Geology of the Frontino-Morrogacho Gold Mining District and metallogeny of the El Cerro Igneous Complex

Geología del Distrito minero aurífero Frontino-Morrogacho y metalogenia del Complejo Ígneo El Cerro

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Abstract

The Frontino-Morrogacho gold district is located on the western flank of the Western Cordillera, NW of Antioquia Province. Gold mineralizations in the area are spatially and genetically associated with the cooling of three mid- to late-Miocene age intrusive centers in the form of stocks and dikes (12-9 Ma): Cerro Frontino, La Horqueta and Morrogacho (El Cerro Igneous Complex). These composite magmatic pulses, with ultramafic to intermediate compositions, vary into diorite-, gabbro- and monzonitic-bearing phases. Mineralization in the complex is present as several structurally controlled fault veins, shear-related veins, sheeted quartz extension veins and quartz-carbonate tabular extension veins, with the development of swarms and nests of veins-veinlets, breccias and stockworks. Structures range from centimeter-wide individual veinlets to several meter-wide swarms of veins developed within broad mineralized structural corridors, with a metallic signature that consists of Au + Ag + Cu + Zn + Pb + As (± Te ± Bi ± Sb ± Hg ± W) assemblages. Veins are composed of multiple stages of mineralization, and the formation of these structures is enhanced by the presence of a local regime of extension and E-trending structures, including evidence of faults and shear zones with right-lateral displacement, which are likely involved in pluton emplacement and cooling. The ore mineralogy is composed of pyrrhotite, pyrite, chalcopyrite, sphalerite, galena and arsenopyrite assemblages formed in two or more mineralization stages, with complex Bi, Te, Sb and Hg mineral specimens associated with Au and Ag. Mineralized structures of the district present a preferential E-strike with dominant vertical to subvertical and occasional subhorizontal S-dips and secondary N- and NW-strikes that are steep to vertically E-dipping.

The Frontino-Morrogacho Gold district presents characteristics related to the architecture, mineralogy and alteration of reduced (ilmenite-series) intrusion-related gold systems but is genetically associated with a parental oxidized magma source. The gold content is associated with three different families involving electrum, tellurides and alloys: gold rich (66 to 78% Au, 22 to 34% Ag),

average (50 to 60% Au, 40 to 50% Ag) and silver rich (32 to 40% Au, 60 to 68% Ag). The formation of these bodies is associated with an N-S magmatic-metallogenic trend of Au-Ag-Cu deposits, which extend for more than 300 km along the Western Cordillera of Colombia. Similar plutonic suites span from the south of Chocó Province to the north of Antioquia Province, which indicates that the Frontino-Farallones-Botón arc can be proposed as an individual metallogenic belt.

Resumen

El Distrito minero Frontino-Morrogacho se localiza en el flanco occidental de la cordillera Occidental, al NW del departamento de Antioquia. Las mineralizaciones de oro en la zona están espacial y genéticamente asociadas con tres cuerpos intrusivos de edad Mioceno (9-12 Ma) medio a tardío en forma de *stocks* y diques: Cerro Frontino, La Horqueta y Morrogacho (El Complejo Ígneo El Cerro). Corresponden a pulsos magmáticos compuestos con composiciones ultramáficas a intermedias que varían entre dioritas, gabros y fases monzoníticas. Las mineralizaciones en el complejo están presentes como estructuras vetiformes estructuralmente controladas y representadas por vetas de falla, vetas relacionas con zonas de cizalla, vetas laminadas de extensión de cuarzo y vetas de extensión tabulares cuarzo carbonatadas con el desarrollo de nidos de vetas, zonas de brecha y *stockworks*. El espesor de las estructuras varía entre venillas individuales centimétricas a vetas que forman nidos, rejillas y enjambres en corredores estructurales multimétricos, poseen una asignatura metálica compuesta por Au + Ag + Cu + Zn + Pb + As (± Te ± Bi ± Sb ± Hg ± W). Las vetas fueron formadas por diferentes estadios de mineralización. La formación de estas estructuras se encuentra favorecida por la presencia de sistemas locales de extensión y por la presencia de estructuras orientadas hacia el E-, incluyendo la evidencia de zonas de cizalla con desplazamiento lateral-derecho, que están aparentemente relacionadas con el emplazamiento y enfriamiento de los plutones. La mineralogía de la mena en los depósitos está compuesta por pirrotina, pirita, calcopirita, esfalerita, galena y arsenopirita formada en al menos dos estadios de mineralización, con especies minerales de Au, Ag, Bi, Te, Sb y Hg asociados a Au y Ag. Las estructuras mineralizadas del distrito presentan una dirección preferencial de rumbo hacia el E- con buzamientos dominantes hacia el S, sub-verticales y ocasionalmente sub-horizontales, con rumbos secundarios hacia el N- y NW-, buzando verticalmente hacia el E-.

El Distrito minero Frontino-Morrogacho presenta algunas características relacionadas con la arquitectura, mineralogía y alteración de los *Reduced (ilmenite-series) Intrusion-related Gold Systems*, pero están asociados genéticamente con magmas parentales oxidados. El contenido de oro es reconocido en tres distintas familias que involucran *electrum* y teluros: rica en oro (66-78% Au, 22-34% Ag), promedio (50-60% Au, 40-50% Ag) y ricos en plata (32-40% Au, 60-68% Ag). La formación de estos cuerpos está asociada con un cinturón magmático-metalogénico con dirección N-S de depósitos de Au-Ag-Cu, que se extiende por más de 300 km a lo largo de la cordillera Occidental de Colombia. Complejos de intrusivos similares abarcan desde el sur en el departamento del Chocó hasta el norte en el departamento de Antioquia, evidencia que permite asumir que el arco Frontino-Farallones-Botón puede ser propuesto como un cinturón metalogénico individual.

1. Introduction

In Colombia, the Miocene represents a period of widespread continental subduction-related magmatism, which is represented in the Central and Western Cordilleras. The axis of the magmatism has migrated geographically over the last 20 Ma in both N-S and E-W directions (Leal-Mejía, 2011). The movement of this magmatic arc has developed different arc-related metallogenic belts that have been partially identified. However, this period spanning the last 20 Ma to 30 Ma corresponds to the deposition of the largest gold ore reserves in the country and some of the most explored and studied mineral deposit targets (Shaw et al., 2019).

Previous studies of the Western Cordillera in Colombia have identified a mid- to late-Miocene magmatic arc related to the approximation of the Baudó terrane to the northern Andean

block (Zuluaga and Hoyos, 1978; Cediel and Shaw, 2003; Zapata and Rodríguez, 2011; Rodríguez and Zapata, 2012; Rodríguez and Arango, 2013; Rodríguez-García and Bermúdez-Cordero, 2015; Silva-Sánchez, 2018; Arrubla, 2018; Leal-Mejía et al., 2019; Shaw et al., 2019). In this collision, the Frontino-Botón arc was formed with the additional intrusion of different magmatic bodies on the western flank of the Western Cordillera, NW of Antioquia Province (Rodríguez and Zapata, 2012). Most of these plutons present a shoshonitic to calc-alkaline geochemical signature with medium to high K contents related to a volcanic arc geological setting. The El Cerro Igneous Complex is part of this Miocene arc, and it is associated with individual stocks and dikes and their thermal contact aureole, including Cerro Frontino, Morrogacho, and La Horqueta stocks (Shaw et al., 2019).

The Frontino-Botón arc is represented by the El Botón Volcanic Complex and a suite of mid- to late-Miocene mafic to intermediate plutons. The intrusive bodies were emplaced in the Cañasgordas-Penderisco sedimentary block and occasionally in the El Botón Basalts Volcanic Complex. These intrusives occur as circular-semicircular and N-S elongated stocks, usually isolated, with satellite bodies in the form of apophyses and dikes of different sizes, and they span radially from intrusive centers, such as Perdidas stock, Carauta stock, La Horqueta Monzodiorite stock and Cerro Frontino and Morrogacho stocks (Mejía and Salazar, 1989; González and Londoño, 2002; Buchely et al., 2009; Rodríguez and Zapata, 2012). The cooling history of these plutons is associated with various styles of gold-silver mineralization, with an extensive metamorphic thermal aureole in the surrounding sedimentary rocks. An initial stage of mineralization is related to gold-diopside-garnet-scheelite skarn deposits, and a later stage is related to exsolved fluids that circulated in shear and extensional-dilational zones within the intrusions and wall rocks, thus developing high-grade, structurally controlled, vein-type Au-Ag-Cu-Pb-Zn-As-Mo mineralizations (Escobar and Tejada, 1992; Rodríguez-García and Bermúdez-Cordero, 2015; Shaw et al., 2019). However, Au mineralizations related to the El Cerro Igneous Complex have not been studied in detail. In the present study, these mineralizations related to the El Cerro Igneous Complex are considered to compose the Frontino-Morrogacho district.

The Frontino-Morrogacho district has been exploited for more than 200 years by artisanal miners for lode and alluvial gold. The first semitechnical exploitation was carried out in 1852 when the companies Frontino and Bolivia Gold Mines acquired the San Diego Mine from a local society of miners who discovered the main gold lode of the El Cerro deposit in 1812. During recent decades, lode gold deposits in the region have been intermittently mined in hundreds of underground workings focused in the northern part of the El Cerro Frontino stock, the San Diego-Cuadrazón-Las Hebras mine and the Popales-Morrogacho area.

The term intrusion-related gold system (IRGS) broadly refers to a group of gold deposits that have intimate spatial and temporal relationships with the cooling history of plutonic intrusive centers with volatile-rich magmas (Lang and Baker, 2001; Hart, 2007). These deposits exhibit certain styles of mineralization, such as skarns, replacement mantos, veins and disseminations that are focused in the apex and brittle carapace of small and isolated cylindrically shaped plutons, which are mainly characterized by the presence of arrays of auriferous sheeted quartz veins (Hart, 2007). The tectonic setting of the IRGS involves convergent continental margins with back arc, collisional, postcollisional and magmatic arcs in orogenic belts, which are usually emplaced in sedimentary and metasedimentary country rocks (Goldfarb et al., 2000). The metallic signature involves Au-Te-Bi-Sb-W content in the mineralogy (Hart, 2007), whereas the metallogeny of source plutons is controlled by the associated magma's oxidation state and the degree of fractionation (Ishihara, 1981), which is why the term reduced intrusion-related gold system (RIRGS) was recently established (Hart, 2007).

The present study aims to characterize and classify the gold ore mineral occurrences related to the main intrusive centers of the El Cerro Igneous Complex: Cerro Frontino, Morrogacho and La Horqueta stocks. In particular, information about the distribution, ore mineralogy, structural geology, lithological patterns and gold mineral chemistry of the associated deposits is provided. This paper presents the metallogenic characterization of the complex based on petrological and fieldwork data carried out in intrusive bodies and descriptions of the mineralogical, structural and hydrothermal features of gold mineralizations. It complements the regional and ore deposit geology information on the mid- to late-Miocene magmatic arc segment in the Colombian Western Cordillera, particularly the metallogeny of gold mineralizations hosted and associated with mid- to late-Miocene intrusive bodies.

2. Method

The geological features of the El Cerro Igneous Complex were obtained based on a core fieldwork campaign that consisted

of mapping and sampling through the intrusives and mineralized structures of the study area. Moreover, the present research provides data for the regional characterization of the El Cerro-Farallones Au (Ag, Cu), including the Carauta, Cerro Frontino, Morrogacho, La Horqueta, San Juan stocks and the peripheral parts of the Páramo de Frontino stock. The mineralized structures and mines that have been studied and sampled include Los Chavos, Los Hoyos, El Apique, La Loaiza, Musinga and La Palma N and NW of the El Cerro Frontino stock. Additionally, other mineralized structures were studied and sampled, including Quebrada La Mina and La Trinidad structures in the Carauta stock; El Socorro and Las Camelias in La Horqueta stock; El Mocho, San Donato, El Silencio, La Cascada and Tajo Abierto in the Morrogacho stock; and Media Cuesta, El Duque, La Petaca, and Pizarro, north of Morrogacho stock. However, the results presented here focus on the most relevant mineralized structures and mineralization styles of the El Cerro Igneous Complex: El Apique and Los Hoyos in the El Cerro Frontino stock, Tajo Abierto and La Cascada in Morrogacho stock, and Las Camelias in La Horqueta stock. The main mineralized structures were studied in terms of the structural attitude, alteration, mineralization and distribution to define the magmatic-hydrothermal and genetic processes related to the gold genesis of the Frontino-Morrogacho gold district.

