minerals

Review

Gold Deposits Related to the Island Arc Formations and Ophiolitic Complexes of Eastern Cuba: A Review

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Abstract: Several gold deposits in the eastern region of Cuba are genetically related to the island arc- and the ophiolitic complex formation. These have been studied and exploited since the time of the Spanish colonization in the mid-sixteenth century. These deposits belong to the Aguas Claras-Guajabales mineral field in the Holguín Province (Cuba) and lie in an elongated zone approximately 15 km in length. The object of this work is to make a methodical, detailed, and chronological review of the geological and mining work carried out in this region, as well as highlight the degree of the previously achieved studies. To realize this, an extensive bibliographic review of all available data, including published reports and articles, as well as unpublished material, was carried out. Moreover, ore mineralogy and petrography were reviewed by thin section analyses from samples from these deposits by petrographic and scanning electron microscopy. The results obtained from this study highlight that the gold mineralization in that area is closely linked to metasomatic processes produced by the circulation of hydrothermal fluids that affected the different volcanic and ultramafic rocks. This study shows that the highest gold contents observed are controlled by the contacts between the different host lithologies with high rheological contrasts. The presence of different alteration styles such as serpentinization, listvenitization, rodingitization, and propylitization have played a primary role in the deposition of gold during mineralization processes. This work could be a very useful exploration guide for future research in this region, as it provides a useful and practical compilation of the characteristics of the mineralization and alteration styles, as well as a precise indication of the spatial position, thicknesses, and contents of the gold-rich horizons.

Keywords: ophiolites; island arc; serpentinization; listvenitization; rodingitization; propylitization; gold; sulfides

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1. Introduction

The deposits mentioned in this study belong to the Aguas Claras mining district, which includes a series of deposits known as Reina Victoria, Holguinera, Nuevo Potosí, Agrupada, Hugo y María, El Oro, Santiago, Milagro, Casualidad, and Nene, among others (Figure 1).

Although mining in the eastern region of Cuba began in the sixteenth century, it was not until the eighteenth century that it was documented [1–3]. López de Quintana [4] investigated endogenous and alluvial deposits in the area of Guajabales and subsequently extracted ores with a content of 3.5 g/t Au. The Holguin-Santiago Mine Co. extracted 98.6 kg of Au between 1907 and 1910 [3] along with another mining company, the Santiago Mining Co. The mining work carried out by Abelspies [5] between 1929 and 1930 at the Santiago mine found mineralized horizons with average grades of 17.8 and 88.8 g/t Au, respectively. In 1937, Schmeling [6] located gold-enriched ores with a grade of 14.2 g/t Au at the

Reina Victoria deposit. Between 1942 and 1945, Biscuccia [7] extracted around 559.8 kg of gold from the Nuevo Potosí, Reina Victoria, and Agrupada deposits. In 1958, Morón [8] constructed two mine shafts at the Milagro mine and found mineralized horizons with contents of 9.8 g/t Au. From 1963 to 1965, Chalyi et al. [9] carried out gold prospecting and exploration work, gathering all the information obtained in the preceding investigation. It was this research that quite possibly started the most challenging and in-depth of all studies compared to those carried out previously. In 1971, Bizet and García [10] drilled several wells at the Nuevo Potosí mine that intersected gold mineralized horizons with an average grade of 1.45 g/t Au. Between 1974 and 1976, Kazakov and Tabachkov [11] carried out gold prospecting work in the areas of Tranqueras I, II, and III, Monte Rojo, La Ventura, and La Fortuna, where they found gold ores of up to 3 g/t Au. In 1983, an extensive geological survey was carried out on a scale of 1:50,000 in this region by Hungarian and Cuban geologists [12]. The activities consisted of prospecting and exploration of gold, copper, and chromium, among others. In 1988, the Santiago de Cuba Mining Company calculated the reserves in categories $C_1 + C_2$ for the Aguas Claras deposits, estimating some 84,969 tons of gold ores and 424.90 kg of gold metal, with an average grade equivalent to 5.0 g/t Au. Costafreda and Velázquez [13] carried out geological and mining prospecting work at the Holguin deposit, which included geochemical and mining in the Holguinera deposit, as well as geochemical and geophysical campaigns, sampling, mapping, and drilling. In 1989, Csillag et al. [14] performed a metallurgical assay on a volumetric sample of gold ores with a weight equivalent to 111.5 kg and a grade of 4.0 g/t Au, which were extracted from the Reina Victoria and Nuevo Potosí deposits, with the following metallurgical recovery results: separation (70%), flotation (57%), and cyanidation (91%). From 1989 to 1994, Costafreda et al. [15] carried out new exploration works in the Reina Victoria, Holguinera, Nuevo Potosí, and Agrupada deposits, which included the calculation of reserves in categories $C_1 + C_2$ and forecast resources in P_1, P_2, and P_3. In July 1994, Rhodes Victoria S.A. was founded in Holguín, an International Economic Association with the purpose of continuing studies in the Reina Victoria, Holguinera, Nuevo Potosí, Agrupada, Hugo y María, El Oro, Milagro, Santiago, and Monte Rojo deposits, which covered a total area of 120 km^2 [16]. The works that were performed in this stage were geological prospecting with mapping, geophysics, geochemistry, and well drilling. Since then, no new works of relevance have been recorded in the region.

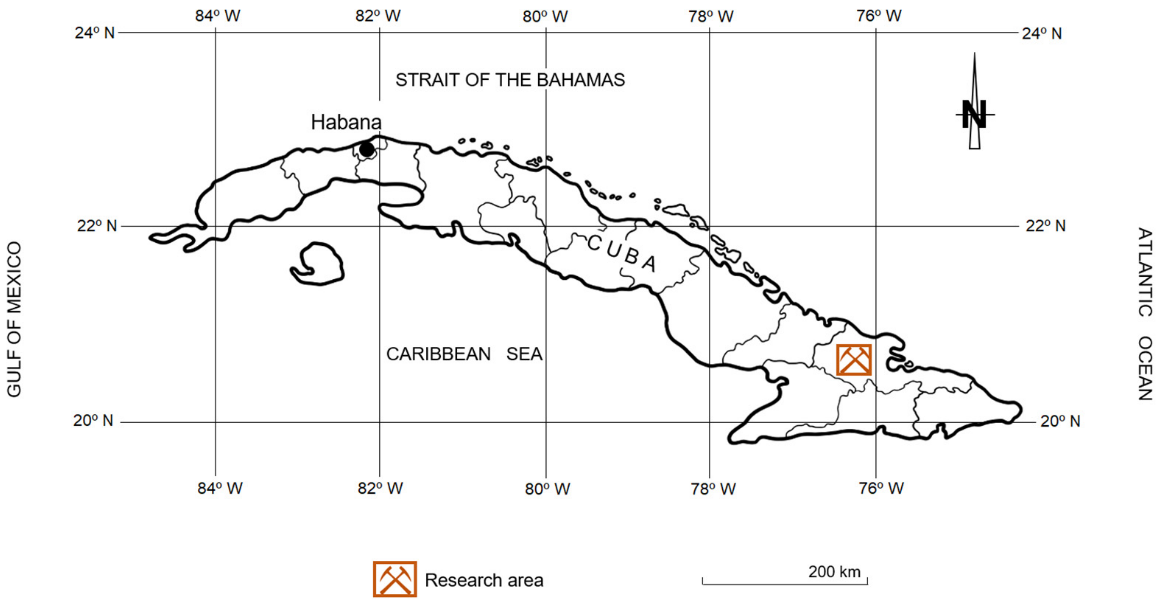


Figure 1. Map of the geographical location of the Aguas Claras mineral field in the province of Holguín (Cuba) [16,17].

The object of this work is to highlight the main results obtained during the most modern stages of geological and mining research in the Aguas Claras mineral field, dating back to the 1960s, in order to gather information on the location of the deposits, characteristics of the minerals, and their relationship with the host rocks, according to the relevance of the information, thickness of mineralized horizons, gold contents, and the role of metasomatic alterations. With all this information, this study could be considered as a practical guide to facilitate the work of potential investors and mining companies in the future, which would have a positive impact on the geological and mining industry of this region.

This work has been structured into several phases. First, there is a description of the regional geological framework; next, there is a geological description on a local scale of the main deposits (Reina Victoria, Holguinera, Nuevo Potosí, and Agrupada); and then there is a description of the geological makeup, the characteristics and potential of the minerals, types of alterations, and calculated reserves and hypotheses about the origin of these deposits. Finally, there is a discussion about the aspects that have not been considered in the previous stages of research, such as the role of metasomatic alterations.

2. Geological Setting

The main geological feature of the region is the alternation of rock units from the ophiolitic complex and the Cretaceous island arc (Figure 2), which form strips facing east–northeast to west–southwest, with layer structures and imbricated mantles. There are also sediments from the Late Cretaceous–Paleogene, which were sourced from the erosion of the arch insular and highly folded ophiolitic formations, which are highly folded [18–20]. These formations have been named Structural Facial Zones (SFZs), and the main ones include Remedios, Placetas, and Auras. The first of these units is made up of a carbonate sequence of several thousand meters and is part of the North American continental margin. On its southern edge, in an allochthonous position and bounded by the Auras SFZ, are the formations of the Superimposed Basins [18–20].

