

Article

Unraveling a Rare Polygonal Gold–Pyrite Assemblage: Insights from the Lena Province, Bodaibo Mining District (Russia)

Isabella Pignatelli ^{1,*} , Gaston Giuliani ^{1,2}, Christophe Morlot ³ and Louis-Dominique Bayle ⁴

¹ Centre de Recherches Pétrographiques et Géochimiques (CRPG), UMR 7358 CNRS-UL, Université de Lorraine, 54500 Nancy, France; gaston.giuliani@univ-lorraine.fr

² Géosciences Environnement Toulouse (GET)/Institut de Recherche pour le Développement (IRD), UMR CNRS-IRD-CNRS 5563, Université Paul Sabatier, 14 Avenue Edouard Belin, 31400 Toulouse, France

³ Laboratoire Energie & Mécanique Théorique et Appliquée (LEMTA), Université de Lorraine, 54000 Nancy, France; christophe.morlot@univ-lorraine.fr

⁴ Independent Researcher, 590 Chemin de Glavenas, 43200 Saint-Julien-du-Pinet, France; baylelrm@wanadoo.fr

* Correspondence: isabella.pignatelli@univ-lorraine.fr

Abstract: A rare polygonal gold assemblage from the Bodaibo mining district (Russia) was analyzed in this study. It resembles cubic native gold from the same area described as a gold pseudomorph after pyrite. The polygonal assemblage differs from these cubic gold samples by the absence of striations, its stepped morphology, and the presence of euhedral pyrite. It was analyzed with non-destructive techniques (SEM, VSI, and X-ray CT) in order to preserve the integrity of this exceptional sample. The experimental data allowed us to understand how this rare sample could be formed. A formation of secondary deposits, i.e., eluvial placers, is compatible with the mobilization and precipitation of gold by surface effects on primary pyrite, as well as oxidation episodes producing iron oxides/hydroxides. The redox condition in the geological environment caused the pyrite dissolution and release of gold in its structure, leading to the formation of a thin layer of gold on pyrite by epitaxy rather than pseudomorphism.

Keywords: gold; pyrite; polygonal habit; Bodaibo mining district; epitaxy; pseudomorphism; mineralogy; supergene alteration



Academic Editor: Qingfeng Guo

Received: 25 November 2024

Revised: 9 December 2024

Accepted: 16 December 2024

Published: 24 December 2024

Citation: Pignatelli, I.; Giuliani, G.; Morlot, C.; Bayle, L.-D. Unraveling a Rare Polygonal Gold–Pyrite Assemblage: Insights from the Lena Province, Bodaibo Mining District (Russia). *Crystals* **2025**, *15*, 4. <https://doi.org/10.3390/cryst15010004>

Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

In the past century, the Bodaibo region has been widely exploited for non-renewable natural resources; this led, in 1961, to the discovery of the giant Sukhoi Log deposit. This deposit is considered the largest gold deposit in Russia, and is one of the largest in the world [1]. From 1965 to 1975, other gold deposits that are currently exploited were discovered, and these provided some rare mineralogical oddities, including native gold crystals with cubic habit, hopper gold octahedra, and unusually large gold nuggets [2]. These exceptional samples originated from an old prospect located on the banks of the Ust-Urjach river, 12 km north of its confluence with the Vitim river [2,3]. The authenticity of these unique samples has been questioned by the community of mineral collectors, but the research performed by Rakovan et al. [2] concluded the natural genesis of these atypical samples of cubic gold.

In the present study, we focus on another mineralogical oddity from the same samplings carried out by Russian prospectors involved in the large-scale exploration program carried out by the Soviet Union in the last century. This is a polygonal gold that presents macroscopic inclusions of pyrite; it resembles the striated gold cubes described by [2]. These

authors assumed that the cubic gold samples are pseudomorphs after pyrite, although this event is quite rare. Our observations and the X-ray tomographic data suggest that the sample is more likely the result of a thin gold layer grown by epitaxy on a twinned pyrite, rather than a pseudomorphic replacement of pyrite by gold. The data also allowed the determination of the deposit type from which the sample comes: its composition, comprising a big pyrite crystal as well as secondary iron oxides/hydroxides, indicates that it probably originated from eluvial placers.

2. Materials and Methods

The analyzed sample was a polygonal gold assemblage ($\sim 2 \times 2 \times 2 \text{ cm}^3$) devoid of matrix (Figure 1). It is not striated, contrary to the cubic gold crystals described by Rakovan et al. [2]. A portion of a euhedral face of pyrite was observed on a face of the assemblage. The sample was irregular: the faces were stepped or with cubic hillocks. Smaller cubic crystals were visible on the surface, and the biggest one was located on a corner (its section was about $2.5 \times 2 \text{ mm}^2$). The surface was rough, with etching evidence filled by brown-reddish secondary minerals. The sample was not cleaned in an ultrasound tank, nor by chemical application, in order to preserve its integrity, as it is a rare specimen. For the same reason, the sample was analyzed only with non-destructive techniques.

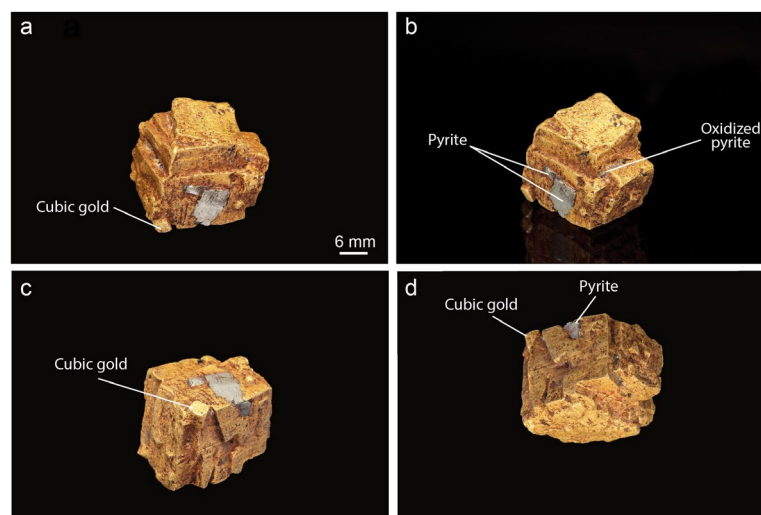


Figure 1. Different views (a–d) of the gold–pyrite assemblage showing macrosteps and polygonal habit.

2.1. Scanning Electron Microscopy (SEM)

Scanning electron microscopy was carried out with a JEOL JSM-6510 equipped with an energy-dispersive X-ray (EDX) Genesis detector, using a 3 nA primary beam accelerated at 15 kV. Point EDX analyses of secondary minerals were carried out with the same microscope on the surface and between the macrosteps without coating the sample.

2.2. X-Ray Computed Tomography (CT)

X-ray computed tomography was used to reveal high-resolution three-dimensional details of the sample, as previously performed for emeralds and rubies [4–6]. Additional details, advantages, and limitations of CT applications in the geosciences are provided by [7–9]. For the present study, in collaboration with the Plastinnov technology platform, CT images were produced with the Phoenix V|tome|x S240 tomographer equipped with two X-ray generators: a 180 kV/20 W nanofocus tube designed for low-absorption materials, with a detection capability of $0.2 \mu\text{m}$, and a 240 kV/320 W microfocus tube used for larger and/or denser samples. The sample holder supported 10 kg, and the DRX250RT detector was able to scan large samples up to 500 mm.

For the gold–pyrite assemblage, we used the microfocus generator set to 210 kV and 150 μ A, collecting 1000 projections during a complete rotation of the sample with a resolution of 6.80 μ m/voxel. Visual cross-sections were extracted and analyzed with Dragonfly 3D world 2024 (version 2024.1) and Avizo 2024 software (version 2024.2) in order to visualize the 3D details of the sample and determine the volume of gold and pyrite.

2.3. Vertical Scanning Interferometry (VSI)

VSI was used to analyze the surface topography of the sample faces. This technique allowed for rapid digitizing and processing of the inference pattern to obtain 2D and 3D topographical maps with nanometric resolution (up to 0.1 nm in the z-direction, [10]). A Zygo ZeGage Pro HR interferometer fitted with a 5.5 $\times$ Michelson objective (numerical aperture = 0.15) was used to collect images with a scan length of 100 μ m and an acquisition time of 8 s. This setup permitted visualization of a scanning area of 1.56 mm $\times$ 1.56 mm² per image field.