The second stage of the study corresponds to the petrography of the intrusive bodies and mineralization, including the different pulses differentiated in each case. Samples of intrusive bodies were classified according to the nomenclature of plutonic rocks from the IUGS Subcommission (International Union Geological Sciences) on the Systematics of Igneous Rocks (Streckeisen, 1974). Furthermore, the ore and gangue mineralogy, textures, and hydrothermal features were described for each mineralized structure according to the petrographic analysis. This information was complemented with mineral chemistry analyses on selected ore samples by SEM-EDS at the Microscopy Center of Universidad de los Andes. These analyses were carried out to determine and identify the metallic signature of the deposits and the native gold and electrum grain characteristics, including the fineness, size, and mineral association.

Finally, the results are discussed and complemented with geochemical analyses taken from previous studies carried out in the El Cerro Igneous Complex (Rodríguez and Zapata, 2012; Rodríguez-García and Bermúdez-Cordero, 2015). The geochemical data reinterpreted in the present study permitted to characterize the genesis and evolution of the complex.

3. Tectonic framework related to the El Cerro Igneous Complex

The evolution of the Northern Andes Block records a complex geological history associated with the accretion of different tectonic blocks (Figure 1) (Cediel and Shaw, 2003). Therefore, the lithological, structural and geomorphological characteristics of the northern Andes are mainly the result of the processes that occurred during the Mesozoic-Cenozoic orogeny, which are responsible for the features that are currently found in the Western Cordillera, where the Frontino-Morrogacho gold district is located. The geological setting of the study area is related to the Choco arc (Cediel and Shaw, 2003), which is the eastern segment of the Panamá Double arc and consists of the Cañasgordas and Baudó terranes (Etayo-Serna et al., 1983; Duque-Caro, 1990).

The evolution of the northern Andes in the study area presents characteristics related to a highly oblique convergence, where collisions of the Gorgona, Cañasgordas and Baudó terranes took place (Cediel and Shaw, 2003). As the collision of the Panamá-Chocó Terrane ended in the middle Miocene, arc magmatism developed in the middle to late Miocene as a response to the subduction of the Nazca Plate and the accretion of the Baudó Terrane (Cediel and Shaw, 2003). Early stages of this magmatic event are recorded in the intrusion of calc-alkaline bodies along the Cañasgordas terrane, such as the Mistrató-Farallones Batholiths and El Cerro Frontino stock, which mark erratic subduction-related magmatism due to the early approximation of the Baudó terrane at 11 Ma-12 Ma (Maya, 1992; Cediel and Shaw, 2003). These intrusives correspond to the northern calc-alkaline granitoid arc segment associated with Miocene subduction along the Colombian trench and the Farallones-El Cerro-Dabeiba holocrystalline suite (Leal-Mejía, 2011; Leal-Mejía et al., 2019; Shaw et al., 2019).

The result of the accretion of the Panamá-Chocó block is recognized in an N-S trend of monzonitic to granodioritic plutons in the form of isolated batholiths and stocks, from the Torrá and Farallones Batholiths in the south to the Nudillales monzonitic stock located north of Dabeiba, Antioquia Province. The late- to mid-Miocene plutons are commonly found in very steep isolated areas with rugged morphologies that dominate the landscape, with some of them commonly reaching more than 3000 m in altitude. Geomorphological characteristics and prior studies of the Western Cordillera suggest that the
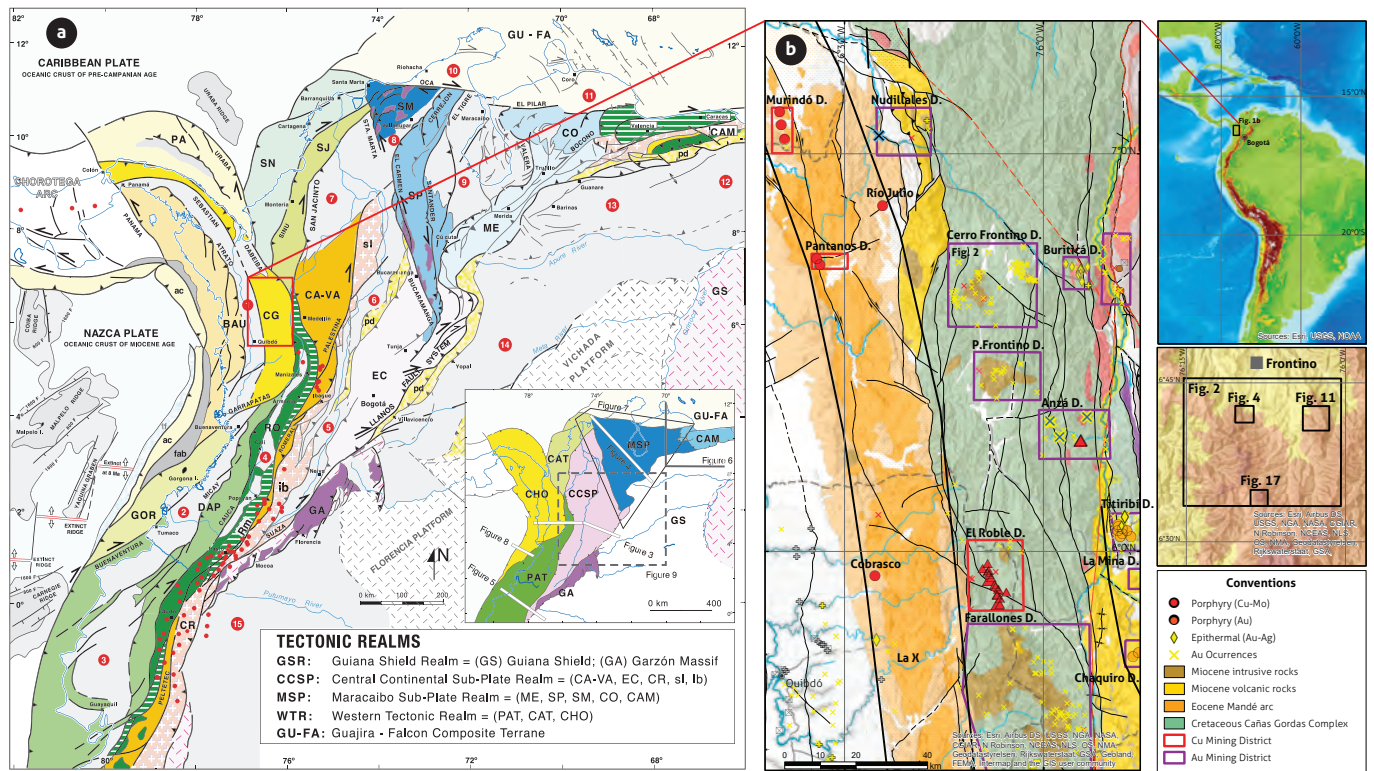
Figure 1. a) Geological terranes of the northern Andes segment (Cediel and Shaw, 2003). b) Geological and metallogenic map of the northern segment, Western Cordillera, with the location of the Frontino-Morrogacho gold district
Modified from Leal-Mejía et al. (2016).

uplift and exhumation of tectonic blocks that host the Miocene intrusives allowed for a higher rate of erosion and surface exposure (Villagómez and Spikings, 2013). Most of these igneous bodies are found intruding the Cañasgordas basement, such as El Cerro Frontino, La Horqueta and Morrogacho stocks, which make up the El Cerro Igneous Complex (Shaw et al., 2019). The intrusion of the El Cerro Igneous Complex developed gold mineralizations that conform to the Frontino-Morrogacho gold district.

After the El Cerro Igneous Complex plutonic event ceased, magmatism shifted eastwards at approximately 8 Ma towards the axis of the Cauca River canyon in the form of shallower porphyritic stocks that are associated with ore deposit genesis in the Middle Cauca Metallogenic Belt, which is the most prolific gold belt in Colombia. The migration of magmatism to the middle Cauca valley is attributed to the progressive shallowing of the subduction angle due to trench clogging by the presence of the subducting Sandra Ridge, which is a buoyant aseismic material (Leal-Mejía et al., 2019). Here, the intrusion of metal

fertile plutons led to the genesis of different mineral deposits as well as the migration of hydrothermal fluids associated with epithermal-type deposits. This belt is located along the margin of the Cauca-Romeral fault zone and hosts late Miocene-Pliocene (6-8 Ma) porphyry-related Au-Ag and base metal deposits spanning more than 20 Moz for gold (Maya, 1992), such as La Colosa, Buriticá, Marmato, Miraflores and Nuevo Chaquiro (Gil-Rodríguez, 2010; Leal-Mejía, 2011; Lesage et al., 2013; Bartos et al., 2017).

4. GEOLOGICAL SETTING

The Frontino-Morrogacho gold district is located along the Cretaceous Cañasgordas complex and associated with the intrusion of El Cerro Frontino, La Horqueta and Morrogacho stocks in the mid- to late-Miocene (Leal-Mejía, 2011; Leal-Mejía et al., 2019; Shaw et al., 2019) (Figure 2). The Cañasgordas complex consists of two different formations: the volcanic sequence of the Barroso Formation and the sedimentary Pende-

risco Formation. The Barroso Formation consists of basaltic and andesitic lava flows with porphyritic and amygdaloidal textures formed in a volcanic arc environment with ages ranging between 85 Ma and 115 Ma and interbedded with tuffs and sedimentary layers (Álvarez and González, 1978; Rodríguez et al., 2016). The Barroso Formation displays two principal geochemical trends within a continuous tendency: one associated with P-MORB (Plateau) and another associated with N-MORB (destructive margins, i.e., subduction) (Geoestudios, 2005).