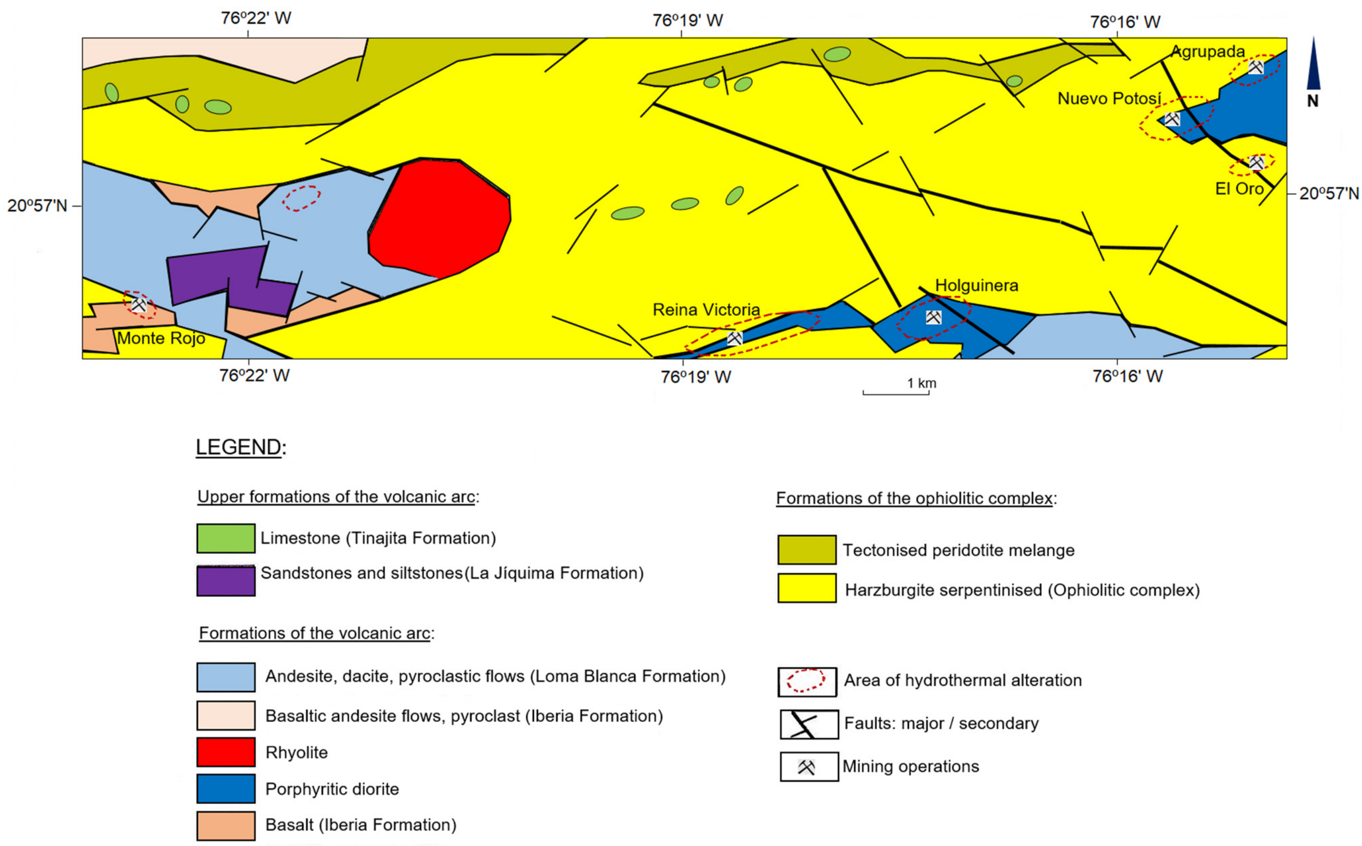


Figure 2. Regional geological map including the research area [3,12,13].

The Structural Facial Subzone Placetas (SFSP) is a place where the materials of the Auras SFZ have been installed due to a thrust fault. These installed materials are part of the North American continental edge and are inserted within the so-called La Palma Formation in the Paleozoic to Mesozoic age. They are made up of strongly tectonized orthogneiss of granitic and granodioritic origin, aleurolites, and weakly carbonated pelites of euxinic facies, black schists, clayey–calcareous schists, and gray limestone, partly silicified [21–24].

The Auras SFZ is made up of lithologies from the ophiolitic complex, the formations of the volcanic arc, and the covert formed during the Upper Cretaceous and Middle Eocene (Figure 2). These formations completely cover the continental slope and the southern part of the Bahamas Shelf [18,25,26].

After the Cuban Phase, the Remedios and Auras Structural Facial Zones were covered by terrigenous–carbonate deposits of the neoplataformic phase through a process that began in the Upper Middle Eocene until the present day [18].

2.1. Rocks of the Ophiolitic Complex

The rocks of the ophiolitic complex account for 30% to 60% of the formations of the outcrops in the area [18,20] (Figure 2), despite being an incomplete series, where the middle and upper levels are absent [27,28]. Andó [29] performed a geological and structural palinspastic reconstruction of the ophiolitic association of this region as a complete system, in which he highlights five main complexes: (1) complex of the level of rhythmic construction, (2) complex of tectonic peridotites, (3) cumulative complex, (4) complex of parallel and subvolcanic bodies, and (5) effusive or basalt complex.

The first two complexes, belonging to the tectonic level, include tectonic and transitional peridotites. Tectonic peridotites consist of harzburgites, chromitites, lherzolites, and dunites, whereas the transitional ones are made up of harzburgites and dunites.

The cumulative complex encompasses ultramaphytes, the products originating in the transition from these, and gabbros, tonalites, and trondjemites. Within this complex, there are two well-defined series: the banded and the isotropic. The banded series represents lithological species, such as dunites, lherzolites–wehrlites, and pyroxenites (ultramafic series). They also contain normal and amphibolic gabbro olivine, hornblendites, troctolites, websterites, clinopyroxenites, and chromitites. On the other hand, the isotropic series includes lithological species, such as tonalites, trondjemites, diorites, gabbro, and amphibolic and amphibolized micro-gabbro.

The lithologies that form the parallel dikes and subvolcanic bodies consist mostly of dolerites, micro-gabbro, and spilites.

The basalts of the effusive complex are made up of several related lithologies, such as basalt–dolerites and spilites, as well as aphiric and thoholeitic varieties.

The sedimentary level is rich in siliceous and carbonate series, where sequences of jaspers, radiolarites, aleurolites, and limestones have been formed.

2.2. Rocks of the Volcanic Island Arc

The rocks of the volcanic island arc in the region are part of two large units: the Iberia Formation and the Loma Blanca Formation [22]. The Iberia Formation (Ib. $K_1{}^{a}$–$K_2{}^{cp}$) is made up of lavas, basaltic and andesite–basaltic lava breccias, tuffs and tuffites of the same chemical composition, volcanomictic sediments, silicites, and limestones. The main lavas are basaltic, andesite–basaltic, and andesitic. Basalts lie in the lower part of volcanic complexes, while basaltic andesites outcrop in the upper parts. Several varieties of basalt are common, among which there are aphiric, porphyry, pyroxenic, olivine, and those that are usually rich in feldspars.

The Loma Blanca Formation (Lb. $K_1{}^{a}$–$K_2{}^{cp}$) is made up of tuffs, zeolitic tuffs, tuffites, marls, lenticular limestones, tuffitic aleurolites, and carbonate volcanomictic sandstones. This stratovolcanic sequence is cut by magmatites, mainly diorites, andesites, dacites, and calc-alkaline and potassium rhyolites, which are relatively enriched with sodium. The final series consists of andesites, pearlized basalts, dacites, and rhyolites.

2.3. Rocks from the Folded Formations of the Cretaceous Cover

These rocks of the Cretaceous cover consist of limestones from the Tinajita Formation, conglomerates, sandstones, and aleurolites from the La Jíquima and Sao Redondo formations [20]. The conglomerates are of fluvio-marine facies, while the sandstones and aleurolites are either neritic facies or from more distal environments. The La Jíquima Formation (Lj. $K_2^{cp\text{-}m}$) is made up of fine- to medium-grained superficially oxidized stratified sandstones that are brownish-gray and yellowish-brown in color. The thickness of the strata varies from a few centimeters to two meters, generally showing gradational stratification, which is interlayered with stratified aleurolites and argillites, which are often carbonated and have decimetric thickness. The thickness of this formation can be up to three hundred meters [20], with abundant foraminifera and nannoplankton.

The Sao Redondo Formation (Sr. $K_2^{cp\text{-}m}$) is a volcanomictic and carbonate sedimentary series, highly dismantled by tectonics and weathering. The lithology consists of greenish-brown volcanomictic sandstones of indeterminate thickness and is heavily eroded. It has intercalations of redeposited and argillitized tuffites of basic to medium composition, which are sometimes carbonate and have planar pelagic limestones contaminated by fine volcanomictic sediments. The thickness of these limestones is just a few meters [22].

3. Materials and Methods

3.1. Materials

To carry out this research, 45 documents were compiled, cataloged, and studied in detail. They consisted of reports, maps, and articles available in the archives of the Ministry of Basic Industry (Havana, Cuba), the National Office of Mineral Resources (Habana, Cuba), the Eastern Geomining company (Santiago de Cuba, Cuba), the Holguin Geominera (Holguín, Cuba), and the Rhodes Victoria. S.A. company (Holguín, Cuba). The work that was used the most was from the 1960s onwards. In addition, twenty thin sections were reanalyzed for petrographic study and one sample for scanning electron microscopy.

3.2. Methods

All available documents underwent a process of selection, sorting, cataloging, studying, interpretation, and synthesis. The structure used for the presentation and discussion of the results consisted of summarizing the geological, petrological, and mineralogical characteristics, and the state of the reserves and resources, as well as making a hypothesis on the genesis of the gold mineralization of the main deposits, such as Reina Victoria, Holguinera, Nuevo Potosí, and Agrupada. A Leica DM6000M Scope microscope (Universidad Politécnica de Madrid, Spain)was used for the thin section petrographic study and was composed of a DTA-13 monochromator filter system. The microscope integrates the CAMEVA System and the Märzhäuser automated stage. Aphelion software was used for image processing. For the SEM study, a Hitachi S-570 electron microscope (Universidad Politécnica de Madrid, Spain) was used, equipped with a Kevex 1728 analyzer, a BIORAD Polaron DCEPS, and the Polaron SEM Coating System. Winshell and Printerface software were used for image management. The resolution achieved is 200×103.