3. Geological Setting

The Bodaibo mining district in the Lena gold province is located 850 km northeast of Irkutsk in Siberia. It produced more than 30 tons of gold between 1863 and 1900 [1,11,12]. This district includes both primary and secondary gold deposits.

The primary deposit of Sukhoi Log, discovered by drilling in 1961, and exploited intensively from 1971 to 1977, constitutes the largest gold reserves in the world. These reserves are estimated at 1500 tons of gold averaging 2.73 g/t [13]. The Sukhoi Log deposit is the typological reference for all the primary deposits in this region, notably those of Verninsky, Golets Vysochaishy, Ozherelie, Ikan, Ugakhan, and Nevskoe. All of these gold deposits formed in a ductile-brittle tectonic context in a sedimentary series of argillite-turbidite type, and metamorphosed in greenschist and sometimes amphibolite facies. They are characterized by shear zones located in the hinges of isoclinal folds and subjected to the circulation of CO₂-H₂O-NaCl hydrothermal fluids at temperatures between 128 and 385 °C and pressures between 0.6 and 3.3 kbar [14].

The primary deposits in this area are hosted in Neoproterozoic claystones and sandstones (Ediacarian, 635–540 Ma) metamorphosed during the Paleozoic (Upper Ordovician, 375–360 Ma). The gold mineralization dated between 450 and 430 Ma by the Rb-Sr and ⁴⁰Ar-³⁹Ar method is marked by an episode of remobilization at 330 Ma relating to the intrusion of a granite complex [15]. Gold is located either in sulfide micro-veins disseminated in the meta-claystone or in quartz, carbonate (dolomite, ankerite), and sulfide (mainly pyrite, pyrrhotite, arsenopyrite) veins, accompanied by significant carbonatization and silicification of the surrounding rocks [1,16,17]. The disseminated pyritic tabular orebody is located in the axial zone of a regional near-isoclinal reclining anticline over a length of 3.3 km, and the gold-sulfide-bearing quartz veins crosscut the axial zone of the fold, forming cylindrical ore shoots [1]. The upper edge of the orebody is 40 m below the surface and extends down to more than 400 m. Gold presents different forms: (i) invisible, when it is incorporated into the structure of pyrite during sedimentary deposition (framboids, nodules in meta-argillites); (ii) in micro-inclusions in hydrothermal sulfides; and (iii) native gold visible in quartz veins. Several generations of pyrite are described (at least seven types) which correspond to different episodes of the deposition and metamorphism of sedimentary rocks, and the formation and remobilization of deposits [17].

The secondary deposits, i.e., placers in the Bodaibo region, have been exploited since the 1860s [15]. The source of alluvial and eluvial gold is still debated because the primary deposits of the Sukhoi Log type are of limited extent, or even not outcropped. Moreover, the occurrence of gold grains sized less than 0.1 mm is not a favorable factor for gravity

accumulation of gold in alluvial placers. The possible source of gold in the Bodaibo district was recently discussed by Lalomov et al. [18]. They analyzed gold sampled from different locations in order to link the morphology, chemistry, texture, and inclusions of gold to its source to aid local and regional prospecting.

4. Results

The polygonal gold has a macroscopic inclusion of pyrite (Figure 1). Both minerals were identified under the binocular microscope and by SEM-EDX analyses (Figure 2). The brownish color of gold and the presence of silver (Figure 2a) indicate that the alloy is electrum. It was not possible to know its exact composition because (i) trace elements (i.e., Pt, Ni, Cu, etc.) are not detected by SEM, and (ii) above all, the composition is probably heterogeneous. Some analyses of the alloy are reported below; they were carried out where the contamination of secondary minerals was as little as possible (Table 1). If one excludes Fe and O (likely due to secondary minerals), the composition of alloy is made up of 96–98% gold and 2–4% Ag, at least at the surface of the sample.

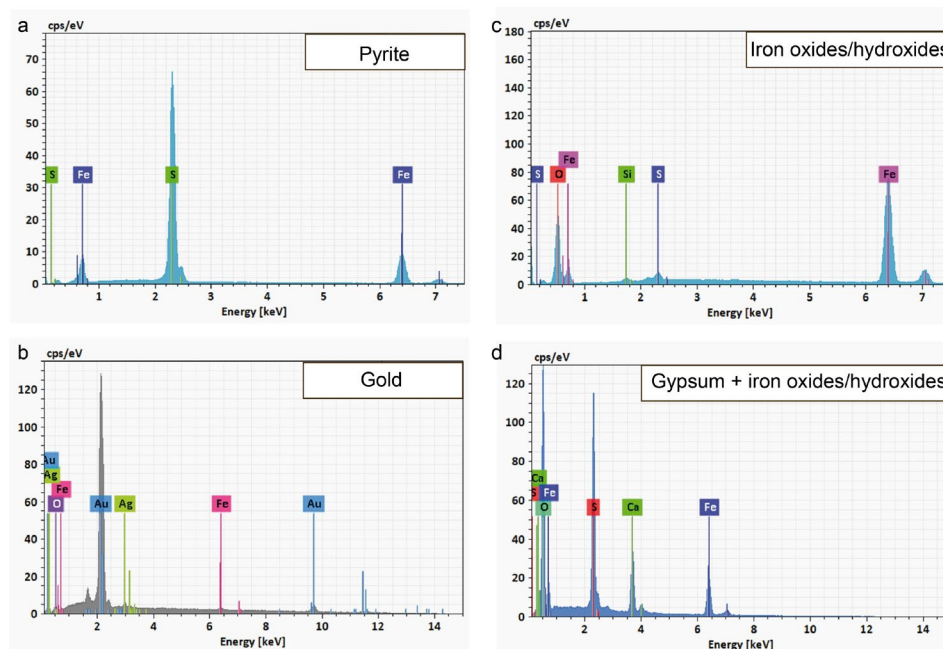


Figure 2. SEM-EDX spectra of pyrite (a), gold (b), iron oxides/hydroxides showing a residual peak of S due to the pyrite destabilization and a peak of Si (c), a mixture of gypsum and iron oxides/hydroxides (d).

Table 1. SEM-EDX analyses (in wt. %) of gold surface with less contamination of secondary minerals. The highest error is 1.7 wt. % for gold.

	Au	Ag	Fe	O
Analysis 1	76.83	3.03	9.96	10.17
Analysis 2	61.38	1.42	19.89	17.70
Analysis 3	93.84	2.19	1.83	2.14
Analysis 4	84.27	3.30	8.35	4.08
Analysis 5	81.57	2.34	9.99	6.19

The assemblage has a weight of 40.3 g and a volume of 4.47 cm³, calculated from X-ray tomography data. The estimated error in the volume calculation is ± 0.05 cm³. Thus, if one considers the density of pure 24 karat gold ($d = 19.32$ g/cm³), the sample should weigh 86.3 g if it is made only of gold. In the case of 18 karat gold, the weight would decrease to 69.64 g. CT data highlight the presence of re-entrant corners in pyrite, and no marked separation between the individuals is observed (empty spaces or gold precipitation), suggesting that pyrite is likely twinned (at least three individuals; Figure 3). CT data also suggest that what one sees macroscopically on a face of this assemblage is only a small portion of the total pyrite (Figure 3). Thus, the volume occupied by pyrite can explain the lower weight of the specimen than what was expected. If the total volume of the assemblage is 4.47 cm³, its density (gold+pyrite) is 9.02 g/cm³. The density of pyrite is 5.01 g/cm³, it follows that the gold corresponds to 28% of the assemblage (assuming a purity of 24 karats) and its estimated volume is 1.25 cm³, whereas the pyrite occupies the remaining volume of 3.22 cm³. As the gold is likely impure, it should correspond to 38% of the assemblage, assuming a purity of 18 karats. This means that the gold volume should be between 1.25 and 1.69 cm³, whereas the pyrite volume is between 2.78 and 3.22 cm³. In any case, the assemblage is mostly made of pyrite. In order to estimate the volume of gold and pyrite, we measured the thickness of gold given by the different contrast on X-ray images, where the gold appears darker than pyrite (Figure 4a). The average gold thickness is 2 mm, and this value can be used to calculate the volume of the gold envelope around pyrite (Figure 4b). The volume of gold obtained in this way is 1.7 cm³, and the remaining volume of pyrite is 2.7 cm³. These values highlight that (i) pyrite occupies a larger volume than what is visible on the sample surface; and (ii) the composition of gold is not constant. Its surface is purer (see Table 1), but the composition is likely to vary inside the gold layer, becoming less pure with depth. It is likely that at the contact point with pyrite, it is richer in Fe and other metals. This compositional heterogeneity can explain the apparent inconsistency between the SEM-EDX and CT data. In fact, the SEM-EDX data concern only the surface of the gold layer, whereas the CT data give its total volume.

