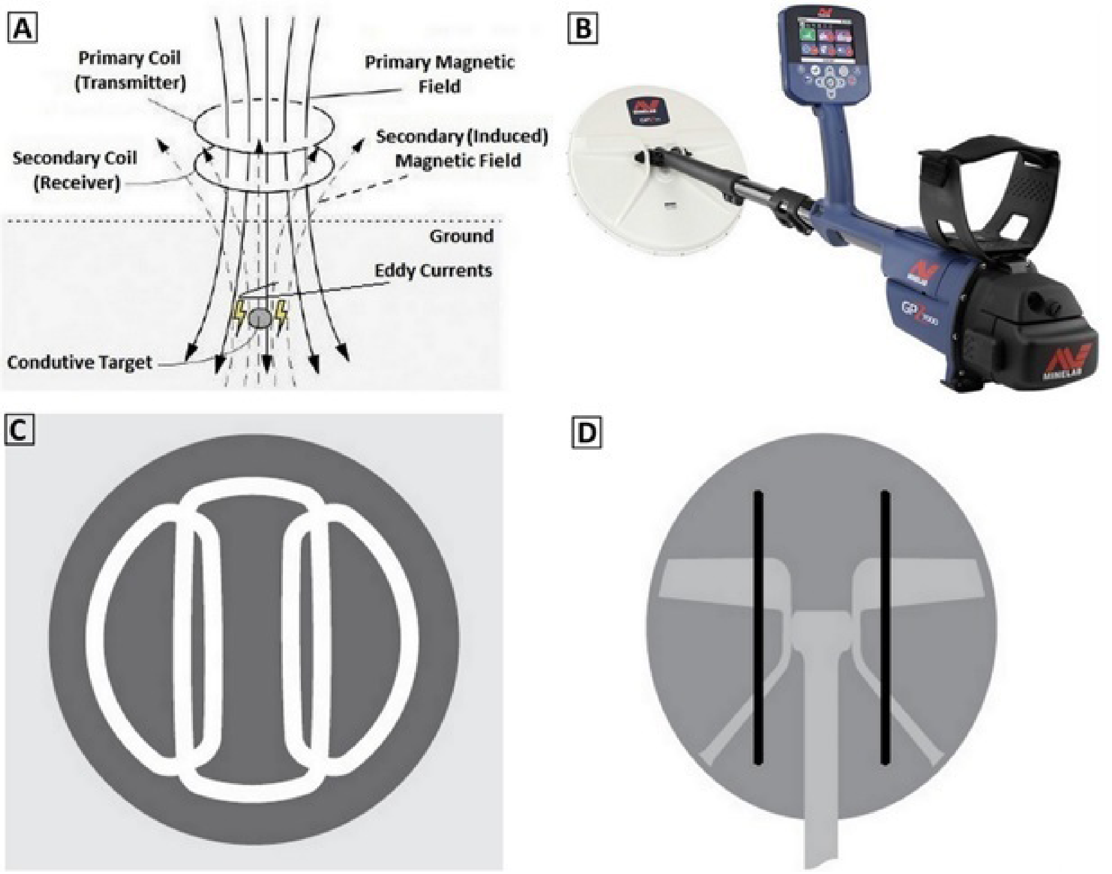

Figure 4. (A) Schematic illustration of the time domain electromagnetic detection principle showing the primary and secondary fields (modified from Bruschini 2002). (B) Geophysical equipment for detection of metallic materials – Minelab Model GPZ 7000 based on time-domain electromagnetics. Source: Minelab (2022). (C) The schematic Super-D technology model for positioning the coils; (D) the parallel lines represent the intersection area between coils, where the signal is strongest (modified from Minelab 2022).