4. Results

4.1. Reina Victoria Deposit

One of the main gold deposits of the Aguas Claras mineral field is Reina Victoria, which is in the westernmost part (Figure 1), specifically at the following coordinates: 26°56′2.56″ N and 76°18′35.65″ W [17]. The geological nature of the deposit is made up of rocks of the ophiolitic complex, such as serpentinized harzburgite, dunite, and gabbro, which are in close contact with strongly propylitized porphyrite diorite (Figure 3a–c). Diorite forms elongated bodies parallel to each other, extends in an east–northeast and west–southwest direction, and always outcrops on the surface [10,13,16,27–31].

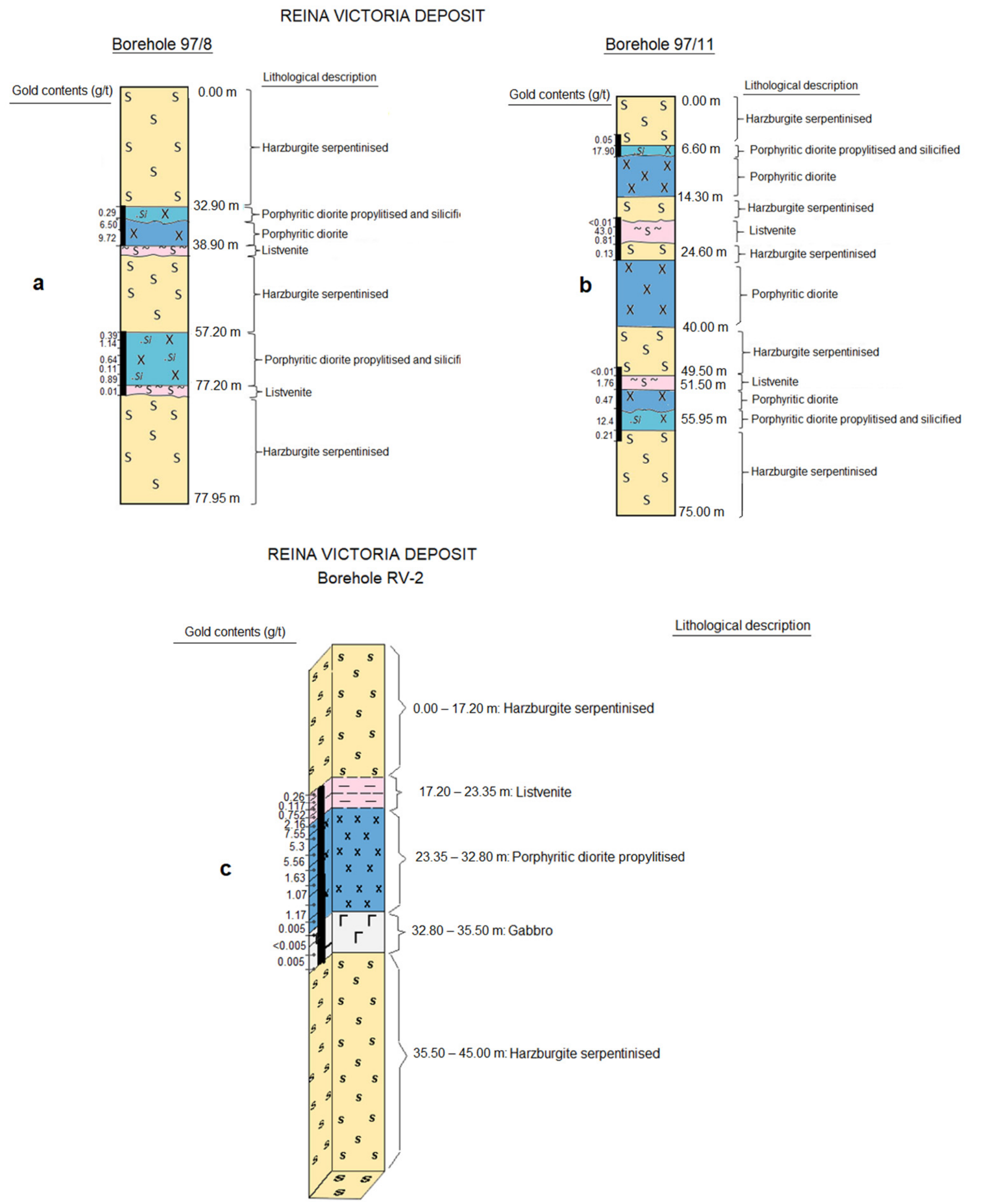
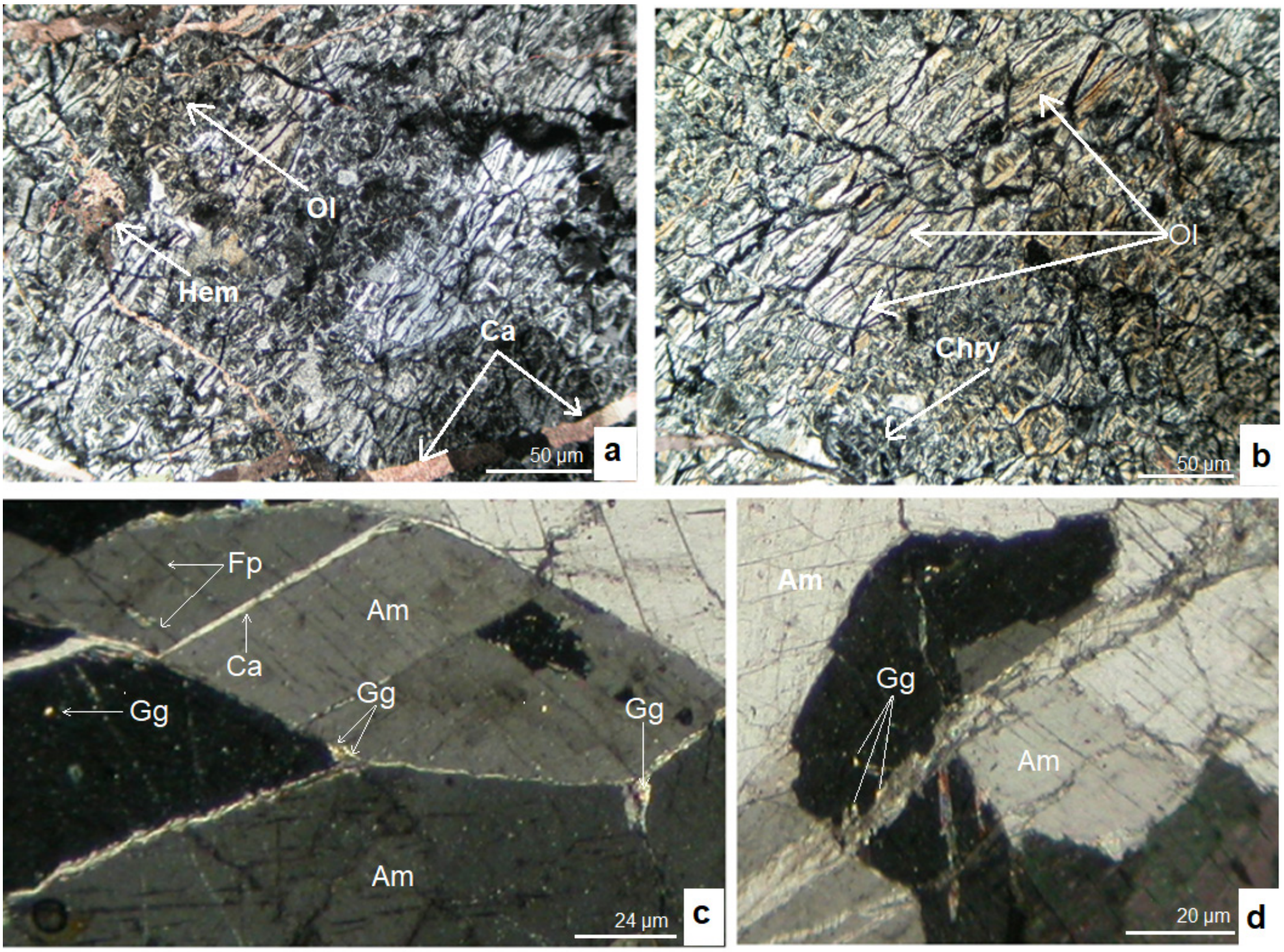


Figure 3. Stratigraphic columns from the central part of the Reina Victoria deposit (**a**,**b**) and the eastern flank (**c**) showing the distribution of gold contents and its relationship to different lithologies [30,32–37].

The mineralization of gold and other accompanying minerals lies in zones of metasomatic alteration caused by the eruption and diffusion of hydrothermal solutions during the processes of obduction, thrust, and emplacement of the ophiolitic complex [27–29]. These fluids simultaneously altered both the ophiolitic lithologies and the arch island rocks in proximal contact. Diffusions through serpentinized harzburgite and dunite results in the listvenitization of peridotites and the digitization of gabbro sequences (Figure 3a–c) [30–32]. When diffusion took place in insular arc rocks, such as porphyritic diorite, they were altered to propylite [30].

There are veins filled with carbonate and serpentine material with listvenita (Figure 4a,b); in addition, both olivine and pyroxene are replaced by tremolite and serpophyte [36]. Fine veins filled with tiny grains of gold are visible, which developed along the contact between the edges of altered amphiboles (Figure 4c,d). Noteworthily, veins can also be seen in the entire visual field (Figure 4c).



Ol: Olivine; Am: amphibole; Gg: Gold grains; Ca: Carbonates in veins; Fp: Foliation plans; Hem: Hematite; Chry: Chrysotile

Figure 4. Microphotographs of thin sections (**a**,**b**) taken with crossed Nicols (Nx-crossed Nicols) from a sample of serpentinized harzburgite that lies at about 15.60 m deep on the eastern flank of the Reina Victoria deposit. The (**c**,**d**) (N//-parallel Nicols) are microphotographs of a doubly polished diorite sample taken at 30.90 m and strongly propylitized [36,37].