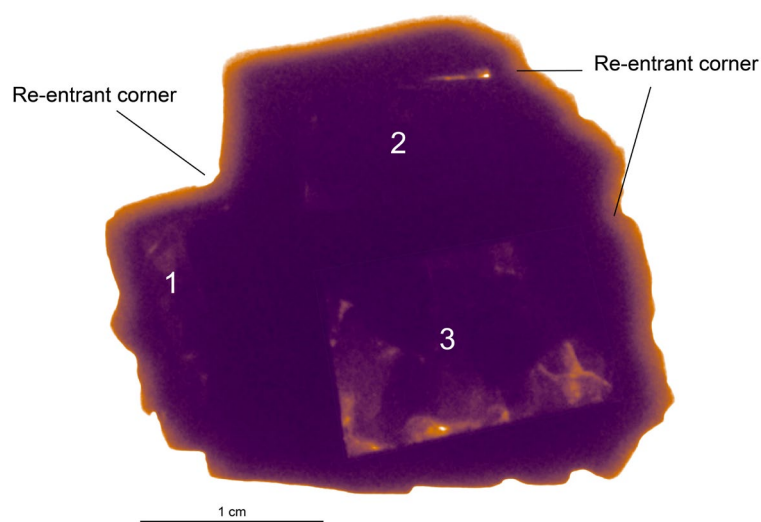


Figure 3. CT image showing the orientation of three individuals (indicated by numbers 1 to 3) of twinned pyrite inside gold. The absence of empty spaces or gold between the individuals indicates that they are not isolated crystals; in addition, the presence of re-entrant corners suggests that the pyrite is twinned (probably a penetration twinning, which is very common in pyrite). Another view of the three individuals is shown in Figure 4a.

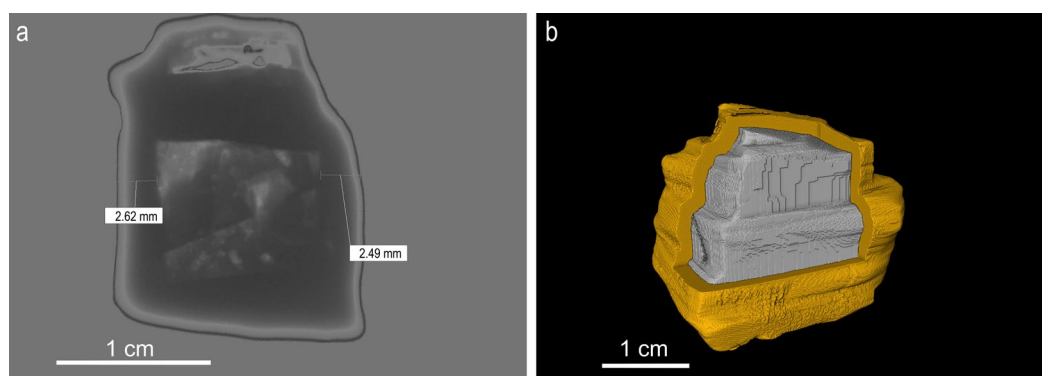


Figure 4. (a) X-ray image of the assemblage showing the thickness of gold around pyrite. (b) False-color CT image obtained from the volume calculation and showing the gold layer (yellow) around the pyrite (grey).

The morphology of the analyzed specimen is characterized by several steps (Figure 5), which gives the overall impression of a successive stack of polygonal gold clusters. The height of the steps varies from 1.2 mm to 4.4 mm (Figure 6). No gold cube is observed, apart from small cubic crystals (Figures 1 and 7).

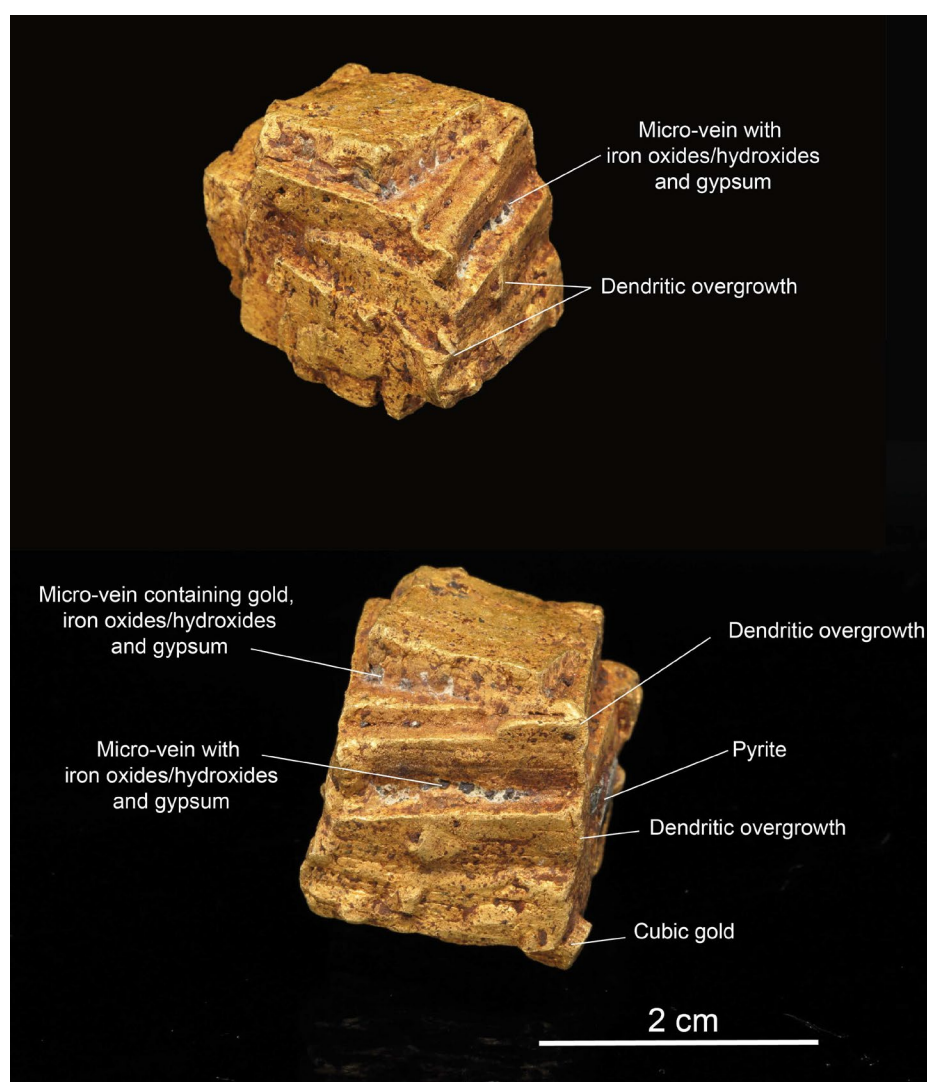


Figure 5. Optical images of macrosteps and micro-veins with white gypsum crystals and reddish-brown iron oxides/hydroxides.