The equipment incorporates the Zero Voltage Transmission (ZVT) and Super-D technologies and works at a standard frequency of 3675 kHz with a maximum investigation depth of 2 m (Minelab 2022). It repeats the signal cycle composed of at least one receiver period and one non-zero transmitter period, keeping the current substantially constant from cycle to cycle regardless of the inductance of the transmission coil due to the ZVT technology (Candy 2014). The Super-D coil (Fig. 4C) consists of one middle transmission winding and two outer receiving windings, which essentially form the equivalent of two symmetric Double-D coils, one on the left and one on the right. This winding interception setting results in a double response for targets close to the surface of the coil, whereas for deep targets it behaves like a traditional coil, which will show a stronger signal in the central parallel lines (Fig. 4D) (Minelab 2022).

RESULTS

The metallic targets were quantified for both gold and other metallic targets (any conductive metals), and the proportion between the two was calculated, as shown in Table 1.

A total of 114 targets were identified during the 3 days of exploration, of which 35 were samples of native gold and 79 were samples of other conductive metals. Individually, exploration days 1, 2, and 3 obtained 19, 11, and 5 gold targets, respectively. As mentioned in Table 1, the targets found for other metals were substantial, such as cans, nails, horseshoes, coins, and other discarded objects. The large number of discarded objects is probably due to the proximity to the road (Fig. 2A).

Figure 5 shows the variation in weight per sample of native gold between 0.05 and 1.50 g, with 75% of the samples found having masses up to 0.5 g. The depth at which the gold samples were found was also determined to range from surface level (0 cm) to 35 cm. Around 75% of the total samples were found in depths up to 19 cm (originally 79 cm).

The relationship between depth and weight for the gold targets was analyzed through the sample Pearson correlation coefficient (r) along with its population significance (Fig. 6). A crescent-linear correlation was found to exist between the variables weight (g) and depth (cm). For the gold targets, as the depth increases, the weight (g) also increases. Pearson's correlation coefficient (r) between the variables depth and weight, calculated for this scenario, is 0.35. Using a hypothesis test at the 10% level, a p-value of 0.03 (3%) was found.

Figures 7A, 7B, and 7C show the total number of gold samples found at exploration days 1, 2, and 3, respectively. In terms of mineralogy, the samples were mostly xenomorphic, spherical, angular, and intensely pitted, with the presence of cavities and voids. Rarely, in just one sample, multiple crystals with an arborescent habit were observed (Fig. 7D). Few samples were also xenomorphic with low sphericity, elliptical geometries, angular, intensely pitted, and numerous cavities and voids (Figs. 7E and 7F). Despite the results of this prospecting campaign for gold resulted in only grains and small gold nuggets, local gold prospectors report having found larger gold nuggets using the same geophysical device previously in the same region. Two of such samples (Figs. 8A and 8B) weighing 15.06 and 26.30 g, respectively, were temporarily provided to this study to be further described and characterized.

DISCUSSIONS

Prospecting and efficiency

Gold nuggets and grains are symbolic objects of mineral wealth, highly sought after by individual prospectors and, often, neglected by the mineral industry and academic world.

Table 1. Total targets and proportion of gold and other metals found through prospecting.

Exploration (day)	Total targets	Gold		Other metals	
		Absolute number	Proportion (%)	Absolute number	Proportion (%)
1	60	19	31.7	41	68.3
2	33	11	33.4	22	66.6
3	21	5	23.8	16	76.2
Total	114	35	30.7	79	69.3

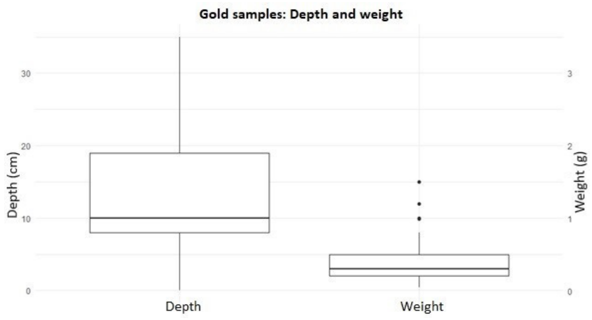

Figure 5. Boxplot for depth and sample weights of prospected native gold samples.