Gold shows different textures, such as spherical, laminar, hooked, and filamentous, and is found with other mineral phases, such as pyrite and sphalerite (Figure 5).

Costafreda et al. [30] classified the bodies and mineralized zones of the Reina Victoria deposit into four main groups, in accordance with their morphology and structure, taking into account their shapes and dimensions, the relationship of the mineralization to its host rocks, and petrological and tectonic characteristics. The groups are as follows:

- Veins, veinlets, streaks, and disseminations;
- Large diameter ore bodies;
- Lenticular mineral zones;
- Mineral zones in friable materials of a clayey, mylonitic, and cataclastic nature.

In all cases, gold ores are always closely linked to the zones of metasomatic alteration and are made of pyrite, native copper, malachite, iron oxides and hydroxides, covellite, arsenopyrite, pyrrhotite, sphalerite, chalcopyrite, galena, chromite, magnetite, titanates, quartz, carbonates, and native gold. Mineralized zones can extend over an area from 10 to more than 20 m [30].

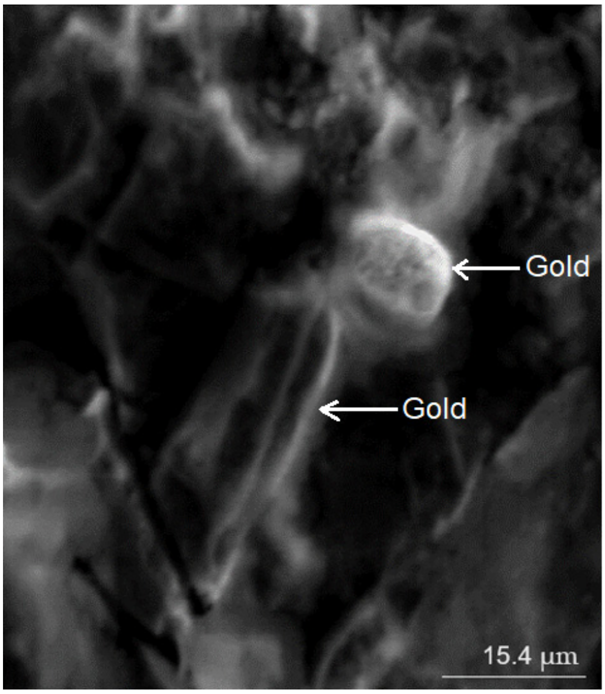


Figure 5. Microphotograph obtained by scanning electron microscopy showing the presence of native gold grains and sheets embedded in a diorite sample extracted at 25 m depth (Borehole RV-2) on the eastern flank of the Reina Victoria deposit [32,36].

The gold morphology is dendritic, hooked, elongated, cylindrical, and sometimes has clear needle-like finishes on the crystals. Occasionally, at the extremes, there is a change in coloration, which indicates a variation in its composition. It is often spherical shaped and has small plates. The color of gold changes based on the shape and composition of the crystals. For example, the gold with a dendritic and/or hooked structure is coppery yellow because of the presence of significant iron and copper. In contrast, gold with a spherical or plate structure shows a light-yellow color due to the higher content of silver (electrum). Native gold can be found in the form of independent aggregates within carbonate mass; it can also be found in intergrowth with chalcopyrite or forming irregular aggregates with galena. The size of the grains varies between 2–10 µm and 30–150 µm [38].

The latest calculation of reserves made at this deposit was 2,200,739 tons of ore and 3657 kg of gold metal, with an average content of 1.66 g/t Au [3].

4.2. Holguinera Deposit

This deposit is located 4 km east of the Reina Victoria deposit at the following geographical coordinates: 20°56′18.81″ N and 76°16′59.18″ W (Figure 1). Holguinera is one of the oldest deposits in this region. The surface of the reservoir is covered by complex geochemical anomalies of Au-Cu-Zn, and contrasting anomalies of Au-Ba, with high values of induced polarization and radiometry [13,30].

The Holguinera deposit is made up of the surface of a thick soil that developed from the decomposition of the residual material from the weathering of porphyry diorite (Figure 6). The rock is strongly propylitized, silicified, and limonited, and exhibits abundant sulfide mineralization accompanied by gold. In general, its contact with serpentinized harzburgite is usually very breccious and mineralized.

Harzburgite is highly serpentinized and listvenitized and exhibits marked mineralization of sulfide, gold, quartz, carbonate, and talc.

The gabbro forms thin bodies and usually shows a moderate alteration to rodingite.

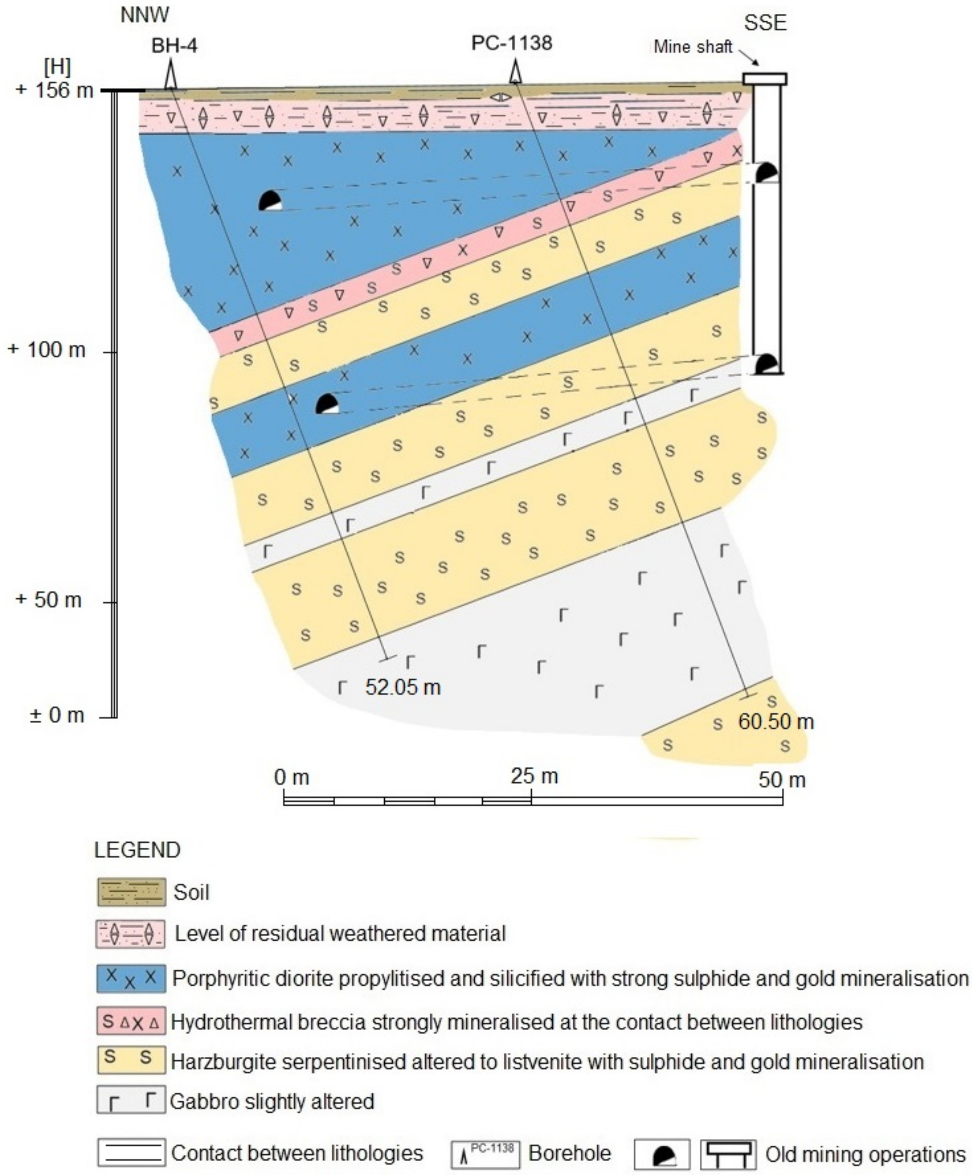
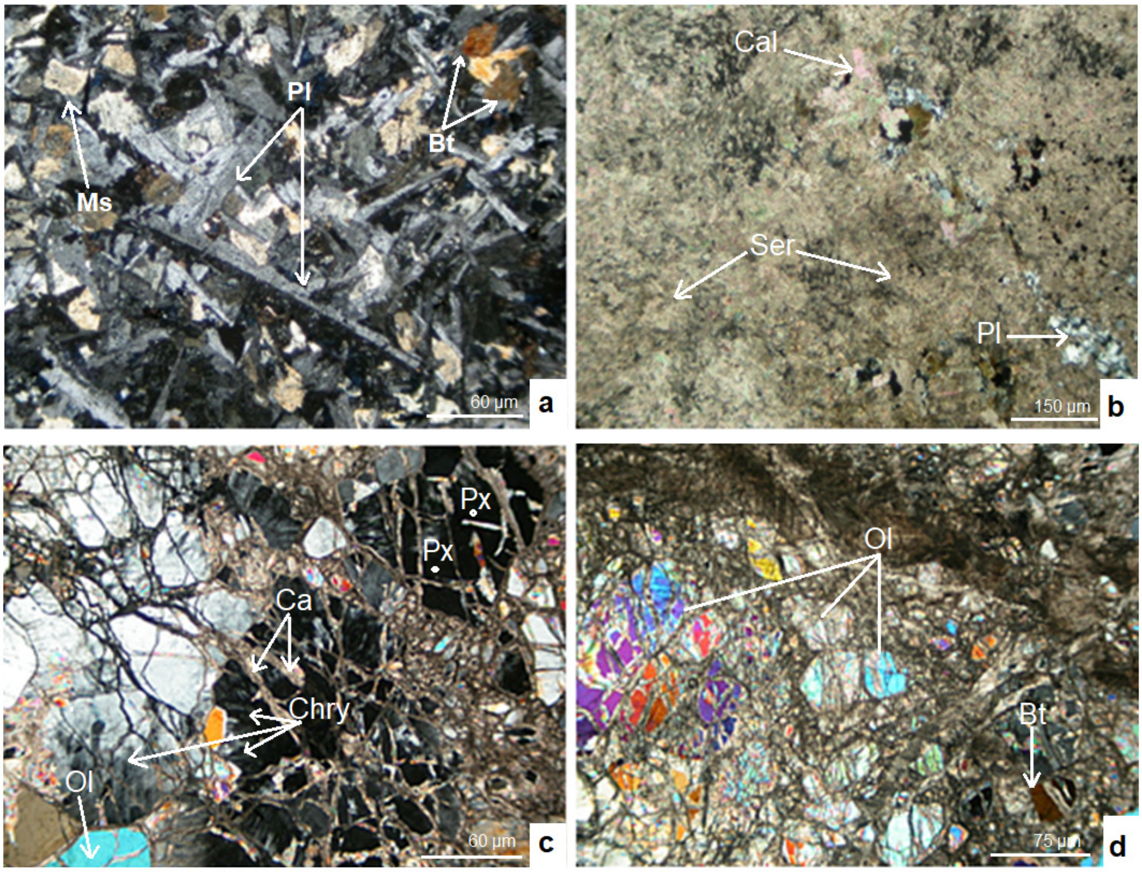


Figure 6. Lithological column of the central part of the Holguinera deposit [30,32].