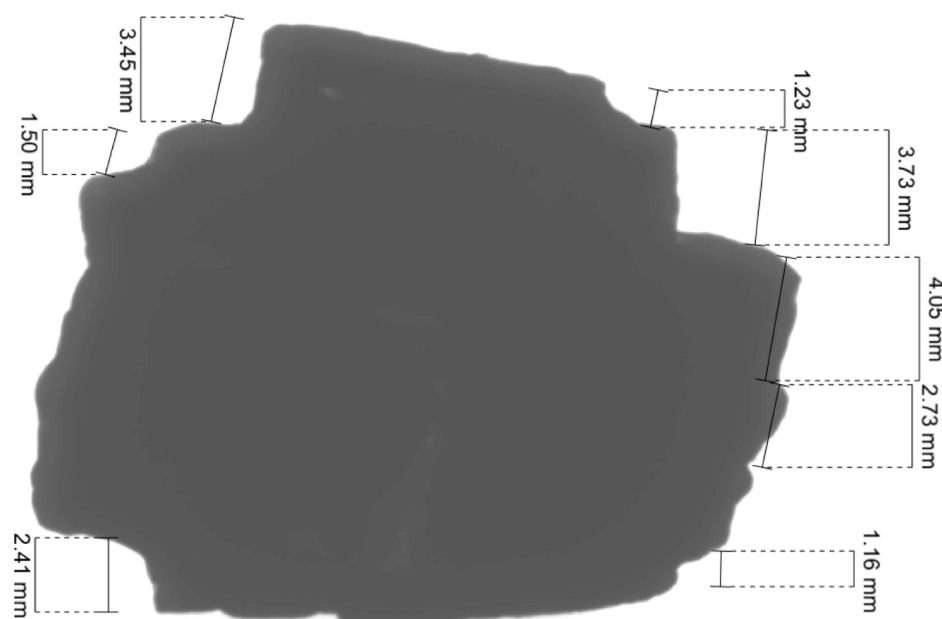


Figure 6. CT image allowing for the measurement of macrosteps' heights.

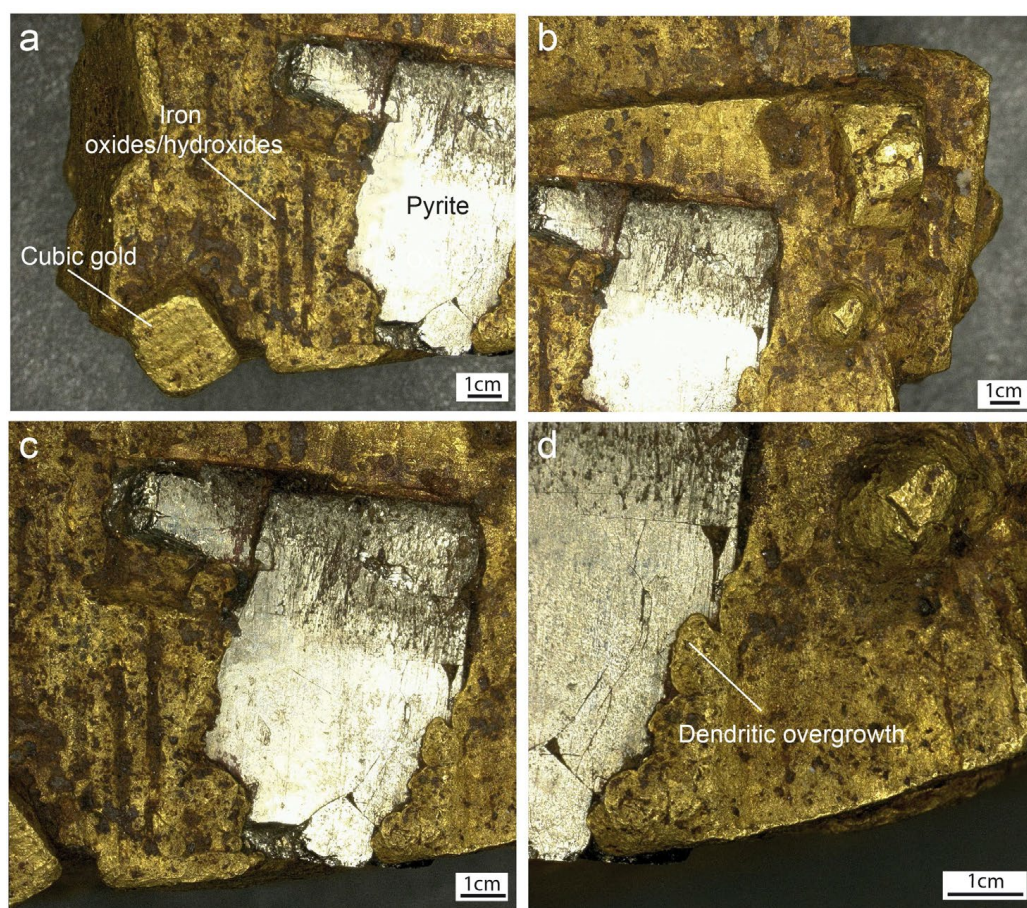


Figure 7. Optical images showing textural details of gold–pyrite assemblage. (a) Big crystal of pyrite inside gold. Iron oxides and hydroxides are visible on gold, as well as the small cubic crystal at the corner. (b) Pseudo-cubic hillocks of gold on the assemblage. Magnification of the contact between pyrite and gold, showing that the pyrite faces are fractured and deformed (c), and gold dendritic overgrowth (d).

VSI data show that the surface of this specimen is wrinkled and very irregular, but no striations are recognizable. An example of the face's roughness is shown in Figure 8, where the vertical difference is about 117 microns and it is possible to observe depressions due to etching and heights related to the precipitation of secondary minerals, which appear reddish-brown macroscopically. The SEM-EDX analysis indicates the presence of O and Fe and thus iron oxides and/or hydroxides (Figures 9 and 10) due to late oxidation processes. Among them, lepidocrocite was identified by VNIR reflectance spectroscopy, but a mixture such as limonite seems more plausible (hematite, goethite, lepidocrocite). As the exact nature of these minerals is unresolved, we refer to them as “iron oxides/hydroxides” in the following text. These oxides/hydroxides mark also the thresholds of different steps (Figure 5). Three kinds of steps can be distinguished as follows:

- Steps having a white micro-vein parallel to the step edge (Figure 10a,b). The micro-vein contains blackish iron oxides/hydroxides, and some parts display a metallic luster (Figure 10c,e). The SEM-EDX analysis shows the presence of iron peaks and a smaller quantity of sulfur (Figure 2c), confirming that they result from pyrite oxidation. This oxidation leads also to the precipitation of gypsum (Ca and S peaks in Figures 2d, 10f, and 11c), which gives the white color to the vein. On the SEM-EDX spectra of gypsum aggregates, the peak of silicon can be detected, and this suggests that gypsum is associated with silica (Figure 2c). Figure 10b,d shows that this micro-vein is cut by a native gold crack with the occasional crystallization of gold flakes in the gypsum matrix (Figure 10d). The inhomogeneous distribution of small oxides in the vein and near the larger oxide crystals (Figure 10f) suggests that the micro-vein was entirely pyritic before the oxidation.
- Steps similar to the previous one, but having a sigmoidal shape (Figure 11).
- Steps with few white micro-veins as previously described, but located in an area with high porosity, where gold grains have variable sizes (fine, medium, and coarse grains; Figure 11b). This is probably the result of etching processes (explaining the high porosity) and the precipitation of gold, which becomes progressively coarser overtime.

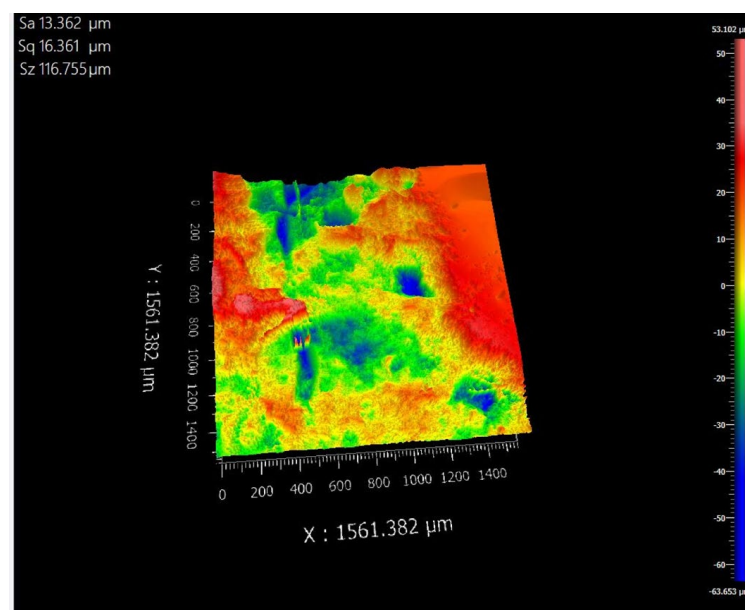


Figure 8. 3D VSI image showing the roughness of the gold surface, characterized by depression and heights corresponding to etching and precipitation of secondary minerals, respectively.