The Penderisco Formation is divided into two sedimentary members with different lithological characteristics and geographical positions: the Urrao member and Nutibara member (González and Londoño, 2002). The Urrao member is compo-
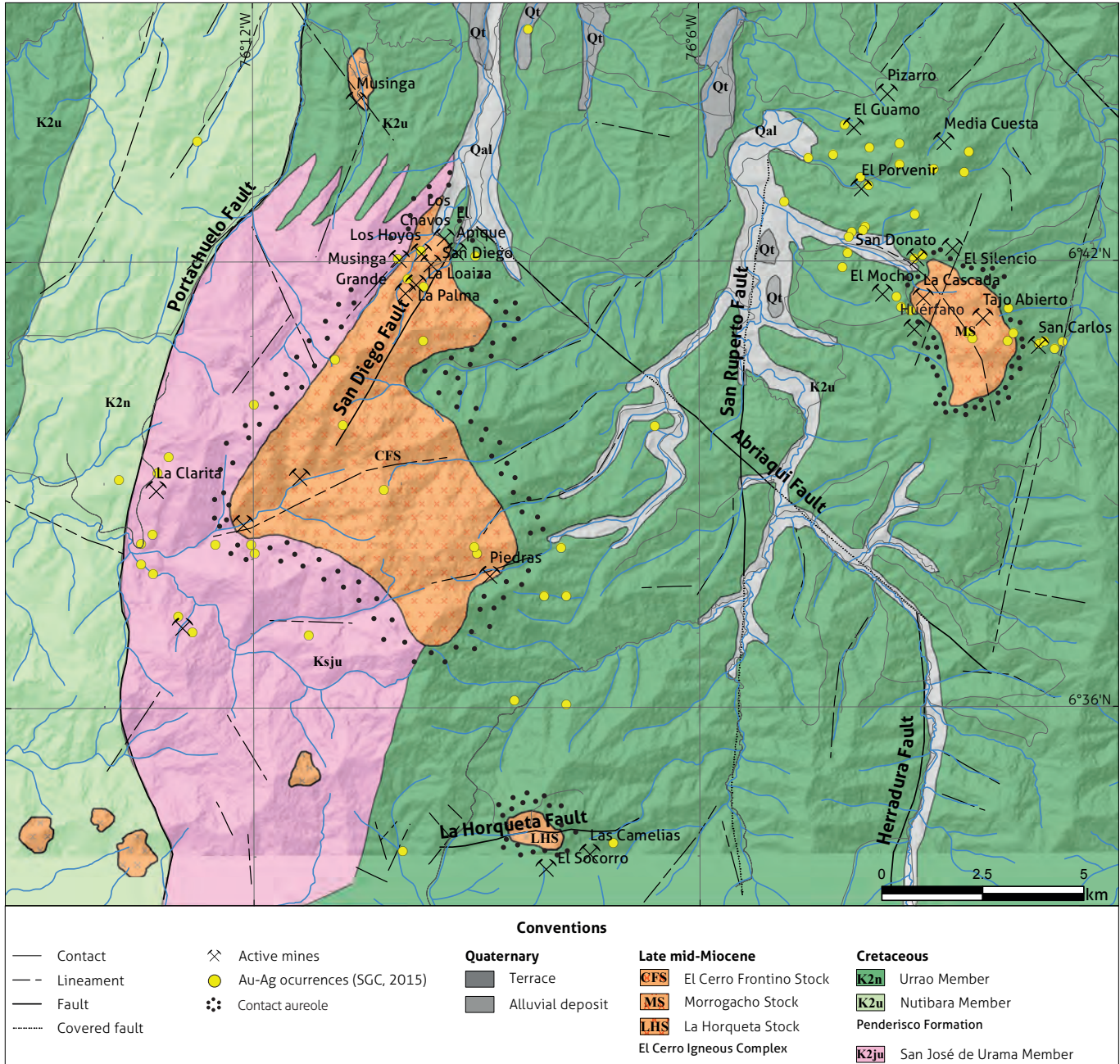

Figure 2. Regional geology of the El Cerro Igneous Complex Modified from González and Londoño (2002).

sed of a sequence of distal and proximal turbidites represented by conglomerates, wackes, lithic sandstones, shale, siltstones and siliceous mudstones. Nutibara members include pelagic and calcareous sedimentary rocks, fine-grained limestones and cherts (Álvarez and González, 1978). The Penderisco Formation was intruded by different Miocene plutons, thus causing contact metamorphism. Therefore, hundreds of meters of wall rocks adjacent to intrusions are commonly found as hornfels in the facies of pyroxene-hornblende-biotite-albite (Álvarez and González, 1978; Rodríguez-García and Bermúdez-Cordero, 2015).

Skarn mineralizations are found in selected areas, where thick calcareous wall rock strata of the Nutibara member were intruded by dioritic pulses, such as the La Loaiza gold-diopsi-de-garnet skarn, which is located in the apex of the El Cerro Frontino stock (Molina and Molina, 1984). La Loaiza skarn is possibly linked genetically and spatially to gold-diopside-garnet skarn mineralization inside the San Diego Mine.

The El Cerro Igneous Complex corresponds to the mid- to late Miocene plutonic suite dated by the K/Ar and Ar/Ar methods in magmatic hornblende and biotite in the range of 12 Ma-10 Ma (Mid-Miocene); however, it has been related to a maximum age of mineralization of 11.8 Ma (Leal-Mejía, 2011; Rodríguez and Zapata, 2012; Shaw et al., 2019). This complex presents a general N-S to NNW-SSE orientation and is associated with Frontino-Botón volcanic arc activity.

The El Cerro Frontino stock has been related to different compositional facies due to the intrusion of more than one pulse and the presence of satellite stocks with areas less than 1 km^2 and ages of 11.8 ± 0.4 Ma (K/Ar) (Leal-Mejía, 2011), 9.87 ± 0.18 Ma and 11.44 ± 0.36 Ma (Ar/Ar) (Rodríguez-García and Bermúdez-Cordero, 2015). Cerro Frontino Monzonite is described by Alvarez and González (1978) as an intrusion of 40 km^2 with equigranular, phaneritic texture, medium grain size, high content of pyrite filling fractures and two main facies: felsic and mafic. The mafic pulse is associated with mineralization processes in the fractures; furthermore, modal classification shows a compositional variation between monzonite and pyroxene diorite.

Rodríguez-García and Bermúdez-Cordero (2015) renamed the pluton to Cerro Frontino Gabbro and described at least three magmatic pulses in a short period of time: (i) an initial facies of gabbros and pyroxenites that is present as xenoliths, (ii) a second and larger facies of gabbros and diorites with variations to pyroxenites and (iii) a final facies of monzonites

that intruded the previous pulses. Geochemical data suggest the contribution of a subduction component in magma to the genesis, and this contribution is related to a magmatic arc environment (Rodríguez-García and Bermúdez-Cordero, 2015; Shaw et al., 2019). Evolution started with tholeiitic affinity and ended with alkali enrichment with a shoshonitic geochemical signature. In the San Diego mine, intrusive phases have been described as pyroxenites, pyroxene gabbros and melanodiorites cut by minor auriferous pegmatite dikes containing clinopyroxene, hornblende, biotite and plagioclase crystals (Shaw et al., 2019). Wall rocks show high to low contact metamorphism and are commonly found as hornfels of albite-epidote to pyroxene facies (Álvarez and González, 1978). The closure age of amphiboles in the hornfels indicates that the intrusion was prior to 12.2 ± 4.6 Ma (Rodríguez-García and Bermúdez-Cordero, 2015).

Morrogacho diorite is an elongated and rectangular-shaped stock of approximately 6 km^2 (Álvarez and González, 1978). This intrusion is related to the crystallization of fine- to medium-grained phaneritic equigranular diorites in a single phase with important textural and compositional differences (Álvarez and González, 1978). Wall rocks around the stock are commonly found as hornfels of hornblende and albite facies (Álvarez and González, 1978).

La Horqueta Monzodiorite outcrops in a very prominent hill that has the same name and occurs as a circular-shaped stock spanning approximately 1.2 km^2 (Álvarez and González, 1978). It has been described as a monzonite to pyroxene diorite with a locally high content of biotite related to late hydrothermal K-metasomatic processes without the presence of satellite igneous bodies (Álvarez and González, 1978). Wall rocks around the stock occur as hornfels of albite-epidote facies with a contact aureole of 100 m-200 m width (González and Londoño, 2002). According to Rodríguez and Zapata (2012), La Horqueta and Morrogacho stocks present a hipidiomorphic texture with a mineral assemblage of Pl + Cpx + Opx + Bt ± Or ± Qz and Pl + Cpx + Bt ± Opx ± Ol, respectively.

The Cañasgordas Complex (Penderisco Formation) is highly deformed with the presence of faults and folds that are controlled with a clear morphologic expression (Álvarez and González, 1978; Page, 1986), mainly with a N-S to NW-SE strike. Structurally, the Penderisco Formation in the Farallones-El Cerro area is limited by a set of major terrane boundary faults, which are the Garrapatas-Dabeiba transform fault to the south and east and the Uramita Fault zone to the west.

The most relevant structure in the El Cerro Igneous Complex is the N-striking San Diego Fault (Figure 2) due to its relation with the mineralization processes at the San Diego-La Cuadrazón mine. However, several other preferentially E- and secondary N- and NW-striking mineralized corridors involving fault veins and shear-related structures are commonly found in the district. These structures are considered important for focusing fluid in structurally prepared wall rocks, which also influenced dilatational cooling of extensional structures within the plutonic suites (Hart, 2007). Furthermore, various pre- and postmineral dominantly N-striking fault structures have been described in the area, such as La Herradura, San Ruperto, San Juan-Portachuelo, La Encarnación and Río Verde (Noriega et al., 2012). These structures are affected and displaced by the NW-Cañasgordas, Abriaquí, and Carauta faults. The mentioned structures are not currently related to mineralization processes. La Herradura and San Ruperto faults present neotectonic activity, with sinistral inverse movement related to the regional deformation regime associated with the Panamá-Chocó block push (Noriega et al., 2012).

The Frontino-Morrogacho gold district is classified in the metallogenic map of Colombia as an Au-Ag district in which mineralizations occur in veins and shear zones (Leal-Mejía et al., 2016). Mineralizations have been included in the Buriticá-Frontino district proposed by Leal-Mejía (2011), with gold content not as high as other nearby localities of the Middle Cauca Belt (Lesage et al., 2013)Colombia. It is hosted by the late Miocene Buriticá andesite porphyry, a shallow-level pluton dated at 7.41 ± 0.40 Ma (2σ, MSWD = 2.30; 40Ar/39Ar on hornblende. Shaw et al. (2019) include the El Cerro Igneous Complex in the Oligocene through Pliocene granitoids belonging to this metallogenic epoch in the Colombian Andes. Overall, this district is related to Au (Cu, Zn, Ag, As, W, Co ± PGE) mineralizations hosted in dikes, sheeted veinlets, and contact zones within intrusives and hornfels. Additionally, skarn mineralizations occur along the contact aureole and in sheeted veinlets and stockworks, replacement-style mantos and breccia zones developed in sedimentary rocks of the Penderisco Formation (Shaw et al., 2019).

In the El Cerro Frontino Igneous Complex, the mineralization style is mainly mentioned as nondisseminated textures related to veins and veinlets with coarse-grained native Au and Au-rich electrum that compromise quartz and calcite gangue and two paragenetic phases: Au-molybdenite-scheelite-cobaltite ± lollingite and quartz followed by chalcopyrite-pyrrhoti-te-sphalerite-quartz ± scheelite (Molina and Molina, 1984; Escobar and Tejada, 1992). Furthermore, the presence of pyrite, pyrrhotite, chalcopyrite, sphalerite, galena and arsenopyrite has been described (Flórez, 1988; Agrominera El Cerro, 1992). The hydrothermal alteration mineralogy consists of late magmatic potassic metasomatism with the replacement of augite and diopside by hornblende and euhedral Fe-rich biotite, local replacement of biotite by chlorite and epidote, and alteration haloes along the veinlet margins marked by biotite coarsening and a calc-silicate mineral assemblage (Shaw et al., 2019). Propylitic alteration is related to chlorite and sericite assemblages developed in small halos (Agrominera El Cerro, 1992).

5. Results

5.1 Geological, metallogenic and exploitation considerations of the El Cerro Igneous Complex

Underground gold mining works in the El Cerro Igneous Complex are related to several mineralized structures with different geometries and styles that are always spatially related to plutonic intrusions. Magmatic intrusions are related to prominent topographic changes in relation to surrounding sedimentary Cretaceous country rocks (Figure 3).

5.1.1 El Cerro Frontino

The El Cerro Frontino stock corresponds to an igneous intrusive body located to the south of the Frontino municipality. Mining activities at the El Cerro Frontino stock can be divided into at least four different zones, which include the Carauta-Orquideas area in the west and southwest, Musinga in the northwest, El Cerro to the north and Piedras to the east. The area of interest of this study corresponds to the northernmost sector of the stock, specifically the mineralized structures located in the El Apique and Los Hoyos mines, north of the San Diego-La Cuadrazón mine, representing a new important mineralized corridor in the El Cerro Frontino area (Figure 4).