Macroscopically, diorite is gray in color, with visible greenish and bluish hues, which are indications of a deeply penetrating metasomatic hydrothermal alteration, and sericite, quartz, epidote, and chlorite are present. The textures are porphyry and felted (Figure 7a); although, in some cases, these could be completely erased by the sericitization process (Figure 7b).

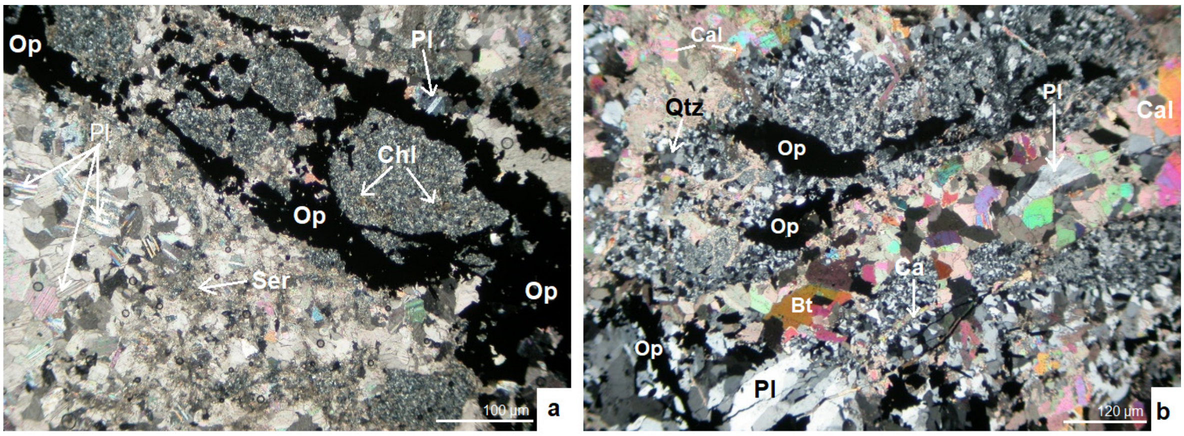
Serpentinized harzburgite exhibits micaceous and crystalline textures and consists mainly of olivine, talc, serpentine, asbestos, carbonate, dolomite, and small amounts of quartz and opaque minerals (Figure 7c,d). The alteration of the harzburgite is also hydrothermal, has a low to medium temperature, and forms listvenite as a product of contact metamorphism [13,30,39].

The ores of the Holguinera deposit are mainly sulfide, sulfide–polymetallic, sulfide with iron, pyrite, and chromitic, located in veins or a dispersed form (Figure 8a,b). Costafreda et al. [30] and Reyes et al. [40] suggest the existence of three different types of mineral paragenesis for this deposit: sulfurous, sulfurous–polymetallic, made of the pyrite–chalcopyrite–sphalerite–arsenopyrite–galena–pyrrhotine association, and the chromite–ilmenite–magnetite association. The latter may indicate a stage of magmatic formation in the levels and sublevels of cumulative complexes and tectonic–transitional peridotites [27], to which gold mineralization is not genetically linked; however, gold is preferentially associated with polymetallic sulfurous paragenesis.



Ol: Olivine; Px: Pyroxene; Pl: Plagioclase; Bt: Biotite; Ms: Muscovite; Cal: Calcite; Chry: Chrysotile
Ca: Carbonate veins; Ser: sericite

Figure 7. Petrographic thin-section microphotographs taken with crossed Nicols (Nx-crossed Nicols. Obj. 0.5×) show a felted texture in a sample of porphyry diorite (**a**) where plagioclase microliths stand out on a matrix visibly affected by incipient sericitization. In (**b**), diorite is observed to be altered by the metasomatic processes of contact where the protominerals have been almost completely erased. Microphotographs of a serpentinized harzburgite (**c**,**d**) altered by hydrothermal processes, close to the diorite contact, are shown [35,36].



Pl: Plagioclase; Ser: Sericite; Chl: Chlorite; Ca: Carbonates veins; Qtz: Quartz;
Op: Opaques filling veins (mainly sulphide mineralisation)

Figure 8. Microphotographs (**a**,**b**) of a specimen taken with Nx-crossed Nicols of porphyritic microdiorite lying at depths of 12.40–24.50 m [32].

Gold mineralization consists of native gold and electrum with associated acanthite. It forms grains between 10 and 30 µm in size and is preferably located in hypogenic primary pyrite crystals or intergrown with arsenopyrite. The most similar mineralogical association to locate gold in this deposit is arsenopyrite–chalcopyrite–galena–sphalerite–cuprite–bornite–native gold [30].

Note in Figure 8a,b the arrangement of the metallic mineralization, in black, within the rock, and how the traces of reaction, corrosion, and assimilation of the original petrogenic minerals are preserved. Veins filled with sulfides, mainly pyrite, arsenopyrite, and pyrrhotine, with the presence of gold, are also visible. These veins also contain a large amount of calcite [34,35].

Gold mineralization achieves grades ranging from 0.13 to 19.9 g/t Au (Figure 9).

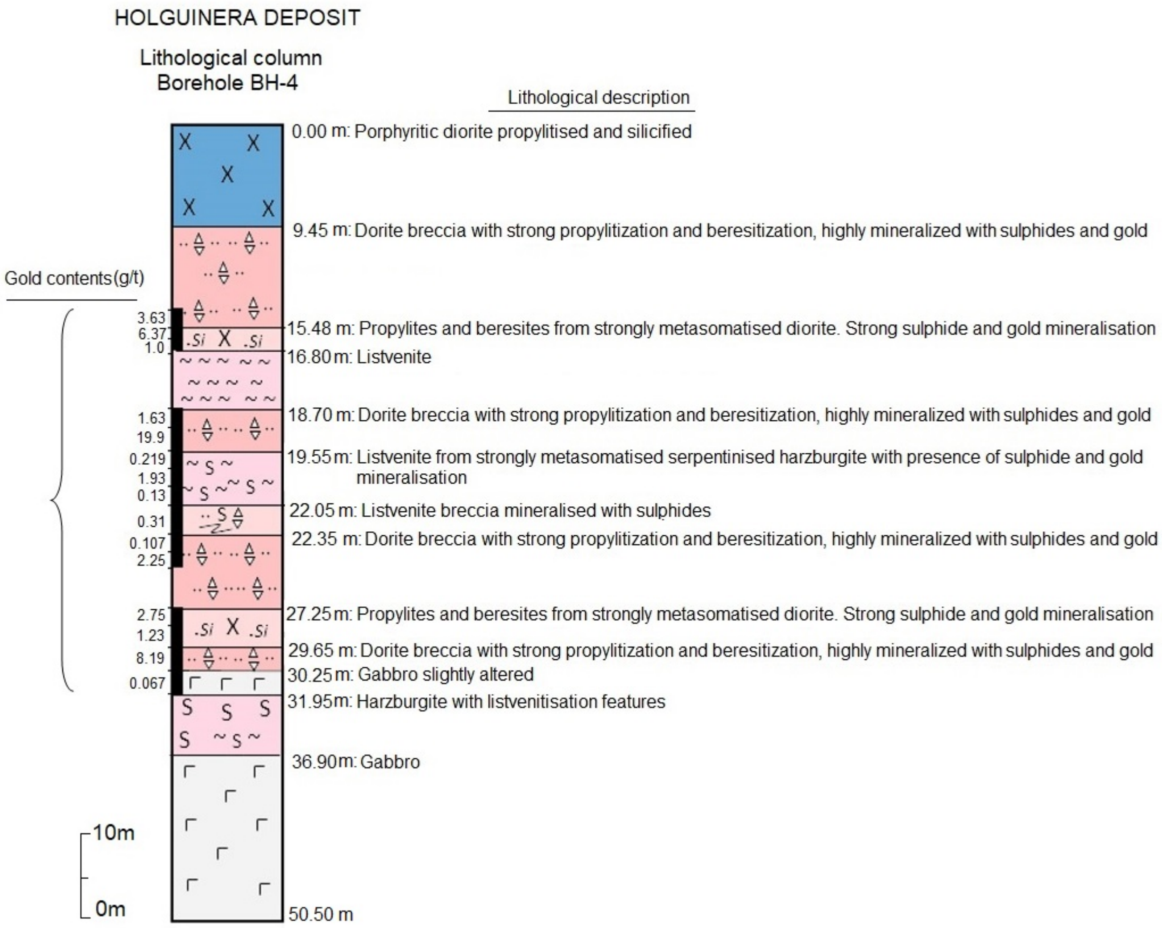


Figure 9. Lithological column from the Holguinera deposit showing the mineralized horizons and the content of gold [30,32,35].