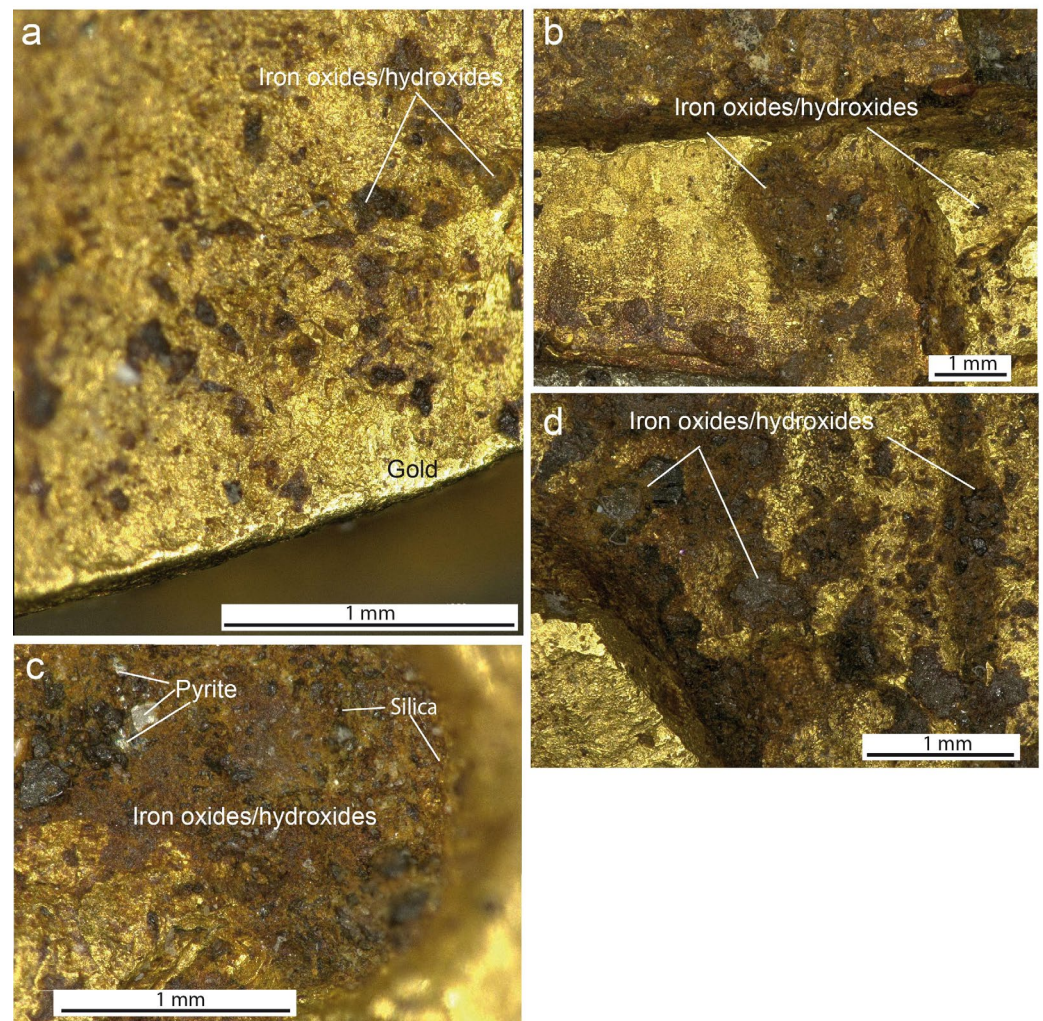


Figure 9. (a) Overview of iron oxides/hydroxide inclusions in gold. (b) Iron oxides/hydroxide inclusion resulting from the complete oxidation of pyrite and bands of iron oxides/hydroxides on the faces of the assemblage. (c) Pyrite destabilization marked by the occurrence of iron oxides/hydroxides and silica. (d) Magnification of oxides/hydroxides.

Three generations of pyrite can be distinguished in this specimen:

- (i) Pyrite I. The bigger pyrite crystal visible in the specimen shows two orthogonal faces (Figure 7), the largest of which measures $6 \times 12 \text{ mm}^2$, gray in color and with a metallic luster. The surface of faces is rough, although there are no striations classically described for this mineral. The crystallization of pyrite I and gold are not contemporary: pyrite formed earlier than gold, similarly to the pyrites described in the quartz-carbonate-pyrite veins of primary gold deposits of the Sukhoi Log type [17].
- (ii) Pyrite II. Very small crystals (500–600 μm or less), brass yellow in color and with a metallic luster, are included in gold (Figure 12). They are located in cavities with iron oxides/hydroxides. This mineralogical association is due to the oxidation of pyrite, which must have been larger before its alteration. SEM data indicate that feldspars and Mg-Fe chlorites are other alteration minerals in association with iron oxides/hydroxides.
- (iii) Pyrite III is located in three gold-bearing levels, arranged in steps. A pyrite with a dimension less than 500 μm is the relic of a strong oxidization (Figure 9c), as suggested by a small sulfur peak on the SEM analysis of surrounding iron oxides/hydroxides (Figure 2c).