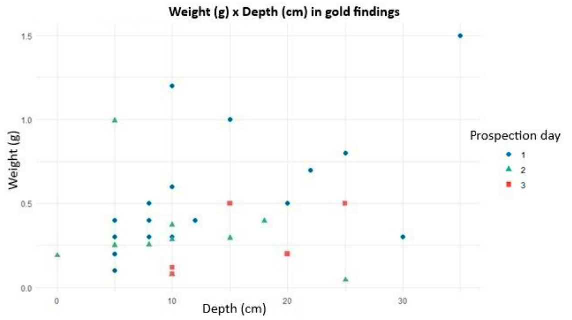

Figure 6. Weight versus depth for gold grains found during three exploration days.

The local concentrations and rarity of these specimens typically do not make large mineral exploration projects viable. Additionally, the high economic value and high liquidity of these finds make it difficult to acquire samples for scientific analysis, given that they are quickly sold and melted down for use in the jewelry industry.

The collected data shows the economic viability of the proposed project and methods, considering that the prospected gold value exceeded the production costs, thus generating profits for both prospectors and the landowner. The 35 gold samples found with the geophysical device amount to 14.64 g in weight, valued at the price of gold at the time of extraction (R$ 310/g) in R$ 4,538 (November 5, 2020). The total exploration and extraction costs, including the backhoe rental, fuel, and team logistics, amounted to R$ 2,750. At the studied area, the other prospection methodology possibility to find gold would be removing all the eluvial blanket by using backhoes and trucks to a washing area associated with