Földessy [3] estimated the gold ore resources in the Holguinera deposit to be around 1,062,000 tons and about 1494 kg of gold metal, with a content of 1.0–4 g/t Au.

4.3. Nuevo Potosí Deposit

The Nuevo Potosí deposit is located about 7.33 km east–northeast of the Reina Victoria deposit and about 5 km north–northeast of the Holguinera deposit at coordinates 20°57′29′′ N and 76°15′59′′ W.

The geological makeup of the Nuevo Potosí deposit is like that described in the Reina Victoria and Holguinera deposits and basically consists of porphyry diorite, serpentinized harzburgite, and gabbro, to which the mineralization of hydrothermal genesis is spatially linked (Figure 10).

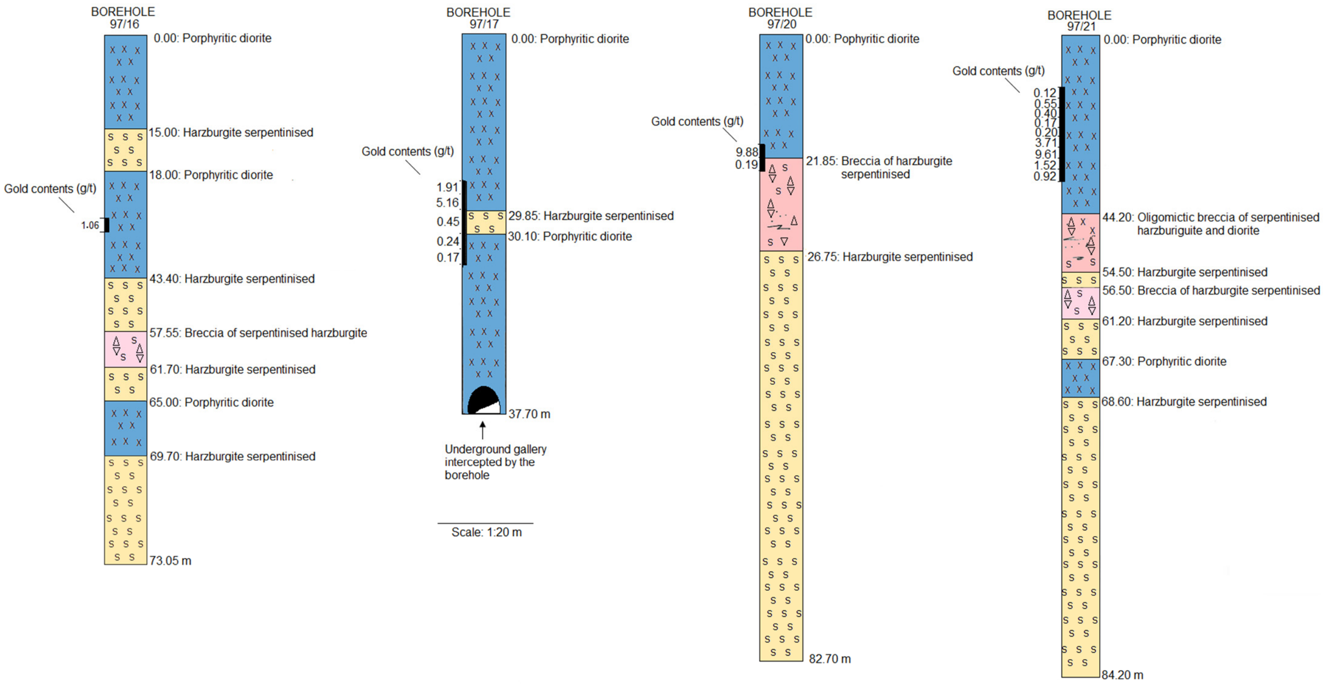


Figure 10. Stratigraphic column from the Nuevo Potosí deposit [30,32,41].

Diorite has a gray color, ranging from light to dark, with green, light brown, pink, and bluish tones. In general, it has a uniform, massive, very consistent, hard, and compact structure, sometimes with a certain porous and tonsillar appearance, perhaps by hydrothermal leaching, but it usually alternates with friable, fragmented, and brecciated parts. The texture (Figure 11a,b) is holocrystalline with the predominance of plagioclase, amphibole, and pyroxene phenocrysts.

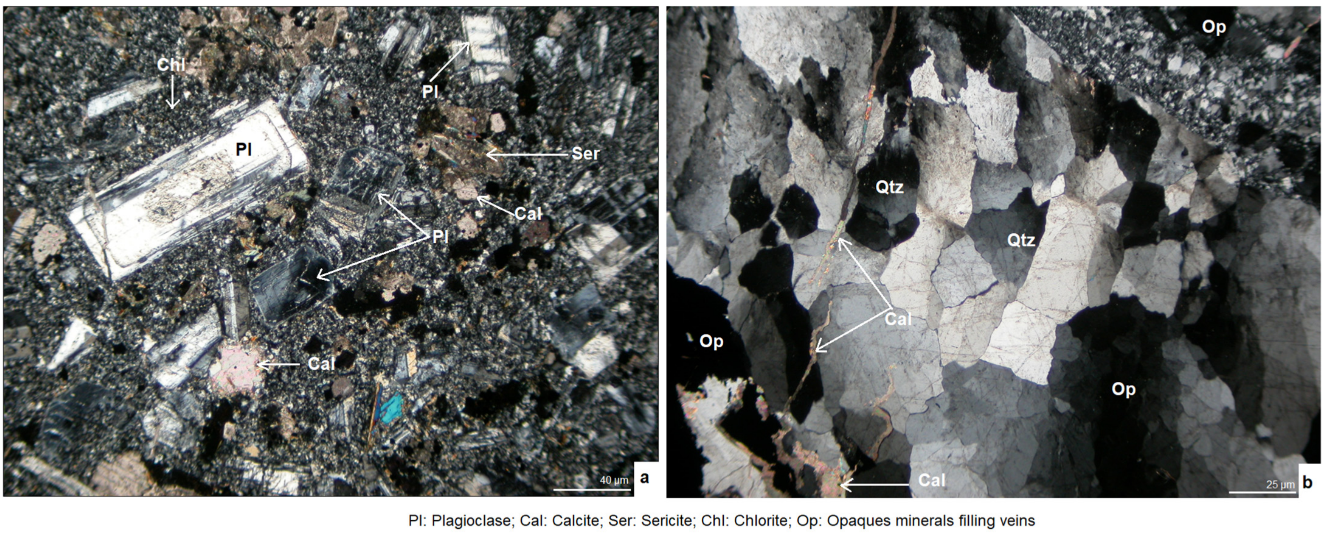


Figure 11. Thin-section microphotography (**a**,**b**) with crossed Nicols from a porphyry diorite sample taken at the Nuevo Potosí deposit at a depth of 21.50 m. The textures are mainly porphyritic, granular hypidiomorphic, and holocrystalline [32].

The features to be highlighted are the strong predominant sericitization, the generalized alteration of both amphibole and pyroxene, and the low presence of quartz, which may be masked by sericite. Large phenocrysts of plagioclase show signs of reaction with the paste. Opaque minerals are dominated by pyrite (Figure 11a). In Figure 11b, there is a clear predominance of xenomorphic quartz and saccharoidal in a section of a vein in which metallic mineralization is also located (lower left). The presence of calcite veins that bisect the quartz indicates that it corresponds to a later mineralizing pulse [35].

The serpentinized harzburgite has colors ranging from dark green to black, with reddish, brown, bluish, and yellowish hues, with a strong banded appearance (Figure 12a,b). Its structure is massive, uniform, virtually compact, hard, and coherent, although it frequently becomes a breccious, cataclastic, mylonitic, and clayey structure. The texture is coarsely granular, phaneritic, and panidiomorphic granular, where the olivine crystals appear very tight and completely altered to serpentine and magnesite. The texture can also be poikilitic when olivine phenocrysts contain chromite and pyrite spinel inclusions. Pyroxene crystals appear strongly altered to chrysotile asbestos.