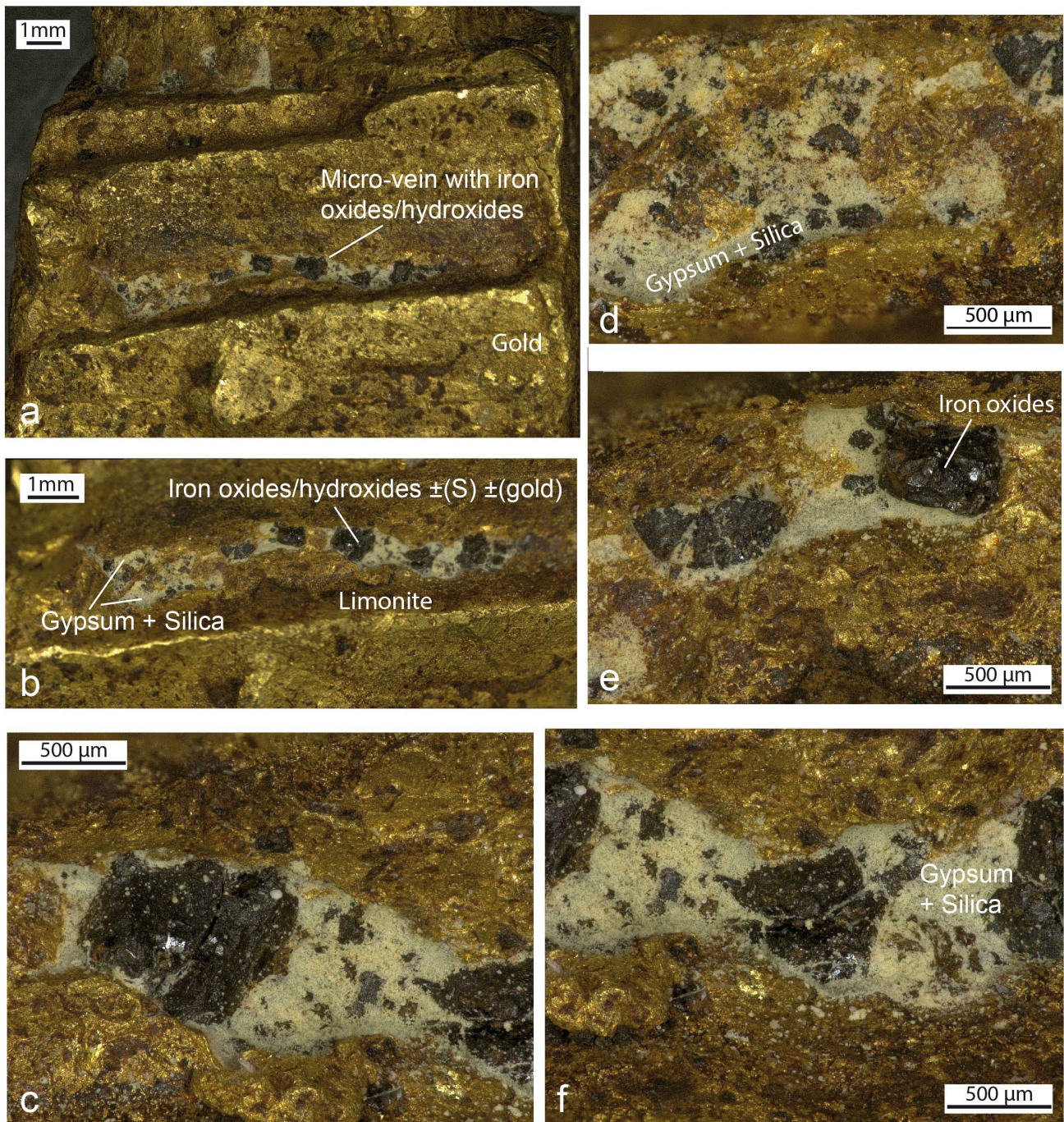


Figure 10. (a) Micro-vein containing reddish-brown iron oxides/hydroxides and white gypsum between two macrosteps of gold. (b) The step edge is underlined by the presence of iron oxides/hydroxides due to the destabilization of pyrite (S peak on SEM-EDX spectra). The micro-vein is slightly faulted and contains also gypsum. (c) Magnification of iron oxides/hydroxides associated with gypsum. (d) Fracture filled by gold intersecting a micro-vein. A gold grain is formed in the gypsum. (e) Iron oxide with metallic luster, which is likely hematite. (f) Fragments of iron oxides/hydroxides and gypsum resulting from pyrite alteration.

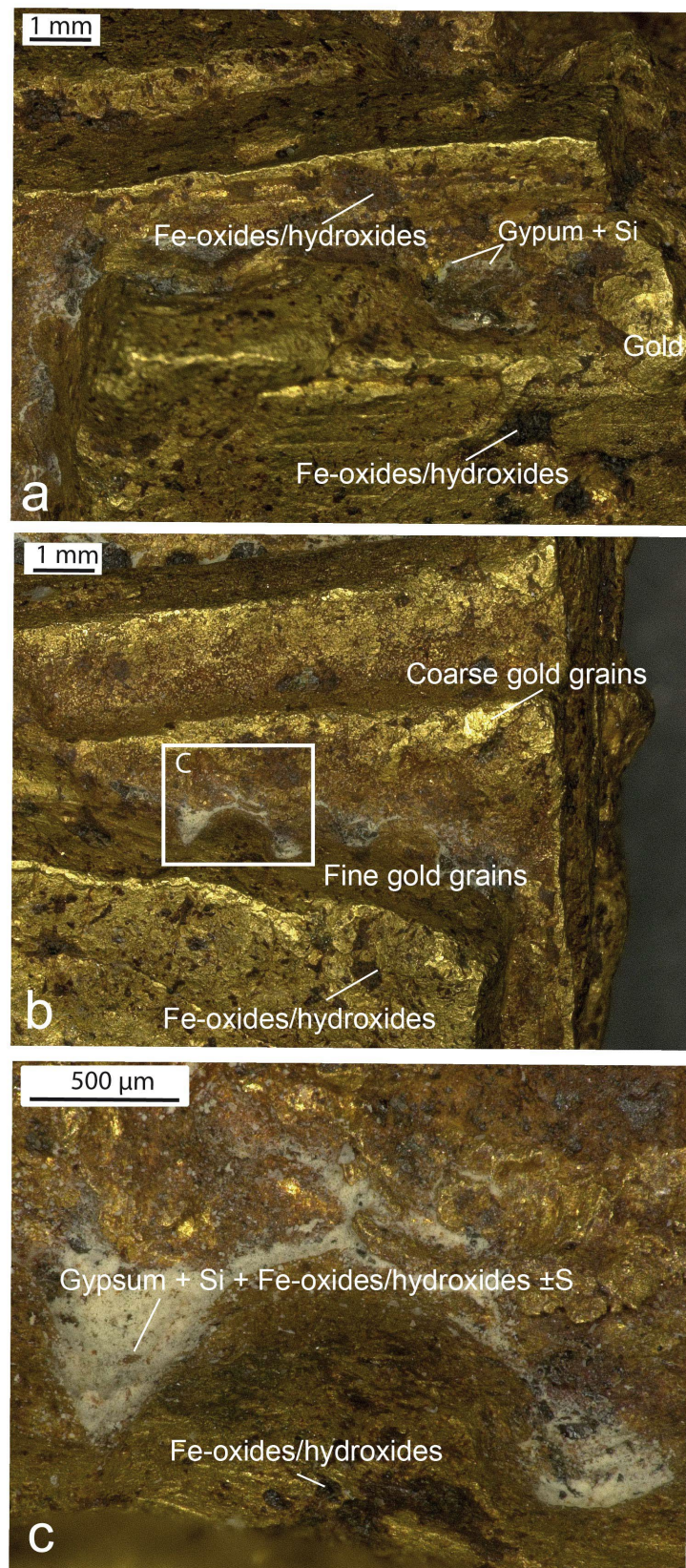


Figure 11. (a) Hollow micro-vein filled by gypsum and silica parallel to the step edge. On the edges, gold forms coarse grains containing scattered iron oxides/hydroxides. (b) Variations in grain sizes of gold (fine to coarse) and faulted micro-vein. (c) Detail of the faulted micro-vein with a sigmoidal shape.

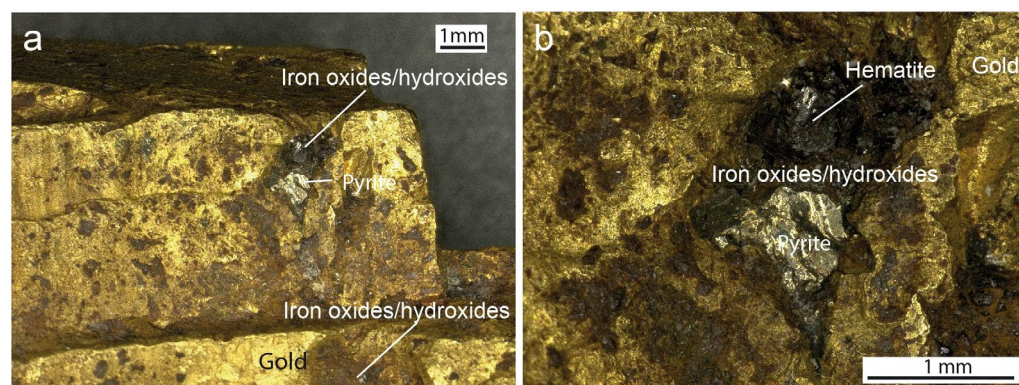


Figure 12. (a) Strongly oxidized pyrite forms small crystals included in gold. (b) Detail of pyrite inclusion, showing the presence of hematite.

5. Discussion

The gold samples found in the Bodaibo region are exceptionally rare [2]. Among them, the studied sample has particular textural and morphological features that witness a special mechanism of gold deposition.

The geological and mineralogical studies published by different authors on both primary and secondary gold deposits of the Bodaibo region allow a discussion about the possible origin of the studied sample, i.e., a primary origin versus a secondary origin (placers).

The association of pyrite I with gold nuggets indicates that a secondary deposition took place in placers, because the native gold present in the quartz veins with sulfides and carbonates is generally small (10 to 80 μm), or it occurs between different generations of nodular and framboidal pyrites [17]. In addition, pyrite I has two faces, well preserved and without superficial deposits of iron oxides/hydroxides. This underlines, on the one hand, its primary character, and on the other hand, that the analyzed specimen has not undergone river transport, or at least very little. Thus, the question arises: is it alluvial gold or eluvial-coluvial gold?