Igneous bodies found in the El Apique and Los Hoyos-La Rompida structures vary into gabbroic with high pyroxene content and dioritic phases (Figure 4). Diorite is phaneritic and holocrystalline with leucocratic aspects, small to medium grain sizes and composed of plagioclase of the andesine series (62%), clinopyroxene of the augite-aegirine type (17%), coarse-grained biotite (11%) and quartz (3%). Amphibole is present as primary hornblende and related to the

Figure 3. Panoramic view of the El Cerro Igneous Complex
These profiles show important topographic changes that conform the prominent landforms related to the intrusive centers and the peripheral resistant ridges of hornfels and country rocks. Frontino-Morrogacho gold district.

uralitization of pyroxenes (3%), whereas opaque minerals are mainly identified as disseminated pyrite and magnetite, with the pyrite content being incremented by alteration processes into the host rock in the immediate margin of the veins (4%) (Figure 5). Diorite phases in the Los Hoyos and El Apique areas are found either as thin dikes or as massively N trending elongated outcrops with poor contents of fractures and joints. The textural characteristics of the Los Hoyos diorite are very similar to those in La Palma diorite bodies found in the upper part of the El Cerro, assuming that they are a single widespread phase.

Gabbro corresponds to phaneritic intrusive rocks with fine to medium grain sizes, melanocratic aspects, equigranular and idiomorphic textures, and compounds by plagioclase of the labradorite series (45%), clinopyroxene of the augite-aegirine type (36%), biotite (15%) and orthopyroxene (4%) (Figure 6).
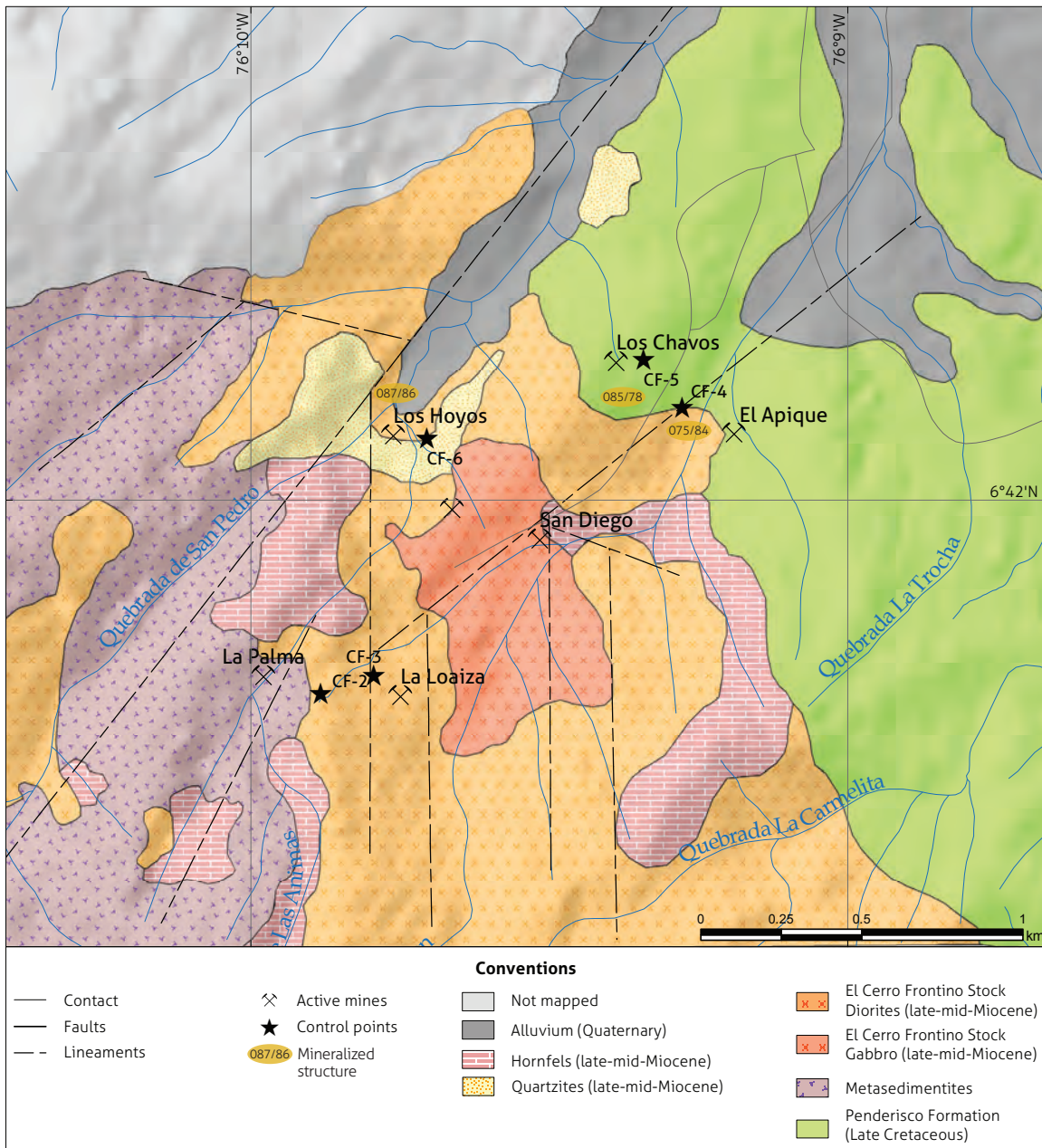
Figure 4. Geological map of the El Cerro Frontino stock with the main mineralized structures relating to this study
Modified from Serviminas (2017).
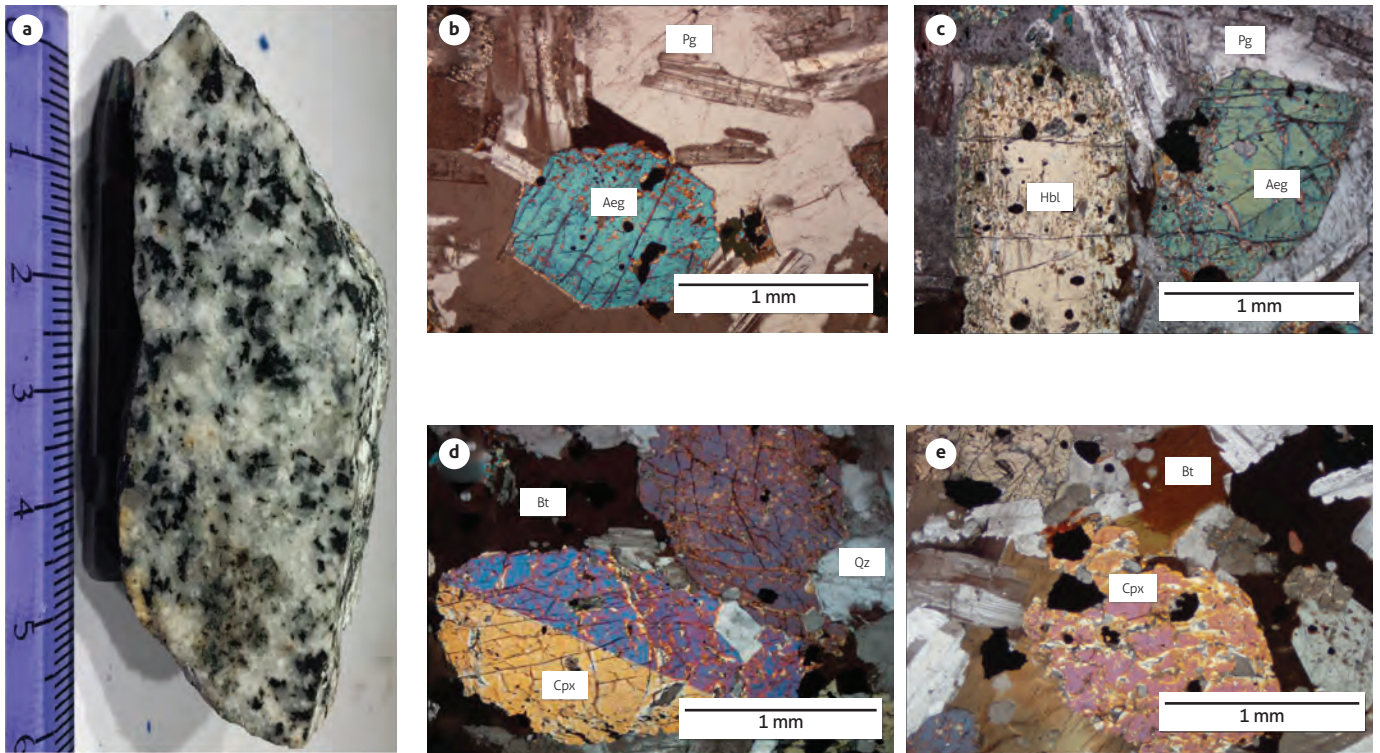
Figure 5. Hand sample and mineralogical composition in thin section. Cerro Frontino diorite
a) Hand-sample. b) Aegirine crystal partially rounded by euhedral plagioclase crystals. c) Presence of hornblende with oxide inclusions and aegirine with plagioclase (andesine). d) Twinned clinopyroxene crystal with quartz. e) Presence of biotite next to plagioclase (andesine) and clinopyroxene crystals. Pg: Plagioclase. Aeg: Aegirine. Hbl: Hornblende. Cpx: Clinopyroxene. Qz: Quartz. Bt: Biotite.
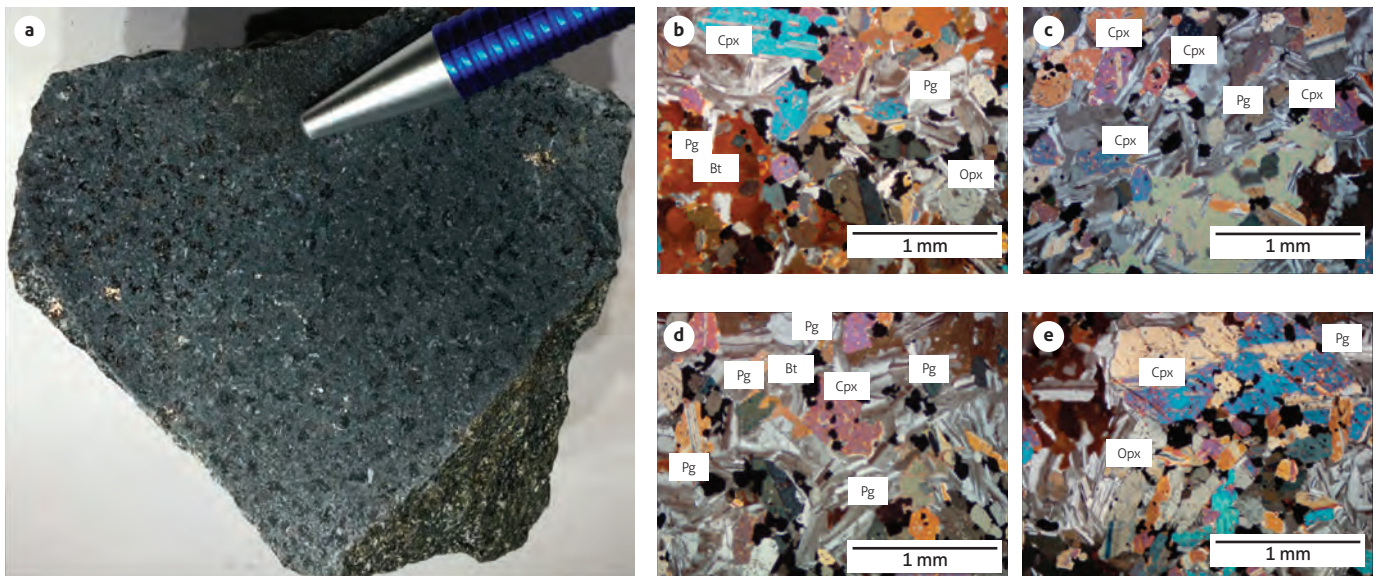

Figure 6. Cerro Frontino gabbro
a) Hand sample. b-c-d-e) High contents of plagioclase (labradorite) and clinopyroxene in the presence of biotite and orthopyroxene. Pg: Plagioclase. Aeg: Aegirine. Hbl: Hornblende. Cpx: Clinopyroxene. Opx: Orthopyroxene. Bt: Biotite.