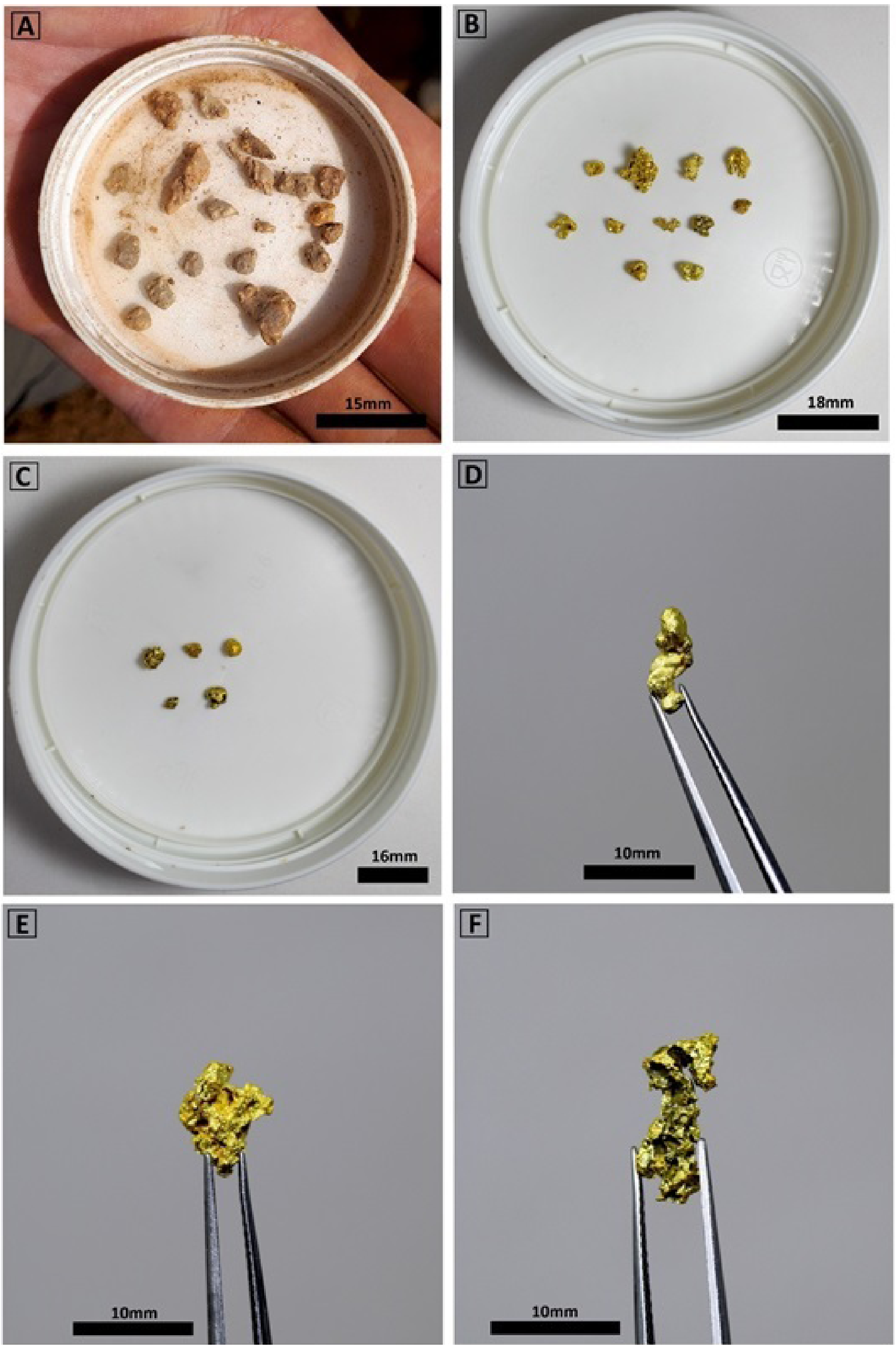

Figure 7. (A) Total native gold samples prospected during the first day, grains and nuggets with debris. (B) Total native gold samples prospected during the second day, clean grains. (C) Total native gold samples prospected during the third day, clean grains. (D) Native gold sample crystallized in arborescent habit with dimensions of 9×3×2 mm and a weight of 0.5 g. (E) Xenomorphic native gold sample, low sphericity, angular, with the presence of cavities and voids with dimensions of 9×7×5 mm and a weight of 1.0 g. (F) Xenomorphic native gold sample, low sphericity, angular, with numerous cavities and voids. Some voids have geometric surfaces, which are evidence of the dissolution of other minerals existing there (box works). Iron oxides/hydroxides were also found within the holes with dimensions of 13×6× 2 mm and a weight of 0.9 g.

a gravimetric concentrator. This kind would need a considerably larger monetary investment and would definitely represent a huge environmental impact. Furthermore, that was not done in this and any nearby area to compare the results. It is worth mentioning that the project area is considered by the local prospectors as already depleted of large gold volumes, with previous reported exploitation of considerable gold volumes at the local level.

From a statistical standpoint, the value determined for the sample correlation coefficient (0.35) demonstrates a positive association between the weight of the samples according to the depth found. Despite the value of the sample association determined (0.35 << 1) not being considered a noteworthy value, the (r) value at the significance level of 10% found a p-value of 0.03 or 3%. As the p-value obtained in the hypothesis test was lower than the established significance level of 10% (error probability), it was concluded that the population correlation coefficient is statistically different from zero; hence, admittedly, the correlation coefficient is significant. Therefore, its population significance is confirmed, which, in turn, validates the tendency for larger nuggets to be found at a greater depth at the regolith level.

Except for a few specimens with defined habits and preserved faces typical of the cubic system, the prospected samples were xenomorphic and presented intensely pitted surfaces. This surface, which in some cases produces a spongy texture in the nuggets (Fig. 8B), added to the high angulation — prominent and pointed edges — suggests a low degree of transport of the nuggets, since such metal is highly malleable and ductile. With a small degree of transport, these nuggets would display significant changes in morphology (flattening, smoothing, and low angulation).

Native gold generally occurs in an alloy with silver. The atomic ratio of both metals is equal, allowing the formation of a continuous series between them (Hough *et al.* 2009). According to Butt *et al.* (2020), the depletion of silver can be understood as the first stage of weathering, in which a microporosity develops in the free gold particle, resulting in voids that facilitate the access of weathering fluids and fine particles, such as clays and secondary oxides. According to these authors, in larger samples, an extreme depletion of Ag associated with Au dissolution can lead to the formation of a spongy texture on the intensely pitted surfaces of the gold nuggets.