According to the work carried out by Lalamov et al. [18] on the Bodaibo gold placers, the polygonal gold–pyrite assemblage has formed in eluvial placers. In such secondary deposits, gold originates from iron-rich weathered areas, located in zones of disjointed dislocations of the Neoproterozoic basement in contact with gold-sulfide quartz veins. These weathered areas, reddish to brown in color, are called LWCs (“Linear Weathering Crusts”) and they were exploited during the early stages of development of the Bodaibo mining district [18,19]. The eluvial gold forms large grains (40–160 μm), chemically zoned because almost pure gold precipitates only at their periphery due to supergene enrichment in the weathered areas. It seems that 70% of these gold grains have exceptional purity (between 920 and 998) and form very rich placers. Eluvial gold grains always contain inclusions of pyrite and iron oxides/hydroxides. All these features are observed in the analyzed sample, which is quite big, covered by secondary iron minerals, and contains a pyrite inclusion. It should be underlined that our sample is supposed to be zoned, with the purest gold only at its surface (see Results), as in other gold samples from eluvial placers.

5.1. Paragenesis and Pyrite Formation

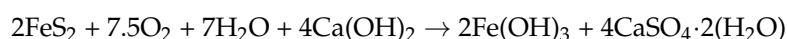
The paragenesis of the analyzed specimen includes electrum-type gold and Fe-bearing minerals, notably pyrite and oxides/hydroxides, which are likely a mixture of hematite, goethite, and lepidocrocite. Three generations of pyrite are identified, i.e., pyrites I, II and III (see Section 4).

Pyrite I is morphologically similar to the crystals described for the primary mineralization of quartz-carbonate-sulfide-gold veins in the Bodaibo region [17]. Indeed, these authors

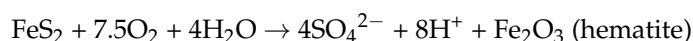
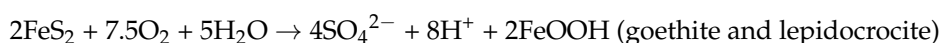
describe seven types of pyrite (Py1 to Py7), which were formed one after another over time, including cubic pyrite of centimeter size (Py5) containing smaller gold-bearing pyrites (Py1 to Py4). Thus, pyrite is the source of gold in these veins. Pyrite I of our specimen has a primary origin and played a fundamental role in the deposition of later gold.

Pyrites II and III witness later episodes of pyrite precipitation (sulfurization) contemporary with the deposition of gold. These pyrites were affected by strong destabilization, leading to the neoformation of gypsum and iron/hydroxides, as well as the precipitation of Si-bearing phases (silica, feldspars, chlorites). The main reactions of pyrite destabilization can be written as follows:

- gypsum precipitation, considering the Ca released by the dissolution of the carbonates also present in the pyrite-gold quartz veins:



- iron oxides/hydroxides formation due to the oxidation of Fe^{2+} into Fe^{3+} . This oxidation is accompanied by a release of H_2S which will promote the dissolution of carbonates, the oxidation of other sulfides, and the hydrolysis of silicates:



5.2. A Possible Genetic Model for the Formation of the Polygonal Gold-Pyrite Assemblage

The aforementioned different oxidation and reduction phenomena modify the precipitation conditions of minerals, particularly those associated with iron and other metals, such as gold, that form typical gossans and supergene iron deposits [20,21]. Both are usually located above the piezometric surface, where groundwater, rich in O_2 and CO_2 , circulates easily and can form a zone rich in Fe-oxides/hydroxides and other secondary minerals (sulfates, phosphates, arsenates, carbonates). Water can also leach and dissolve rocks, where minerals such as pyrite can leave empty cubic-shaped cavities or form complex crystals (e.g., pseudomorphs). In the case of gold-bearing pyrite from eluvial placers as in the Bodaibo district, the oxidation of pyrite releases gold and associated metals. They will be transported towards the bottom of the sequence and finally precipitated at the interface of a piezometric surface (illuvial imbibition zone). In the case of Bodaibo, the frequent occurrence of iron oxides/hydroxide on and in gold, as observed in the analyzed specimen, is strong evidence supporting the occurrence of the presented metallogenetic scheme.

5.3. Growth Mechanism for the Polygonal Gold-Pyrite Assemblage

The formation of the polygonal gold–pyrite assemblage is complex and occurred over several stages. The interaction between pyrite and groundwater causes the dissolution of pyrite, which may contain gold in its structure. The gold released into the water accumulates in the form of chemical complexes until the water become supersaturated with respect to gold. Then, gold can precipitate on the relics of pyrite crystals, preserving the crystallographic orientation of pyrite to reduce the energy at the pyrite–gold interface [22]. In this way, as both minerals crystallize in the cubic system, it is possible to transfer crystallographic information from the parent mineral (pyrite) to the daughter mineral (gold), even if the parent dissolves. In this specimen, the coupling of pyrite dissolution and gold precipitation could be described as epitaxy event rather than pseudomorphism, because the gold formed a very thin layer on pyrite crystals (~2 nm; Figure 4), and no porosity was observed. Rakovan et al. [2] described other cubic gold samples from the same deposit as pyrite pseudomorphs, because they observed other features supporting this

hypothesis: (1) striations through the gold, indicating surface orientations consistent with the faces of pyrite; (2) porosity observed both macroscopically and microscopically on the faces of gold; (3) polycrystalline texture of gold; and (4) a remnant core of suspected pyrite.

If the analyzed specimen is the result of pseudomorphic replacement, the substitution of the parent mineral by the daughter one should occur at a constant molar volume. If this does not occur, a certain degree of porosity should appear [23,24]. The molar volume of pyrite is about $24 \text{ cm}^3/\text{mol}$, and that of gold is about $12 \text{ cm}^3/\text{mol}$ (for 18 karat gold); thus, if the pyrite is replaced by gold, this difference in molar volume will generate porosity. To the contrary, we did not observe porosity via X-ray tomography, nor macroscopically. Another difference between the sample studied by Rakovan et al. [2] and that described here is the gold polycrystallinity; they observed that the gold surface was made of several grains with variable size, shape, and crystallographic orientation, whereas we observed a thin compact layer around the pyrite with an almost constant thickness (Figure 4). In addition, the difference in the molar volumes of pyrite and gold (two times) suggests that one does not need to dissolve much pyrite to deposit a thin layer of gold, resulting in a relic pyrite crystal as big as the pristine one (that is the case here). We also found dendritic overgrowths on the gold, not reported in the aforementioned study [2]. Once the gold layer was deposited, variations in temperature would have caused changes in water saturation. During a cooling episode, supersaturation increases, and thus the gold crystallization becomes faster due to an increase in the driving force. This leads to the formation of dendrites [25]. Supersaturation is higher at the corners and along the sides of the crystals, while at the center of the faces it is minimal (“Berg effect” [26]). Rather than true dendrites, we observe compact dendritic overgrowths, representing a textural ripening of dendrites due to another change in growth conditions. Ripening can result even in the development of a crystal habitus, explaining why there is a small gold cube on one corner of the specimen (Figures 1 and 7).

Rakovan et al. [2] did not observe steps on their cubic gold samples, while the presence of steps in this specimen is most likely due to the fact that the pyrite was twinned (at least three individuals), and thus the thin layer of gold covered the parent mineral, reproducing the differences in levels between each individual of the twin.

According to the redox conditions in the growth medium, the iron released into the water by the dissolution of the pyrite was oxidized, promoting the precipitation of iron oxides and hydroxides. These minerals were observed between the steps, which are the most “sensitive” surfaces to secondary alteration. Iron oxides/hydroxides are accompanied by gypsum, which confirms the late alteration of pyrite under oxidizing conditions.

6. Conclusions

The studied polygonal gold–pyrite assemblage from the Bodaibo district of the Lena province is an exceptional and atypical mineralogical oddity. This study of this natural specimen, showing the association of gold and pyrite with iron oxides/hydroxides and gypsum, highlights that it was undoubtedly formed at a low temperature in a placer-type environment, excluding an endogenous mineralization.

The main feature of the assemblage is the presence of multi-millimeter inclusions of euhedral pyrite (pyrite I), which shows only two faces. This pyrite played a fundamental role in the deposition of the gold layer, whereas the smaller oxidized pyrites (pyrites II and III) witnessed the later episodes of sulfurization contemporary with the gold deposition.