Minor quantities of amphibole are present as hornblende due to uralitization of pyroxene. Outcrops can be found in the deep zones of El Apique (cm wide coarse biotite) and outcropping along San Pedro Creek (fine biotite). Intrusive relationships show that diorite pulses posterior to the gabbro because several intrusive breccias contain dioritic matrix and mafic clasts.

The intrusion of the El Cerro Frontino stock has generated low-grade contact metamorphic rocks with areas of skarn genesis. Leucocratic diorite intrusions emplaced towards thick calcareous strata with developed pyroxene-albite-chlorite hornfels, chlorite-rich quartzite and impure marble. There are extensive outcrops of metasedimentary rocks west of San Pedro Creek. Furthermore, these metasedimentary country rocks exhibit strong deformation and foliation with subhorizontal to vertical attitudes. Skarn deposits and pyritic mantos replacement are developed along both members of the Penderisco Formation in the area with low-grade mineralization content. Furthermore, the main mineralization style has been related to extensional-sheeted veinlets, extensional veins and shear-related veins found along El Cerro Frontino, where gold exploitation is focused.

Metamorphic and metasomatic thermal aureoles appear as steep resistant cliffs, which commonly indicate vertical and subvertical contact of the pluton and the country rocks. At El Cerro Frontino, the contact aureole presents banding and mineral replacement, with gray and white sequences in the hornfels proximal to the pluton. Hornfels are composed of saccharoidal quartz, diopside, tremolite-actinolite with minor calcite, idocrase, garnet, epidote, sphene, magnetite and disseminated pyrite (Escobar and Tejada, 1992), whereas the distal portions of the country rocks present evidence of grain recrystallization several kilometers away from the contact.

In the El Cerro Frontino area, mineralization is hosted in gabbros and diorites of the main intrusive body and in pyroxene-albite-chlorite hornfels or chlorite-rich quartzites of the contact aureole as a continuous structural corridor. Inside the aureole, there is a significant decrease in sulfide content and a decline in the thickness of the mineralized veins, which are related to shear zones. Conversely, in the igneous body, the mineralization increases in grade where the Los Hoyos and El Apique mines are located. Extension of the mineralization can suffer abrupt thinning and deflection when proximal to foliated metasedimentary rocks that outcrop west of San Pedro Creek, where these units conform to resistant massifs that seem to lack any economic mineralization.

Multiple apophyses of the El Cerro Frontino stock are common in other locations intruding the Cañasgordas basement and developing productive mineralized vein-type structures. For example, the Musinga, Carauta and Orquideas plugs are located northwest, west and southwest, where thin stringers of quartz-sulfide veins are hosted within fine-grained diorite bodies, with narrow cylindrical shapes that constitute clusters of intrusions, each between 0.5 km^2 and 1 km^2 in size, and span radially from the main Cerro Frontino stock.

Mineralization is related to tens of E-trending mineralized corridors across the pluton, with the development of extensional-sheeted veinlets, extensional veins and shear-related veins of different sizes that can form nests of veins and veinlets (a few centimeter-wide individual veinlets, and several meter-wide corridors, up to 3 m). These corridors are found along the axis and borders of the main the El Cerro intrusive body, with several tens of these mineralized zones manifested with widths of 30 m-50 m between individual structural corridors.

Small-scale artisanal activities are commonly represented in hundreds of tunnels dispersed in the area. Gold extraction is carried out using free milling techniques and gravitational separation methods, such as the "Antioquian Mill" or "Molino de Arrastre". This technique consists of a wooden circular recipient acting as a mill that uses water flow to push a set of irregular intrusive rocks inside the mill. Continuous movement of the rocks generates crushing and an ultimate decrease in particle size, with subsequent liberation of gold grains from sulfides and quartz. The process is finished with the use of a wood-based sluice box, where gold is collected as fine-grained particles.

5.1.1.1 El Apique mine

The El Apique mine corresponds to a 1-km-long mineralized structure that has been mined from both east and west in the northern sectors of the El Cerro Frontino stock. It was first exploited by the English company Carmen Valley Limited more than a hundred years ago and was recently reopened by the local society of miners (Hill, 1961; Alarcon, 2008). This mine is developed in rocks of the intrusive body but also in rocks from the surrounding country. Inside the first floor of the mine, there is a transition from the outside rim of the thermal aureole to inner contact with the intrusive body. The stock appears with important textural and compositional differences from fine-grained diorite in the first floor to coarse-grained biotite-bearing gabbros, including high pyroxene content, in the deepest level of exploitation, which is a 120-m-deep shaft.

This lithological variation occurs at altitudes less than a hundred meters and exhibits a mineralizing change between two different magmatic pulses of the El Cerro Frontino stock: an initial mafic pulse and a later dioritic pulse.

The contact between diorites of the El Cerro Frontino stock and the Urrao member of the Penderisco Formation exhibits intense silicification and chlorite alteration towards the border of the intrusion. Mineralization at the contact in the first floor evolves from shear veins to thin extension quartz veins a few centimeters wide hosted in the intrusive zone. Veinlets are included in zones of sheeted quartz veins that converge to a principal vein 10 cm to 20 cm wide and E striking. These veinlets are quite poor in sulfide content, and assays indicate that they are poor on gold, suggesting that auriferous mineralization shows a low grade inside the later dioritic phase of the intrusion. Alterations in this zone consist mainly of weak chlorite selvages a few centimeters near the veins.

The country rocks of the Urrao member appear as fine-grained sandstones, siltstones, and chert, which are strongly metasomatized and with bedding striking E- and vertically dipping mainly to the S. These rocks developed a multifractured EEN-striking shear vein with a vertical to subvertical dip to the S and a right lateral sense of movement evidenced by slickensides and vein displacement (Figure 7). It is possible to appreciate breccia zones partially formed when the fluids exsolved from the pluton were channelized through shear zones. Hydrothermal alteration inside and in the margins of the breccia consists of sericite and chlorite halos proximal to the veinlets. The fractures and joints near the shear zone are usually filled by sheeted quartz veins of a few centimeters wide, with low sulfide content into thin stringers of sheeted veinlets or stockwork textures (Figure 7). The width of the shear vein can vary from a few centimeters to more than a meter in the widest zone, with fine quartz-calcite-sericite hydrothermal breccia that contains fine pyrite and combined sulfide gouge with gold values between 5 ppm and 10 ppm.

Mineralization at the deepest level consists of quartz-calcite extension veins with an E strike with vertical, subvertical and subhorizontal dips to the S. Extension veins exhibit three anastomosed veins with constant thickness changes, averaging 0.5 m, varying from a few centimeters to 1.5 m, where multiple veins converge and form nests. Arrays of veins are not separated more than a meter from the other, and selvages of veins are conformed by bands and patches of coarse-grained sulfide assemblages and high-grade gold values up to several tens of
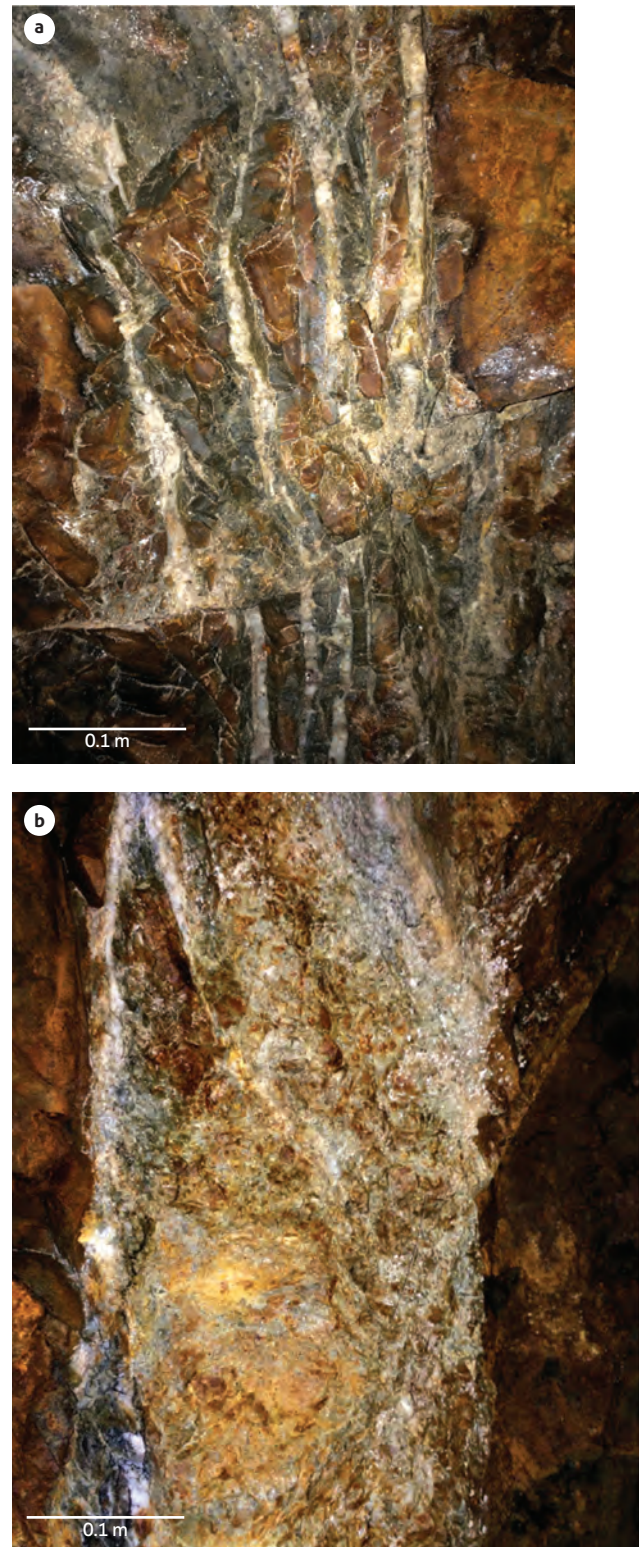
Figure 7. View of the El Apique shear zone located on the first floor of the El Apique mine
Lateral displacement observed in the left photograph related to an extensional shear zone. The shear zone is approximately 1 m wide with the presence of sulfides.

ppm in gold, occasionally visible to the naked eye, with grains several millimeters wide. The vein dip angle varies from vertical and subvertical to subhorizontal (20°-30°) with inclinations towards the S (Figure 8). Minor faults and fractures striking to the NW are displacing the main structure, although the veins appear to be massive and consistent along the strike without internal fracturing.

Both sheared veins and extension veins in El Apique have similar structural control with minor strike deflection from the hornfels to the pluton, which only represent low-order strike changes indicating an oblique sense of the sheared vein with respect to the extension veins. The E-striking direction and S-vertical dip of the shear and extension veins coincide with the E-striking and S-trending dip directions of the stratigraphic planes of the Urrao member country rocks.

Alteration mineralogy in the deepest floors consists mainly of a mild brecciation of the wall rock with the presence of sericite, chlorite and carbonate, with extension of alteration halos spanning a few tens of centimeters around the veins. However, green-colored clay, possibly illite, occurs in some places in the adjacent centimeters near the extension vein-wall rock contact. Extensive pyrite dissemination occurs near the vein margins. Coarsening of the biotite crystals in the gabbro is evident, reaching a few centimeters in size, and it is possibly related to K-rich fluids involving a premineralization event associated with late magmatic metasomatism, which is reflected in the Fe-rich biotite content in this lithotype.