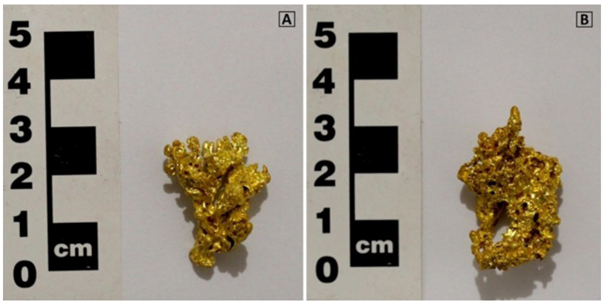

Figure 8. (A) Gold nugget with dimensions of 2.9 cm × 2.3 cm × 1.5 cm and a weight of 15.06 g, crystallized in arborescent habit with a slightly pitted surface. (B) Gold nugget with dimensions of 3.4 cm × 2.3 cm × 1.2 cm and a weight of 26.30 g, xenomorphic, low sphericity, angular geometry, intensely pitted, spongy texture, and presence of voids and cavities, mostly filled with iron oxides/hydroxides.

The geological aspects of the study area integrated with the regional geology and the characteristics of the native gold samples found all indicate that the gold mineralization at the site is hypogenic and comes from quartz veins intruded into the host rocks. The preferential weathering of the host rocks, the Gouveia granite complex, simultaneously with the dismantling and accommodation of the voluminous quartz veins mechanically concentrated the gold nuggets and grains at this regolith level above the bedrock, and large nuggets naturally occupied great depths. The high degree of mineralogical maturity of the unconsolidated sediment of the regolith layer, formed almost exclusively of highly angular quartz pebbles, together with the irregular and angular morphology of the nuggets and auriferous grains, suggest low transport of this sediment, thus being interpreted as an eluvial layer originated from weathered granitic rocks underneath (Fig. 9).

Environmental and social aspects

Traditionally in Brazil, the main artisanal and small-scale gold mining methods use gravimetric concentration, blasting, washing, and dredging (Rodrigues *et al.* 1994). Artisanal alluvial mining, carried out with the help of pans and improvised gravimetric concentrators, is a widespread practice throughout Brazil. In the colonial period, this mining was synonymous with wealth; however, today it represents scarcity; those who practice it do so as a form of subsistence since the shallow alluvial gold deposits have already been exhaustively exploited, leaving tiny amounts of metallic mineral resources in the main water courses. Associated with this method of gold prospecting, it is quite common to use liquid mercury in order to unite fine-grained gold into a single amalgam, which, when burned, volatilizes the mercury and forms a single gold agglomerate. This practice is particularly harmful to the workers in direct

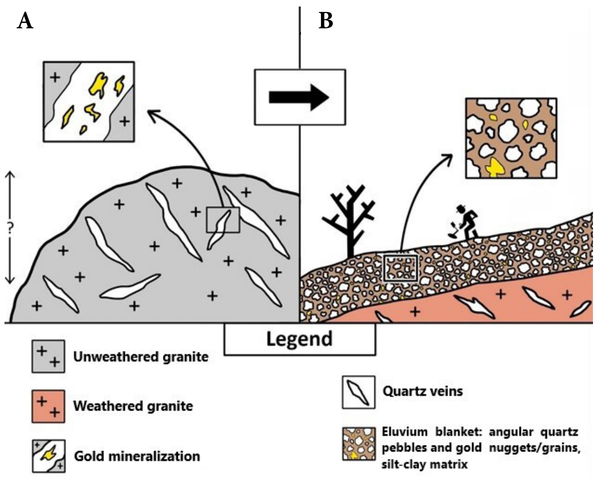

Figure 9. Schematic geological model of the genesis and concentration of the gold at the eluvium blanket. (A) Gold mineralization in quartz veins intruding the unweathered granite and (B) eluvium blanket composed of angular quartz pebbles and gold nuggets/grains, result of the weathering of the granite rock as well the dismantling and accommodation of the gold-quartz mineralized veins.

contact with such substances, as well as to the entire ecosystem since this volatile metal is easily oxidized in the environment and methylated to its most toxic form, methylmercury, which can then be incorporated into organisms through the food chain (De-Paula *et al.* 2006).