The previous studies carried out on the primary and secondary gold deposits of Bodaibo mining district allowed us to discuss the formation of this rare sample and to propose a possible geological model. The different oxidation and reduction phenomena, which reflect the variations in redox conditions during the precipitation of minerals, are also

described in the formation of gossan deposits and supergene iron formations. The observed paragenesis explains the hypothesis of an eluvial deposit containing accumulations of debris or rocks resulting from primary pyrite mineralization, and subject to the variation in superficial oxidation, as well as to the variation in piezometer surface (imbibition zone). The formation in an eluvial deposit is compatible with (i) the mobilization and precipitation of gold by surface effect on primary pyrite, (ii) the deposition of gold on pyrite under changes in driving force conditions, and (iii) oxidation episodes, marked by the precipitation of iron oxides/hydroxides in and on native gold.

Author Contributions: Conceptualization, G.G. and I.P.; methodology, I.P. and G.G.; formal analysis, G.G. and I.P.; investigation, I.P., G.G. and C.M.; resources, L.-D.B.; writing—original draft preparation, G.G. and I.P.; writing—review and editing, I.P. and G.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in the study are included in the article.

Acknowledgments: The authors thank the Plastinov technology platform for the support in CT data collecting.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Wood, B.L.; Popov, N.P. The giant Sukhoi Log gold deposit, Siberia. *Russ. Geol. Geophys.* **2006**, *47*, 317–341.
2. Rakovan, J.; Lüders, V.; Massanek, A.; Nolze, G. Gold crystals from the Léna goldfields, Bodaibo area, Eastern Siberia: Exceptional hopped octahedra and pseudomorph after pyrite. *Rocks Miner.* **2017**, *92*, 410–425. [\[CrossRef\]](#)
3. Wolf, R. Spektakuläre goldkristalle aus Bodaibo im Baikäl-Gebiet. *Lapis* **2016**, *41*, 12–23. (In German)
4. Pignatelli, I.; Giuliani, G.; Morlot, C.; Van Long, P. The texture and chemical composition of trapiche ruby from Khoan Thong, Luc Yen mining district, northern Vietnam. *J. Gemmol.* **2019**, *36*, 726–746. [\[CrossRef\]](#)
5. Pignatelli, I.; Giuliani, G.; Morlot, C.; Cathelineau, M.; Shang, I.L. Flower-shaped trapiche ruby from Mong Hsu, Myanmar: A revised growth mechanism. *J. Gemmol.* **2020**, *37*, 404–415. [\[CrossRef\]](#)
6. Pignatelli, I.; Giuliani, G.; Morlot, C.; Salsi, L.; Martayan, G. Colombian emerald oddities: Review and formation mechanisms. *J. Gemmol.* **2022**, *38*, 26–43. [\[CrossRef\]](#)
7. Ketcham, R.A.; Carlson, W.D. Acquisition, optimization and interpretation of X-ray computed tomographic imagery: Applications to the geosciences. *Comput. Geosci.* **2001**, *27*, 381–400. [\[CrossRef\]](#)
8. Cnudde, V.; Boone, M.N. High-resolution X-ray computed tomography in geosciences: A review of the current technology and applications. *Earth-Sci. Rev.* **2013**, *123*, 1–17. [\[CrossRef\]](#)
9. Richard, A.; Morlot, C.; Créon, L.; Beaudoin, N.; Balistky, V.S.; Pentelei, S.; Dyja-Person, V.; Giuliani, G.; Pignatelli, I.; Legros, H.; et al. Advances in 3D imaging and volumetric reconstruction of fluid and melt inclusions by high resolution X-ray computed tomography. *Chem. Geol.* **2019**, *508*, 3–14. [\[CrossRef\]](#)
10. Kumar, A.; Reed Sant, G. Vertical Scanning Interferometry: A new method to measure the dissolution dynamics of cementitious minerals. *J. Am. Ceram. Soc.* **2013**, *96*, 2766–2778. [\[CrossRef\]](#)
11. Smirnov, V.I. *Ore Deposits of the USSR*; Pitman Publishing: London, UK, 1977; Volume II, p. 424.
12. Benevolsky, B.I. *Gold of Russia*; OOO Geoinformark: Moscow, Russia, 2002; p. 462. (In Russian)
13. Migachev, I.F.; Karpenko, I.A.; Ivanov, A.I. The Sukhoi Log deposit: Reappraisal and estimation of the ore field and district. *Otech. Geol.* **2008**, *2*, 55–67. (In Russian)
14. Prokofiev, V.Y.; Safonov, Y.G.; Lüders, V.; Borovikov, A.A.; Kotov, A.A.; Zlobina, T.M.; Murashov, K.; Yudovskaya, M.A.; Selektor, S.L. The sources of mineralizing fluids of orogenic gold deposits of the Baikal-Patom and Muya areas, Siberia: Constrains from the C and N stable isotope compositions of fluid inclusions. *Ore Geol. Rev.* **2019**, *111*, 102988. [\[CrossRef\]](#)
15. Chugaev, A.V.; Budyak, A.E.; Larionova, Y.O.; Chernyshev, I.V.; Travin, A.V.; Tarasova, Y.I.; Gareev, B.I.; Batalin, G.A.; Rassokhina, I.V.; Oleinikova, T.I. ^{40}Ar - ^{39}Ar and Rb-Sr age constraints on the formation of the Sukhoi-Log style orogenic gold deposits from the Bodaibo district (Northern Transbaikalia), Russia. *Ore Geol. Rev.* **2022**, *144*, 1–20. [\[CrossRef\]](#)
16. Distler, V.V.; Yudovskaya, M.A.; Mitrofanov, G.L.; Prokof'ev, V.Y.; Lishnevskii, E.N. Geology, composition and genesis of the Sukhoi Log noble metals deposits, Russia. *Ore Geol. Rev.* **2004**, *24*, 7–44. [\[CrossRef\]](#)

17. Large, R.R.; Maslennikov, V.V.; Robert, F.; Danyushevshy, L.V.; Chang, Z. Multistage sedimentary and metamorphic origin of pyrite and gold in the giant Suhkoi Log deposit, Léna gold province, Russia. *Econ. Geol.* **2007**, *102*, 1233–1267. [[CrossRef](#)]
18. Lalomov, A.; Grigorieva, A.; Kotov, A.; Ivanova, L. Typomorphic features and source of native gold from the Sykhoi Log area placer deposits, Bodaibo gold-bearing district, Siberia, Russia. *Minerals* **2023**, *13*, 707. [[CrossRef](#)]
19. Razakevitch, Y.P.; Reverdatto, M.V. *Léna Gold-Bearing Gregion: Geology of Cenozoic Sequence and Types of Gold Placers*; Nedra: Moscow, Russia, 1972; p. 152. (In Russian)
20. Kosakevitch, A.; Polomero, F.G.; Leca, X.; Leistel, J.M.; Lenotre, N.; Sobol, F. Contrôles climatique et géomorphologique de la concentration de l'or dans les chapeaux de fer de Rio Tinto (Province Huelva, Espagne). *Comptes Rendus de l'Académie des Sciences. Série 2* **1993**, *316*, 85–90.
21. Jebrak, M.; Marcoux, E. Géologie des ressources minérales. Édition originale publiée par Géologie Québec et Ouvrage réimprimé par la Société de l'industrie minière; In *Géologie des Ressources Minérales*; Société de l'industrie minière: Paris, France, 2008; p. 667.
22. Tauson, V.L.; Lipko, S.V. Pyrite as a concentrator of gold in laboratory and natural system: A surface-related effect. In *Pyrite: Synthesis, Characterization and Uses*; Whitley, N., Vinsen, P.T., Eds.; Nova Science Publishers: Hauppauge, NY, USA, 2013; pp. 1–40.
23. Putnis, A. *Introduction to Mineral Sciences*; Cambridge University Press: Cambridge, UK, 1992; p. 479.
24. Putnis, A. Mineral replacement reactions. *Rev. Mineral. Geochem.* **2009**, *70*, 87–124. [[CrossRef](#)]
25. Sunagawa, I. *Crystals: Growth, Morphology & Perfection*; Cambridge University Press: Cambridge, UK, 2005; p. 295.
26. Berg, W.F. Crystal growth from solutions. *Proc. R. Soc.* **1938**, *164*, 79–95.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.