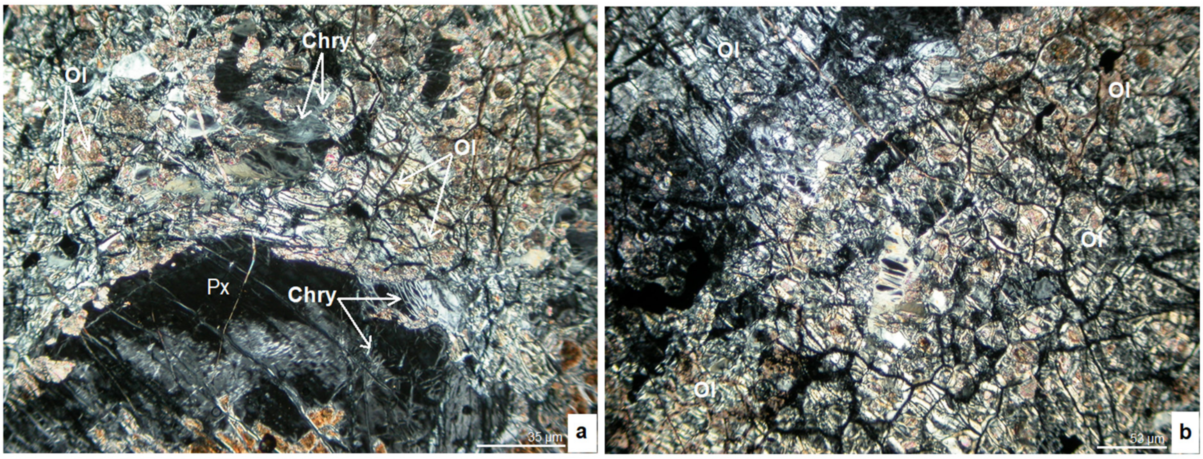


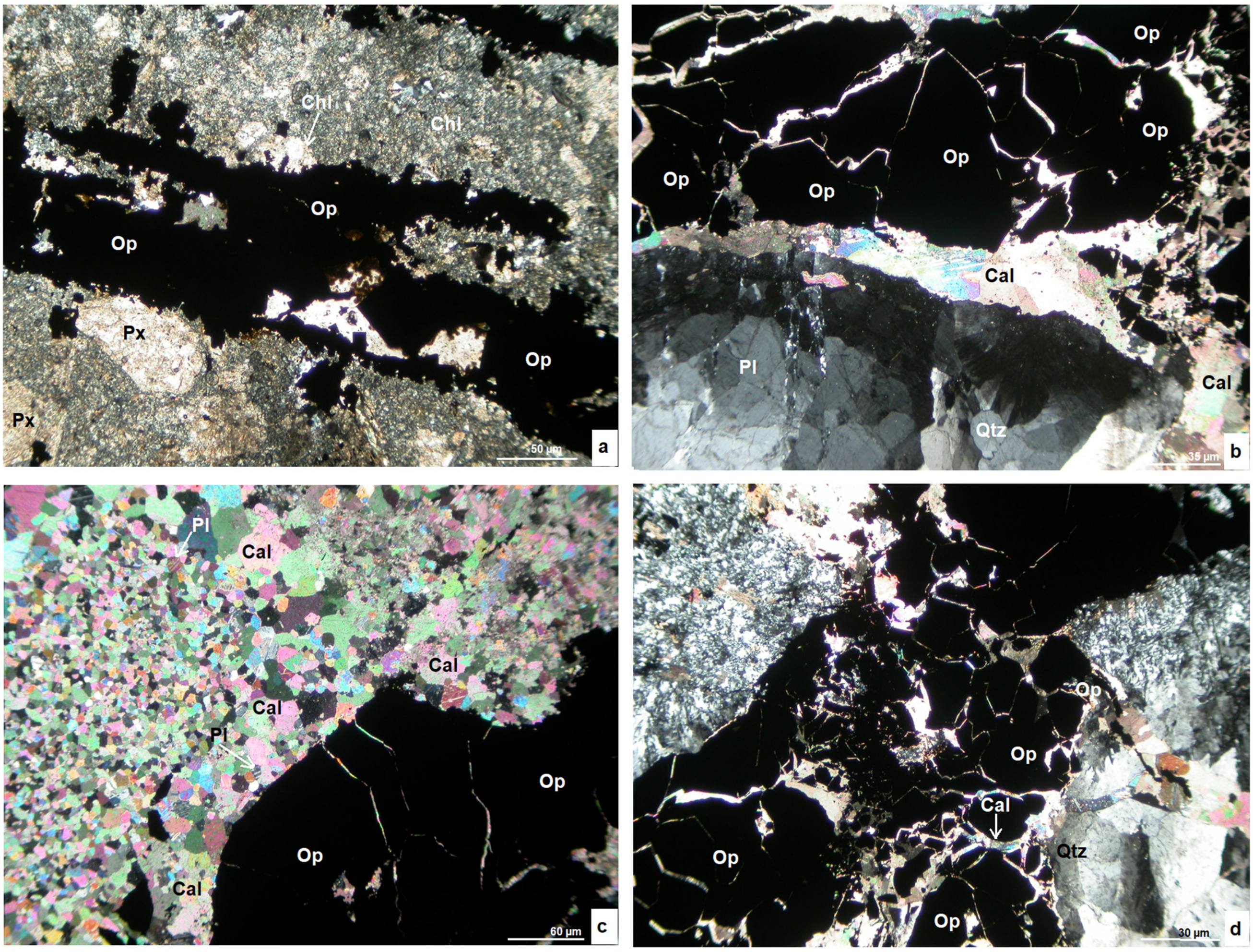
Figure 12. Thin-section microphotographs (**a**,**b**) with crossed Nicols (Nx-crossed Nicols. Obj. 0.5×) from an altered harzburgite sample taken at a depth of 15.60 m on the southern flank of the Nuevo Potosí deposit. Note the degree of serpentinization that olivine crystals have attained and the presence of chrysotile asbestos formed by alteration of pyroxenes. There is reddish-brown hematite and hydrohematite confined to veins. Incipient asbestization can be observed at some points in the visual field [35].

In the Nuevo Potosí deposit, metallic mineralization is composed of pyrite, marcasite, chalcopyrite, sphalerite, arsenopyrite, leucoxene, pyrrhotine, magnetite, chromiferous spinels, and native gold, distributed in the form of disseminations of small grains throughout the rock, as well as inside the veins, where they form elongated, idiomorphic, hypoidiomorphic, and xenomorphic microcrystalline aggregates, yellow in color with marked metallic luster, emplaced as subparallel along the veins [34,38,42–47].

There are black mineralized bands with a subparallel arrangement, as well as a strong propylitic alteration that affects the entire matrix, in which amphibole phenocrysts altered to carbonates persist (Figure 13a). The metallic mineralization is confined to large vein systems in which calcite is almost always accompanied (Figure 13b–d). The emplacement of mineralization, including calcite gangue, was produced by the action of hydrothermal solutions that ran through paleodiaclase developed in the host rock [35,36].

Gold appears occluded in arsenopyrite crystals in the form of particles with diameters between 0.002 mm and 0.08 mm, or as tiny irregular segregations. It is possible that the alteration of arsenopyrite contributed to the release of these fine gold particles [38]. The original arsenopyrite was probably gold, present in the form of a solid solution that formed part of the structure of its crystal lattice. It is also often associated with calcite and quartz in the veins [33,34].

Földessy's reserve estimates indicate a volume equal to 128,529 tons of gold ore and 552.7 kg of gold metal, with a content of 5.67 g/t Au and a mineralized horizon thickness of 1.5 m [3].



Px: Pyroxene; Pl: Plagioclase; Cal: Calcite; Qtz: Quartz; Chl: Chlorite; Op: Opaques

Figure 13. Microphotographs of double-polished sections (**a**–**d**) showing a strongly mineralized porphyrite diorite taken at a depth of 27.40 m [32].

4.4. Agrupada Deposit

The Agrupada deposit lies in the easternmost part of the Aguas Claras mineral field. It is located 2 km north–northeast of the Nuevo Potosí deposit and has the following coordinates: 20°57′49″ N and 76°14′59″ W.

This deposit has been one of the main mining enclaves in which enormous exploration and exploitation works have been carried out since the time of Spanish colonization. However, the most outstanding works took place in the 1960s [3,9,30,34,41,43].

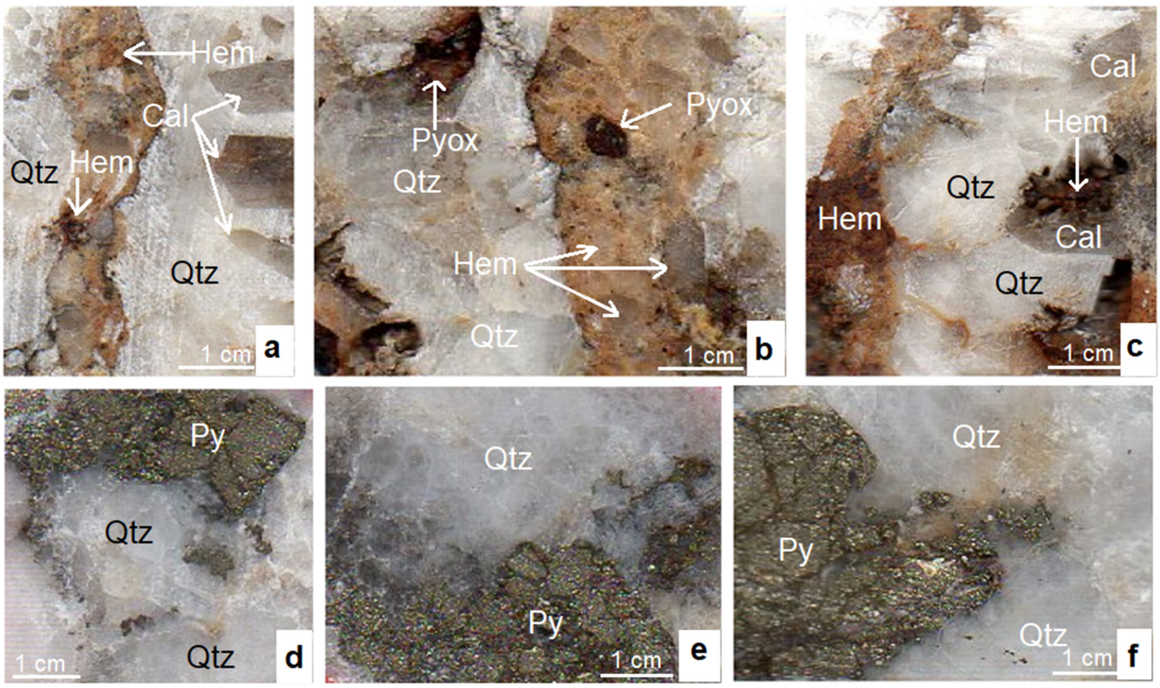
The lithological composition of the deposit is very similar to that of Reina Victoria, Holguinera, and Nuevo Potosí, where there are rocks of ultrabasic, basic, and intermediate composition, represented by serpentinized harzburgite, gabbro, dolerite, and porphyry diorite. The harzburgite is commonly altered to listvenite and is markedly cataclastized, mylonitized, and foliated due to the tectonic processes that caused the emplacement of the ophiolitic complex. Porphyritic diorite is highly propylitized (Figure 14) and forms dikes that dip southward at varying angles between 60° and 90°. They extend in an east–northeast direction for about 300 m, and their thickness reaches 30 m.

Gabbro, gabrodiorite, and dolerite are remnants of the cumulative level and parallel dikes of the ophiolitic complex of the Holguín region, as confirmed by Andó [27] and Andó et al. [28].