Mineralogy of the vein samples studied from El Apique consists of calcite (occasionally bladed) and quartz. Stage one of mineralization consists of crystallization of pyrrhotite with porosity filled by gold associated with hessite, luangeite, imeterite, calaverite, petzite, galena and Fe-rich sphalerite (Figure 9A). Chalcopyrite occurs as inclusions and exsolutions in pyrrhotite crystals and inside sphalerite with disease textures. Gold grains, gold and silver telluride alloys occur mainly as crystals approximately 10 μm-70 μm in size (Figure 9). The second stage of mineralization consists of quartz and high contents of carbonate, pyrite and galena cutting sphalerite crystals locally (Figure 9b). Finally, a third stage is differentiated by the replacement of pyrrhotite by pyrite in borders. Sulfides appear as sutures within and at the borders of the veins, and they exhibit open space filling textures such as oriented pyramidal quartz crystals and coarse sulfides growing within drusiform cavities. The sulfide content averages 5% and can be as high as 20% of the vein mass.
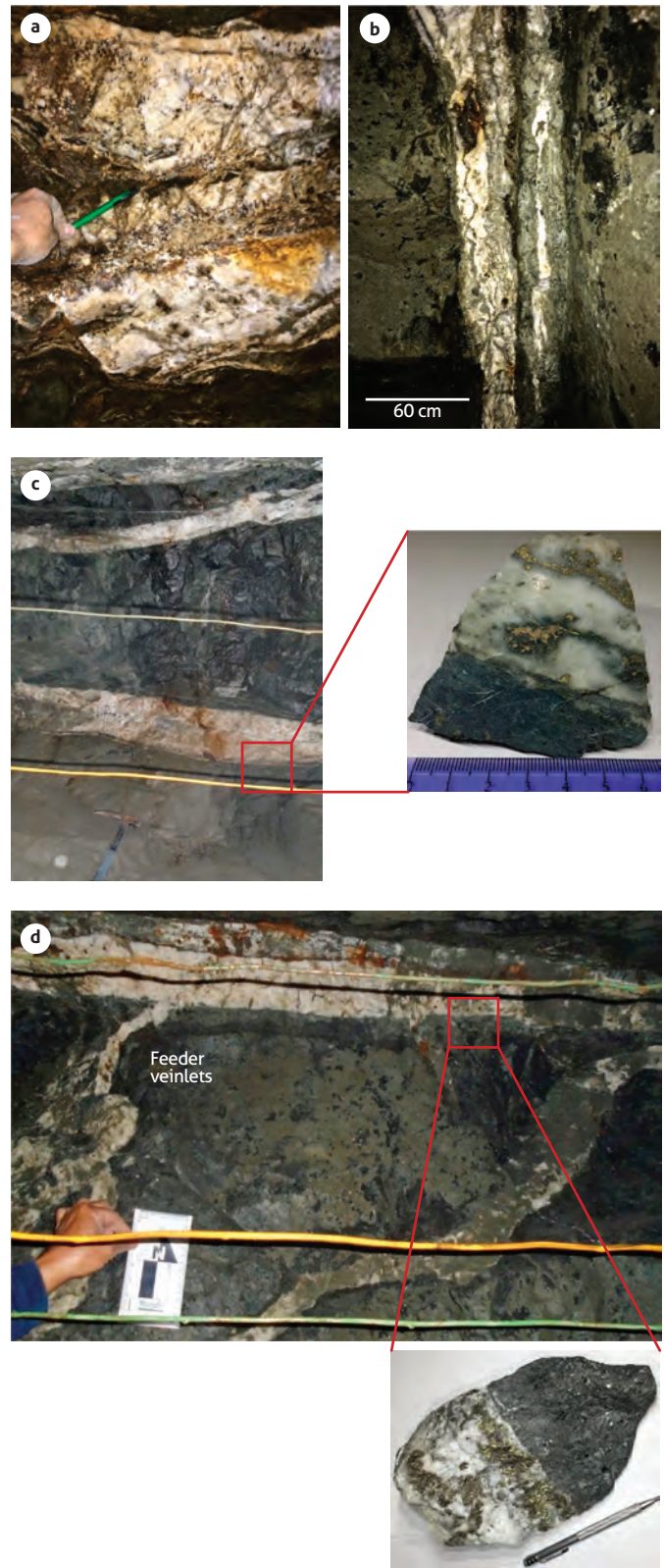

Figure 8. E-W striking extension veins observed in the El Apique mine a-b-c) Quartz-calcite extension vein. d) Mineralized igneous body with chloritization cut by quartz-calcite veins with chalcopyrite, pyrite and sphalerite.
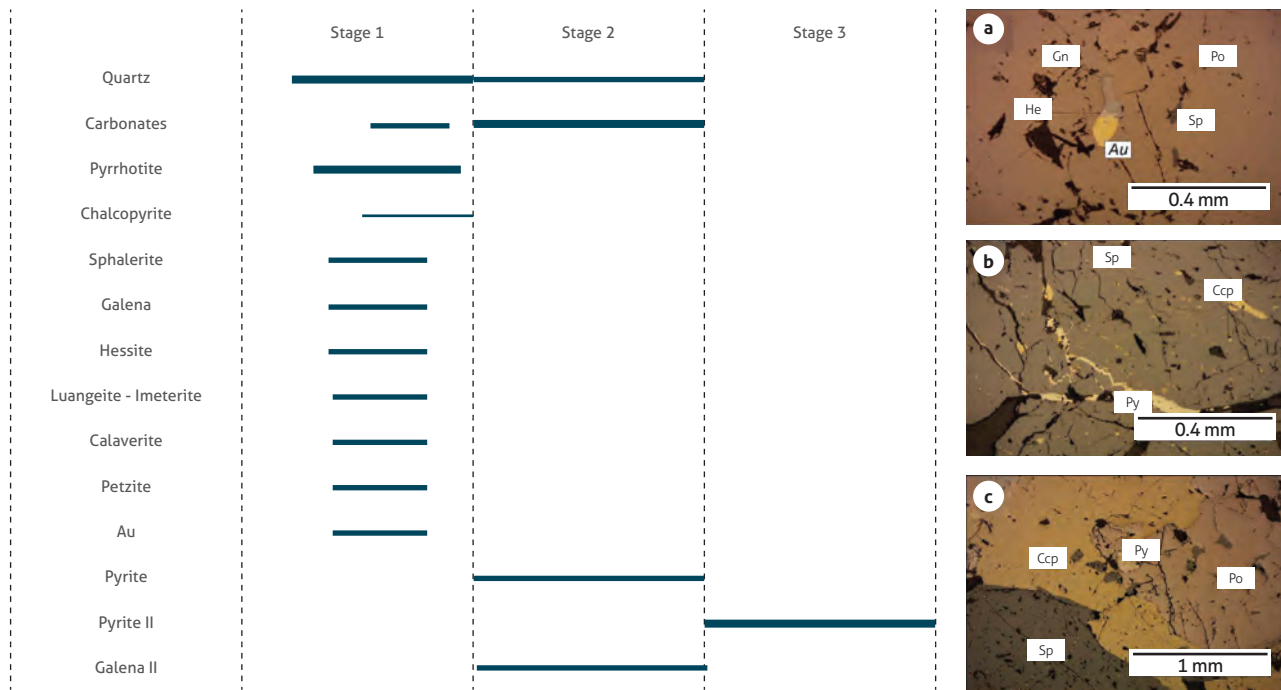
Figure 9. Paragenesis of the El Apique mineralized structure
a) Au, hessite and galena in paragenesis with pyrrhotite. b) Sphalerite cut by pyrite event. c) Chalcopyrite, pyrite, sphalerite and pyrrhotite contents. Ccp: Chalcopyrite, Py: Pyrite, Po: Pyrrhotite, Sp: Sphalerite, He: Hessite, Gn: Galena.

5.1.1.2 Los Hoyos mine

Los Hoyos is an artisanal mining operation that is located on the western part of the northern area of the El Cerro Frontino stock near San Pedro Creek. The most important mining front on Los Hoyos consists of a vertical shaft known as La Rompida. The mineralized structure exploited in La Rompida is thought to be the same as that in El Apique, which can be confirmed in the textural and mineralogical characteristics of the deposit and in the strike of the veins. In this way, these features show that both sets of mineralized vein types correspond to a continuous mineralized structure more than 1 km in length, with at least 200 m in vertical extent.

In the first floor of the Los Hoyos mine, mineralization is related to a set of centimetrically wide subparallel quartz extension veins with low sulfide and gold contents. Veins hosted within a fine-grained diorite show textures and compositions similar to those observed in El Apique. Alterations are mainly characterized by weak chloritization and the presence of clay associated with the wallrock around the mineralization (Figure 10). Host rocks in the deepest part of La Rompida consist of melanocratic gabbro with biotite crystals and green-colored (chlorite content) quartzite, commonly known as Los Hoyos quartzite. Alteration in this area corresponds to narrow selvages of green clay possibly illite, few centimeters adjacent to veins, with wider halos of chlorite spanning tens of centimeters around veins.

Deep in the La Rompida vertical shaft, the mineralized structure has important changes with the location of anastomosed veins with an ENE- to E-striking and S-dipping angle that are vertical to subvertical. The width of the veins varies between 10 cm-30 cm when individually separated to almost 2 m when creating important clusters and nests (Figure 10). In addition to these features, magmatic breccias in the form of dikes can be found surrounding the mineralization, suggesting fractionation processes in the main igneous body.

The ore mineralogy consists of two different phases: the first phase of quartz, pyrite, and galena with high silver contents and the second phase of calcite, pyrrhotite, chalcopyrite and sphalerite selvages, with minor contents of galena and hundreds of ppm gold in selected samples. The sulfide content within the veins averages 5% and can be as high as 30% in selected areas.
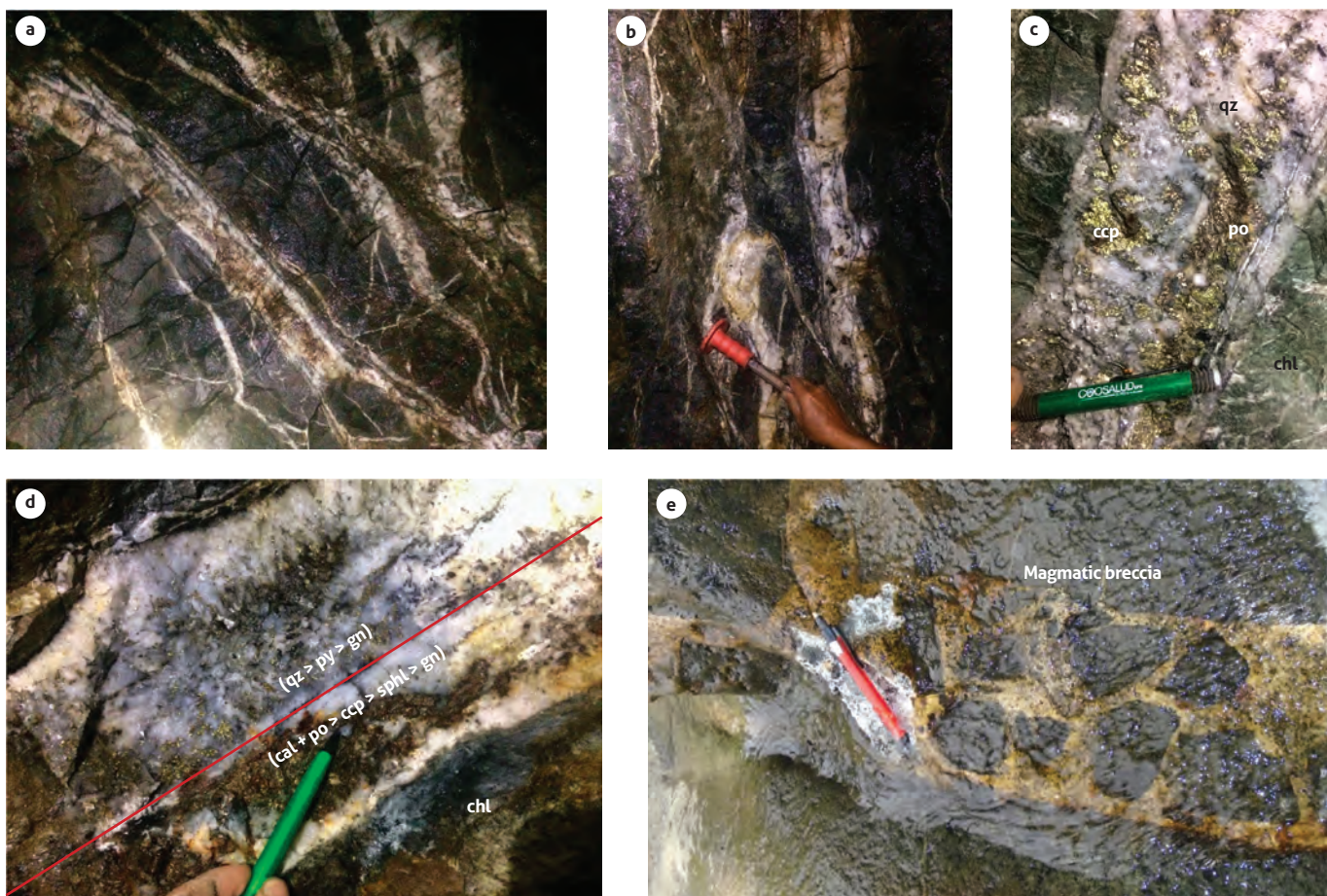
Figure 10. Mineralized structures in Los Hoyos-La Rompida
a-b) Subparallel veins with clay content near the borders. c-d) Decimeter-wide mineralized structures; note the different phases of mineralization and chloritization in host rocks. e) Magmatic-hydrothermal breccia in Los Hoyos creek. po: Pyrrhotite, ccp: Chalcopyrite, gn: Galena, qz: Quartz, py: Pyrite, sphl: Sphalerite, chl: Chloritization.