The dismantling of slopes and thick soils followed by washing, a typical method of artisanal small-scale gold mining in the Amazon region, also presents major environmental impacts, both physical and biotic. This practice encompasses first the deforestation of the target area, followed by removal and intense washing of the lateritic/saprolytic material, which results in the dumping of tons of sediment into waterways. This practice causes direct changes in the particle sedimentation dynamics, causing changes in the color and turbidity of the water (Rodrigues *et al.* 1994). The prospected site completely loses its original geomorphological features and becomes intensely susceptible to accelerated degradation from weathering and erosion. In addition, mercury is also utilized in this practice for separation and beneficiation in cases where the granulometry is fine.

Commonly used in larger watercourses, mining by dredging unconsolidated material deposited in thalwegs and subsequent gravimetric concentration is associated with major environmental impacts. According to Castro and Almeida (2012), the main aspects related to such practices are as follows: change of the hydraulic and sedimentological conditions of the flow, with possible alteration of the circulation patterns, water mixing, and turbidity; alteration of the conditions at the place of release of the dredged material; and pollution by toxic substances existing in the dredging material from its suspension and movement during the activity. In gold mining, the indiscriminate use of mercury is a significant addition in terms of impacts besides the previously mentioned issues since this ore, in large waterways and at great depths, is usually found in fine granulometry. Apart from the environmental impacts, the dredging of sediments in rivers requires a significant financial contribution for the acquisition of equipment and maintenance of activities.

In this study, it is understood that the gold prospecting method by high-resolution metal detectors imposes local impacts restricted to the remobilization of unconsolidated material where the metallic targets are located, usually in eluvium, colluvium, and low-depth alluvium, with this remobilization carried out manually with shovels and pickaxes. Although this technology cannot be considered effective in all environments (for instance, deep underwater environments or very fine-grained ores), prospecting using this method is effective, mercury-free, and has low impacts on local fauna and flora while providing a significant income to many people. It should be noted, however, that the opening of trenches/rows represents a more significant environmental impact, considering the removal of local undergrowth in addition to the remobilization of a greater volume of unconsolidated material.

The small-scale gold mining industry has remarkable economic significance at local level. However, a key point in the artisanal and small-scale gold prospecting issue is its legality, considering that such practices often do not comply with the obligations imposed on them by local authorities. Thus, it is recommended that small local prospectors organize mineral cooperatives that can be duly formalized with the Agência Nacional de Mineração (National Mineral Agency) in favor of cooperation among prospectors, land owners, and proprietors of mineral rights in the area in question.

CONCLUSION

The employment of geophysical methods for prospecting subsurface gold occurrences carried out by time-domain EMI equipment proved to be effective in detecting several samples of native gold in eluvial material. The easy operation of the equipment and the rapid response associated with geological knowledge contribute to the expansion of this method, providing subsidies for investments in mineral exploration in this area and other regions.

Based on the collected data and statistical analyses conducted for both sample and population coefficients, there is a positive linear correlation between weight and depth for gold samples. Larger nuggets tend to be found at a deeper level. The gold mineralization in this area was found to be hypogenic, with native gold crystallized in the quartz veins present in the host rock. The current concentration of gold at regolith levels developed due to preferential weathering of granite rock with posterior dismantling and accommodation of gold in quartz veins in the local relief. The study of gold nuggets and grains provides an understanding of the mineralogy and metallogeny of such occurrences in the Southern Espinhaço Range, and further academic contributions are necessary to deepen the understanding of the subject in this region.

From an environmental perspective, traditional artisanal and small-scale gold mining practices in Brazil are undoubtedly related to several important environmental and social impacts. It is concluded that high-resolution metal detectors are a viable alternative to archaic and damaging prospecting practices and methods, particularly considering their effectiveness, relatively low cost, and significantly lower environmental impacts. Given this context, this study is likely applicable to all areas of the world where similar practices are utilized.

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