Previous studies classify the Agrupada deposit as hydrothermal, which consists of four main veins known as "Abalo I", "Abalo II", "Veta del Pozo de Mina 1", and "Veta-

Emilito" [9,30,44,45]. These veins have gold contents up to 2 g/t and are filled with pyrite, chalcopyrite, galena, sphalerite, chromite, quartz, calcite, chlorite, epidote, and leucoxene [9]. The veins have comb, crustiform, ridge, and breccia textures, in which other minerals of secondary alteration are found, such as hematite, limonite, chlorite, and epidote (Figure 15a–c). Sulfurous ores play a key role in the veins. They form large compact aggregates and irregular masses made of tiny cubic crystals of pyrite with which gold is frequently associated (Figure 15d–f) [30].

Figure 14. Highly tectonized porphyrite diorite that outcrops in the central part of the Agrupada deposit [32].



Py: Pyrite; Qtz: Quartz; Cal: Calcite; Hem: Hematite; Pyox: Pyrite oxidised

Figure 15. Images (**a**–**f**) obtained from partially polished samples extracted at different points of the "Veta Emilito" at the Agrupada deposit [30].

Gold appears in the form of small grains scattered over sulfides but also as a native element associated with silver, calcite, pyrite, and quartz. Its structure is usually irregular, with no apparent geometric habits or idiomorphism, and it has appearances of patches and intergranular fillings. The diameter of the gold particles can reach 0.3 mm.

Native gold, commonly associated with galena and calcite, can take on scaly and lamellar textures up to 0.3 mm in diameter. Its ore content varies from 30 to 50 g/t Au. According to Chalyi et al. [9], gold formation is syngenetic with calcite and postgenetic to sulfide mineralization and quartz. The average gold content reported at the Agrupada deposit ranges from 6.75 to 8.67 g/t Au; although, specific values of up to 200 g/t Au have been reported.

The estimate of reserves made by Chalyi et al. [9] establishes about 36,308 tons of gold ore and about 191.37 kg of gold metal, with an average content of 5.27 g/t Au.

4.5. Hypothesis on the Origin of Mineralization

The origin of the location of the mineralized bodies in the Aguas Claras mineral field remains controversial and unresolved. Traditionally, it has been accepted that porphyry diorite is the main host rock that is responsible for gold mineralization. From a morphological point of view, these porphyry diorite dikes intrude into the ultramaphytes [9]. It was established that porphyritic diorite has a close genetic and spatial relationship with sulfide and gold mineralization. The emplacement of fluids in the exocontact transmitted this mineralization not only to diorites but also to the ultrabasite and basite rocks of the environment by direct diffusion through interlithological contacts, fault, and diaclase planes. These fluids simultaneously altered the felsites, maphytes, and ultramaphytes due to contact metasomatism [9,12,13].

Pentelényi and Garcés [12], Andó [27,28], Kozák [22,23], and Földessy [3] have a new genetic approach, which is divided into three fundamental criteria that are summarized in the following paragraphs.

The genetic approach based on the ophiolitic environment.

Andó [12,27,28] shows that mineralization is found in rocks of the ophiolitic complex (diorite, gabbro, harzburgites). Diorite is a differential of cumulative gabbro and not a product of island arc magmatism. Mineralization may have originated from a process of autometasomatism triggered during the obduction and subsequent overthrusting of the ophiolites, as well as by local anomalous accumulation of metals at the various levels of this complex. According to Andó [12,27,28], mineralization has an allochthonous character.

The genetic approach based on the Cretaceous island arc environment.

According to Kozák [12,22,23], mineralization was deposited in subvolcanic rocks of the Cretaceous island arc. These rocks consist of porphyritic diorite mineralized by sulfides and gold. They intrude levels of serpentinized harzburgite and gabbro with igneous contacts. Its location is autochthonous.

The genetic approach based on mixed geological environments.

According to Földessy [3,12], mineralization does not belong to the main igneous activity of the Cretaceous island arc since it is present not only in the ophiolitic lithologies but also in the effusive and sediments that form the cover. Its position is para-autochthonous, as its emplacement, interlithological contacts, and original alteration haloes have been preserved, despite the regional thrusting and dismemberment experienced.

5. Discussion

According to the analysis, there seems to be a marked similarity in the four deposits studied from a mineralogical, petrological, and tectonic point of view. The factors controlling the mineralization and alterations are repeated in each of these deposits.

After evaluating the results of the authors who have worked in the area, several aspects can be clarified that show that not all the work carried out prior to the 1960s was genuinely scientific in nature. The only objective was the empirical treatment of ores to carry out mining activities, which focused very much on local exploitation of gold ores. The real intention was purely lucrative with minimal investment. It has been established that the most serious work began in 1960.

First, it should be highlighted that the gold mineralization in the Aguas Claras mineral field is uniquely and strongly linked to some felsites (porphyritic diorite, granodiorite), as demonstrated by Chalyi et al. [9].

Another key problem is the hydrothermal classification of these deposits without considering the overall geological context [43,44]. Attention is paid only to the characteristics of the areas of alterations, as well as the places where they are located and their link with areas of strong geophysical and geochemical anomalies outside the scope of direct contact of intrusive dikes with ultrabasic rocks.

The role of alterations was first studied in depth by Pentelénny and Garcés [12] and Costafreda et al. [13,15,16,32,35,36], who carried out a great deal of research to establish the genetic and spatial relationship of metasomatic processes with an anomalous concentration of mineralization. In this way, several types of alterations were established in the Aguas Claras mineral field, which are briefly mentioned in the following paragraphs.

Serpentinization: Andó [27] describes it as a regional allochemical process that, in addition to including the incorporation of water and the release of other chemical components, facilitates ion exchange, the decomposition of complex minerals, the synthesis of compounds, and numerous oxidation-reduction reactions, depending on the affected rocks. In this process, reaction products such as serpentine, magnetite, chlorite, and brucite were formed. On the other hand, metal ions of copper, zinc, gold, and appreciable amounts of silica and calcium were released and deposited. The gold grades determined in serpentinized ultramaphytes range from 0.2 to 3.0 g/t Au [32].

Rodingitization: Földessy and Costafreda [45] argue that this is a process that occurs when hydrothermal fluids affect cumulative gabbro, forming a metasomatic product known as rondingite, consisting of zoisite, prehnite, diopside, actinolite, and chlorite, often accompanied by free gold. This zone of alteration is smaller and consists of a few centimeters up to 5 m, starting from the conduits through which the hydrothermal fluids circulated. Gold content can be as high as 4 g/t Au.

Listvenitization: Pentelényi and Garcés [12], Costafreda and Velázquez [13], and Costafreda et al. [30] justify it as a process of metasomatic alteration that directly affects the ultrabasic rocks that are in direct contact with diorites, microdiorites, and andesites. The reaction product is a listvenite composed of pyrite, chalcopyrite, native copper, pyrrhotite, arsenopyrite, sphalerite, galena, chromite, malachite, cuprite, bornite, magnetite, and marcasite. In this zone, the gold content ranges from 0.4 to 10 g/t Au.

Propylitization: Costafreda et al. [32] and Földessy and Costafreda [45] agree that this is a process of metasomatic alteration that affects diorites and andesites, with the cenotype being a propylite. As a result of this process, secondary minerals such as chlorite, epidote, quartz, carbonate, and calcite are formed, accompanied by sulfides and gold. This process can extend over areas greater than 30 m, and gold contents can reach values of up to 19.9 g/t Au.

In accordance with what has been discussed, it is established that the importance and economic potential of the deposits of the Aguas Claras mineral field lies not only in the presence of diorite dikes or their intrusion into the ultramaphytes but also the typology and extension of the zones of metasomatic alteration developed in different lithologies. Therefore, these observations must be taken into account in the planning of future work.

In addition to alterations, interlithological contacts are observed to contribute to effectively controlling mineralization. As observed in these deposits, the nature of the contacts can be of several types, such as tectonic contacts, in which breccias, cataclasts, and mylonites appear from the proximal lithologies. These tectonic contacts represent the zone with high permeability, which favors the diffusion of ion-charged solutions; on the other hand, these zones contribute to the abrupt depressurization and cooling of hydrothermal fluids, causing the precipitation of mineral ions in such a way that they can act as true thermodynamic sieves. Secondly, there are direct contacts between lithologies without tectonic disturbance but with a halo of varying dimensions produced by metasomatism; in this enclave, there is a bidirectional diffusion of ions that are exchanged between the affected rocks, causing an instability in the hydrothermal solutions and with it ionic discharge, which is usually in the form of veins and disseminations. Thirdly, the presence of faults of different typologies and diaclases that cut all the lithologies of the Aguas Claras mineral field also contributes to the spatial control of mineralization.

Finally, carbonate and silica are also worth being considered in future explorations because their presence indicates the character of the reactions of the fluids with the host rocks.

6. Conclusions

After the description, analysis, and discussion of the results presented in this work, the following conclusions were established:

1. The Aguas Claras mineral field appears to have significant gold reserves given the reported gold contents, the extent of the areas where the deposits are located, and the long period in which they have been exploited without depletion.
2. Geological and mining work has traditionally focused on mineral zones with anomalous gold enrichment, i.e., veins, veinlets, stockwork horizons, and proximal areas of influence, but never beyond these limits.
3. As observed, zones of metasomatic alteration, such as listvenitization, rodingitization, propylitization, and serpentinization, are very important in the control of mineralization. These zones, of varying sizes, are often large areas within the Aguas Claras mineral field, which greatly increases the importance of this region.
4. On the other hand, knowledge of interlithological contacts, areas with the development of breccias, cataclasites, and mylonites, as well as faults and diaclases, would help to better understand the mechanisms of formation of gold ores in these geological environments.
5. The criteria set out in points 3 and 4 could be of great help in future research as both the zones of alteration and the interlithological contacts could be considered in the calculation of the reserves, thus contributing to a significant increase in geological resources.
6. Finally, this work could be used as a safe practical guide for new research projects carried out in this region, providing a more pragmatic, but essentially scientific, sense.

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