At least two different mineralization styles were identified in the El Cerro Frontino area. The first is characterized by a set of ENE-striking steeply S- dipping, right lateral displacement, shear-related veins with milky quartz, pyrite, and low contents of sulfides in sericite-dominant gouges that incorporate wall-rock brecciated clasts. Veinlets inside the shear zone are well developed along with tension fractures that sometimes exhibit echelon structures associated with the right-lateral slip of the shear. The second and main mineralization style corresponds to a set of E-striking extension veins with quartz-carbonate gangue, pyrrhotite, pyrite, chalcopyrite, Fe-rich sphalerite and galena with gold in the form of highly concentrated coarse-grained sulfides in vein selvages. Obliquity in the extension vein with respect to the shear veins suggests episodic filling of the dilatational zones generated by the shear forming mineralized corridors.

5.1.2 Morrogacho-Popales

Morrogacho is a NW elongated stock that composes a 3000-meter-high peak that is the apex of the pluton. Mineralizations in the stock are hosted within the pluton (Tajo Abierto and La Cascada mineralized structures) and in the surrounding Urrao member sedimentary wall rocks (El Mocho, San Donato and El Silencio mineralized structures) (Figure 11). Furthermore, other important mineralizations are located north of the stock (Media Cuesta and Pizarro mineralized structures). The area of interest of this study corresponds to the Tajo Abierto and La Cascada mineralized structures and the Media Cuesta and Pizarro areas.
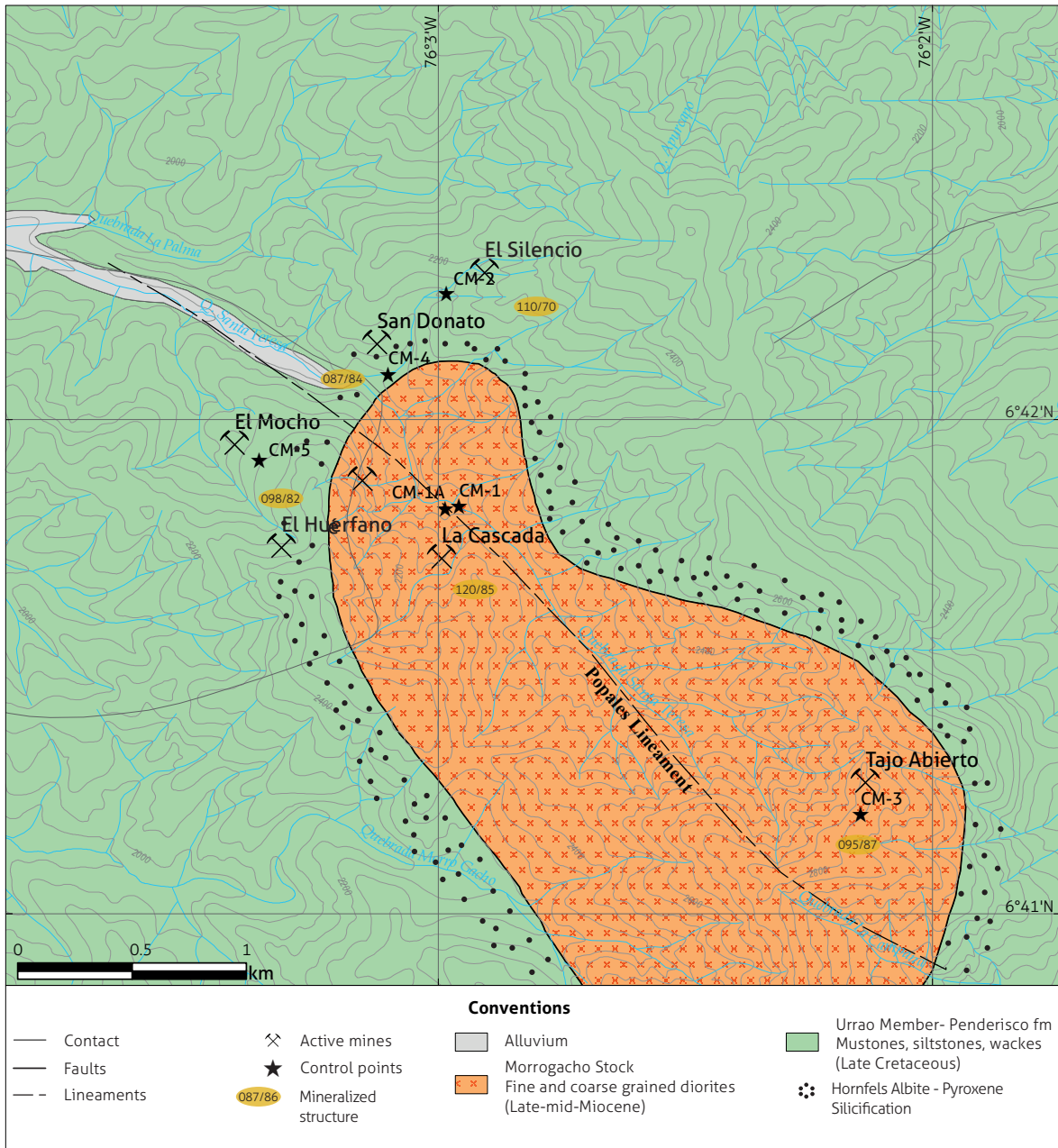
Figure 11. Geological map of the Morrogacho polyphase stock with the main mineralized structures
Modified from González and Londoño (2002), and Fenix Oro (2020).

The Morrogacho stock, as seen in La Cascada mineralized structure in the Popales area and along Santa Teresa Creek, corresponds to a diorite with phaneritic texture of fine to medium grain size. The mineralogy includes plagioclase (andesine series) up to 70%, biotite (12%), clinopyroxene of the augite-aegirine type (15%) and minor quantities of quartz (3%). Opaque minerals occur as disseminated pyrite (Figure 12). Álvarez and González (1978) consider this stock as a single-phase intrusion; however, at least two pulses have been recognized, and they present remarkable textural and compositional changes, one of which is related to dikes and satellite bodies.

Widespread thermal metasomatism traced for at least five hundred meters from the intrusive contact in the facies of hornblende hornfels affects siltstones and shales of the Urrao

member of the Penderisco Formation, whereas distal areas of the country rocks present evidence of grain recrystallization away from the contact.

Mineralizations of Morrogacho stock are mainly distributed in the northern area of the intrusive body but are also located inside the thermal aureole of the pluton along an important E- to NW-striking photogeological lineament, which was named the Popales Lineament in this study (Figure 11), and it is recognized as a cooling structure within the Morrogacho stock. Mining activities have been developed for the last 100 years, with dozens of tunnels found inside and around the stock. Mineralizations near and outside the stock are associated with the movement of fluids that were trapped inside structurally prepared wall rocks.

5.1.2.1 Tajo Abierto mineralized structure

Tajo Abierto corresponds to a mineralized structure located inside the Morrogacho pluton and is related to the apex of the stock, where mineralization occurs as part of the fluid movement that circulates in the cupola and carapace (Hart, 2007). Mineralization hosted in the intrusive consists of a 0.6-m to 1.0-m-wide extension vein with a marked E-strike direction with a vertical S-dipping strike. A dilatational zone observed within the intrusive is hosted of veins of wider margins than others observed in the Frontino-Morrogacho gold district. The sulfide content in the vein is high and reaches 90% of the vein

mass. Intersections of SE- and NE-striking branches of veins can generate the occurrence of ore shoots and demonstrate extensional behavior. At this point, veins become massive in sulfide content, with coarse ore mineralogy dominated by pyrrhotite, chalcopyrite, pyrite, arsenopyrite and Fe-rich sphalerite, indicating high temperatures of the mineralizing fluid during precipitation conditions (Figure 13).

The sulfide content in the ore shoots is uncommonly high for the district. Parasitic veinlets several centimeters wide with high contents of pyrite and chalcopyrite orthogonally disposed to the principal set of vertically dipping veins with S-strikes cut the intrusions surrounded by strong chloritic alteration. This condition coincides with the extension processes of the main vein formation (Figure 13). Hydrothermal alteration in Tajo Abierto corresponds to pervasive chloritic alteration near the veins that occur a few tens of centimeters proximate to the back of the veins with sericite, carbonate and widespread strong pyrite dissemination in the host rock. This alteration occurs mainly in fractures and joints along the vein margin, whereas the alteration that is more distal consists of a chloritic assemblage with weak intensity.

The gangue mineralogy of the veins from Tajo Abierto is mainly composed of calcite and quartz. Pyrite and arsenopyrite in the first stage are associated with gangue minerals. Pyrite is highly fractured and brecciated, which are characteristics that indicate the presence of two different stages of mineralization
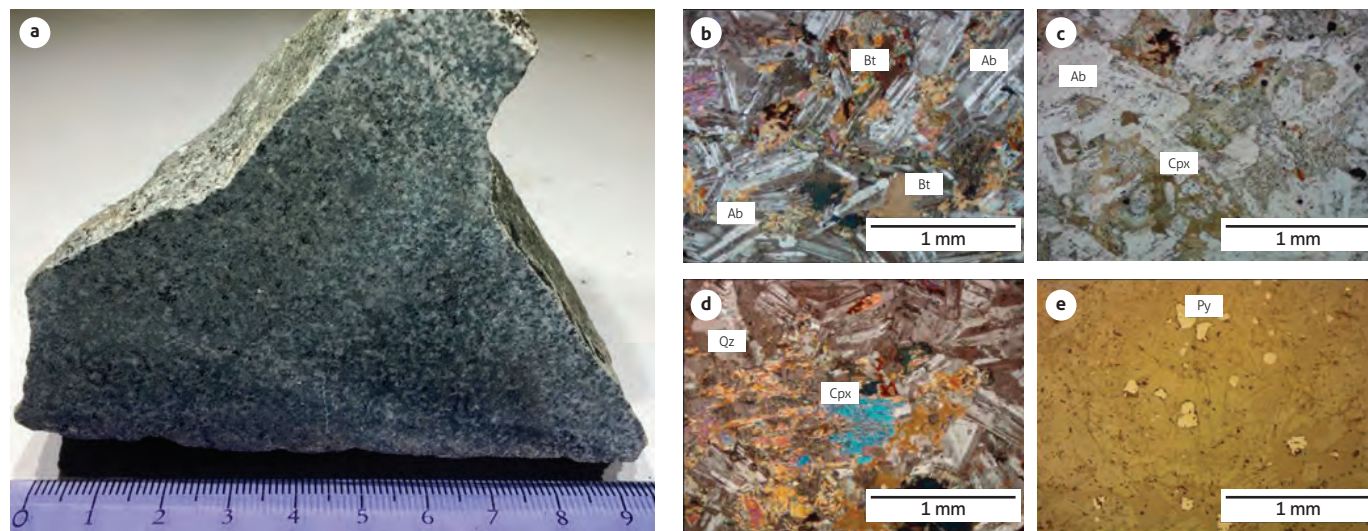

Figure 12. Morrogacho diorite of sample from the La Cascada mineralized structure
a) Hand-sample. b-c-d) Fine-grained holocrystalline diorite constituted by plagioclase of the andesine series, clinopyroxene and biotite. e) Disseminate pyrite crystals in diorite. Bt: Biotite, Pg: Plagioclase, Cpx: Clinopyroxene, Py: Pyrite, Qz: Quartz.
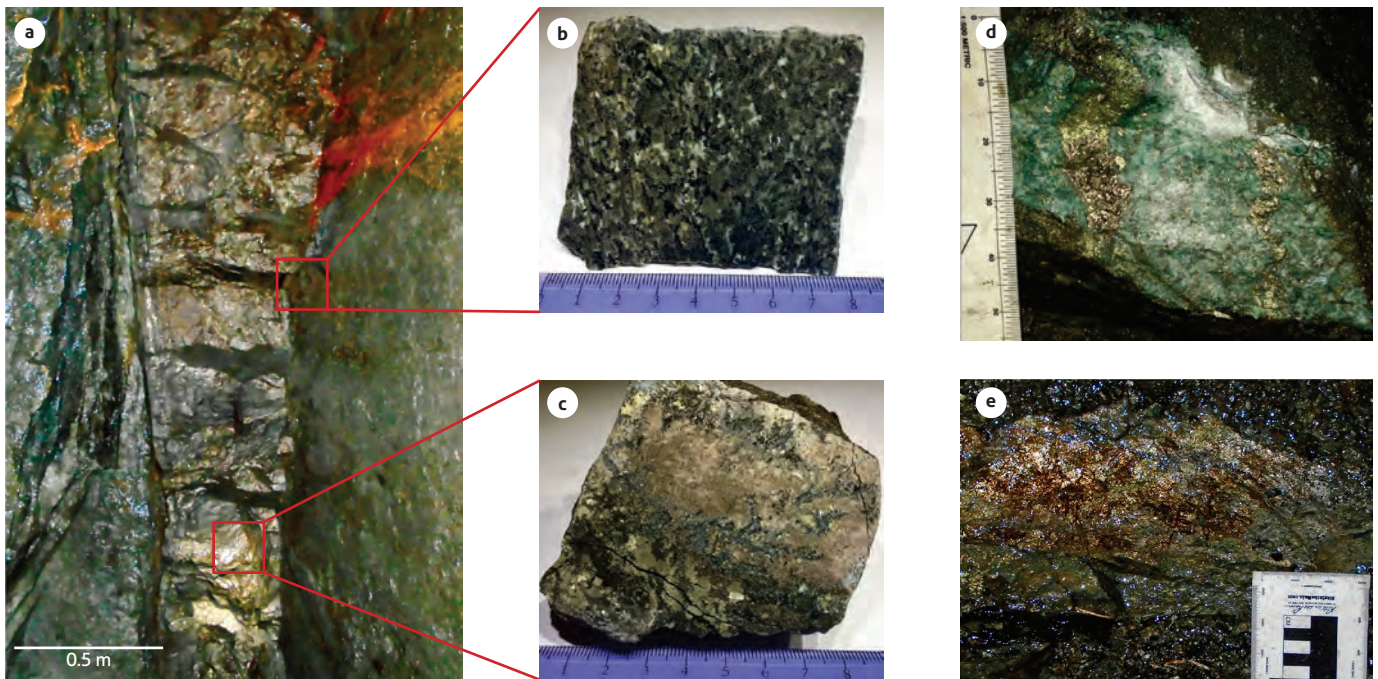
Figure 13. Tajo Abierto mineralized structure
a) Extension veins proximal to the ore shoot with a high content of sulfides. b-c) Hand samples of the mineralized areas with high contents of sulfides. d-e) Chloritic hydrothermal alteration.

(Figure 14 a, b). Gold grains occur mainly as crystals approximately 0.1 mm in size, placed in the rims of brecciated pyrite and associated with pyrrhotite, chalcopyrite, bismuth minerals, tellurides, and silver sulfosalts, such as cuboargirite (Figure 14). Pyrrhotite is the most common sulfide in the second stage. The presence of cubic galena with characteristic triangular pits growing after pyrite is common, and sphalerite seems to be present in a second stage of mineralization and related to gold.

5.1.2.2 La Cascada mineralized structure
The La Cascada mineralized structure includes a series of tunnels near the waterfall of Santa Teresa Creek in the area of Popales inside the dioritic stock (Figure 11). Behind the waterfall is an important NE-striking subvertically S-dipping vein system. The mineralization consists of multiple arrays of sheeted quartz-extension veins and veinlets that are mainly E- and NW-striking with very thin strings of veinlets with different orientations orthogonal between the main trends (Figure 15). It likely developed during the filling of a structural horse tail system because 0.2-m ENE-tabular quartz extension veins appear to join all the zones of planar-sheeted vein arrays with a NW-striking direction.

Quartz veins are a few centimeters thick and hosted in the NW-shoulder zone of the Morrogacho dioritic body, which occurs as a mafic phaneritic fine-grained intrusion. The vein geometry consists of a dense network of tens of subparallel arrays of planar-sheeted milky quartz veinlets and tabular extension veinlets developed inside the dioritic pluton forming massive swarms within a several-meter corridor.

Strong chloritic alteration affects the greenish matrix of the intrusives near the sheeted veins and within the intrusion for tens of centimeters. Quartz occurs in druses and cavities exhibiting the orientation of the extension when growing from the vein margins, and pyrite appears as euhedral cubic crystals representing the most common mineral after chalcopyrite. Vein spacing occurs as a dense array that reaches 6 to 10 veins per meter and suggesting it contains high gold grades (Hart, 2007). Although dissemination is not widespread, mild sulfide dissemination occurs a few centimeters around the veins. Near the mineralized structure, narrow-sheeted quartz veinlets are commonly developed along all outcrops of the intrusive rocks, meaning that mineralization of the sheeting quartz veins is widespread throughout this area.
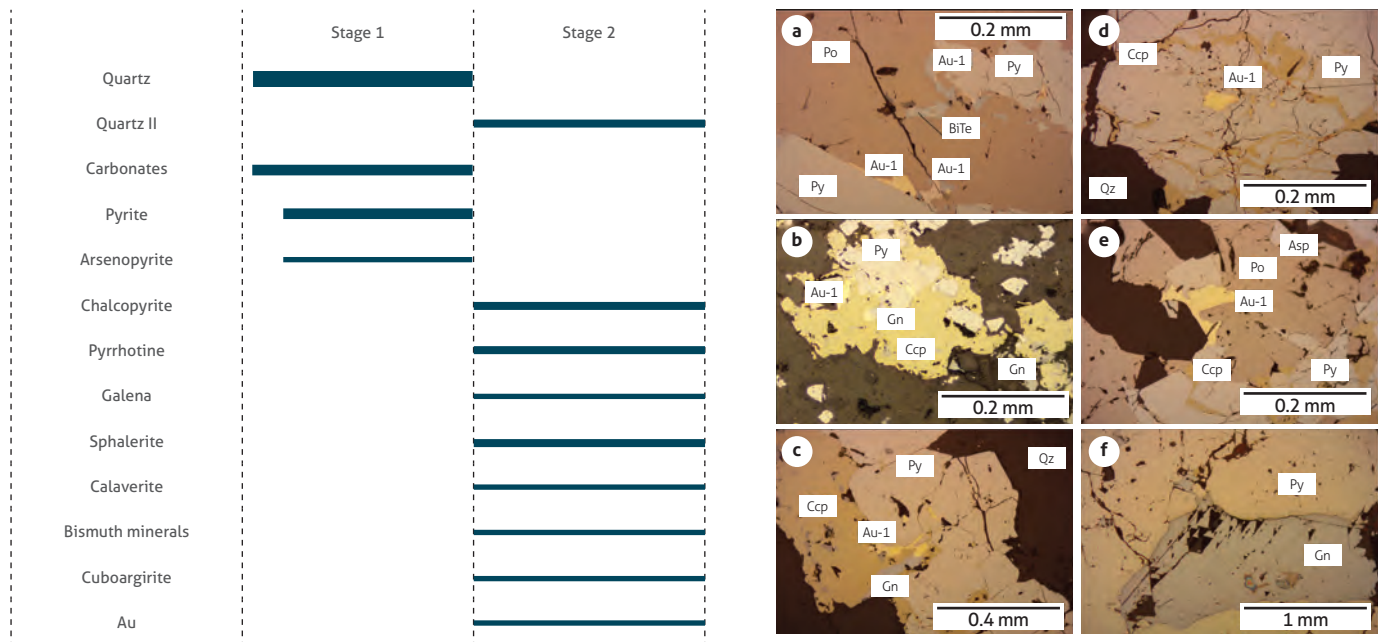
Figure 14. Paragenesis of the Tajo Abierto mineralized structure
a, c, e) Gold crystals associated with BiTe in the rim of brecciated pyrite. b) Gold crystals associated with chalcopyrite and galena. d) Gold crystals associated with chalcopyrite within brecciated previous pyrite. f) Triangular pits in galena next to pyrite crystal. Py: Pyrite, Ccp: Chalcopyrite, Gn: Galena, Asp: Arsenopyrite, Po: Pyrrhotite, BiTe: Bismuth and Tellurium minerals. Au: Gold.

The gangue mineralogy of La Cascada is mainly characterized by quartz. The ore mineralogy includes pyrite and chalcopyrite, which grow after pyrite crystals; sphalerite, which occurs principally after pyrite in minor quantities; and cubic galena is present as small grains growing after chalcopyrite. Samples from this sector do not contain visible gold grains. Important dissemination of the sulfides also occurs as continuous patches from the borders of veins. Propylitic alteration is identified by the strong presence of chlorite staining next to the borders of the veins with the presence of carbonates and sericite in minor quantities. This alteration assemblage suggests replacements of mafic minerals (augite) with chlorite and plagioclase with carbonate and sericite replacements.

5.1.2.3 Media Cuesta and Pizarro mineralized structures
To the north of the Morrogacho stock, several gold mineralizations can be observed in the Media Cuesta and Pizarro areas, which represent a distal expression of mineralizing fluids related to cooling history of the Morrogacho stock (Figure 16) and are associated with satellite bodies of leucocratic pyroxene-bearing fine-grained diorite dykes found in the Media Cuesta area. These mineralizations have different characteristics from those hosted within the intrusive rocks. Vein mineralizations occur mainly hosted in N- to NW-striking vertically dipping, fine-grained siltstone and sandstone sequences of the Urrao member. Gold fault veins and shear veins have dominant N- and NW-striking directions and are steeply E-dipping. These structures are coincident with the right-lateral sense of movement.

Mineralization in the Media Cuesta and Pizarro areas exhibits important fault vein characteristics, with a few centimeters in width in the El Duque mine (Media Cuesta) and up to 0.5-2 m in width in the La Petaca and Pizarro mines. Veins commonly exhibit pyrrhotite dissemination and mild brecciation of the host rock. The gold content in the area is associated with fractures within sulfides involving mineralogy with pyrrhotite, pyrite, arsenopyrite and galena in quartz gangue. The fault vein N- and NW-striking directions coincide with the N-striking, steeply E-dipping stratigraphic planes, a condition that apparently favors vertical shear vein development in the area.

5.1.3 La Horqueta
The La Horqueta stock corresponds to a prominent mountain with an altitude of more than 3600 m associated with a semicircular kilometer-wide intrusion (Figure 17). Mining activities
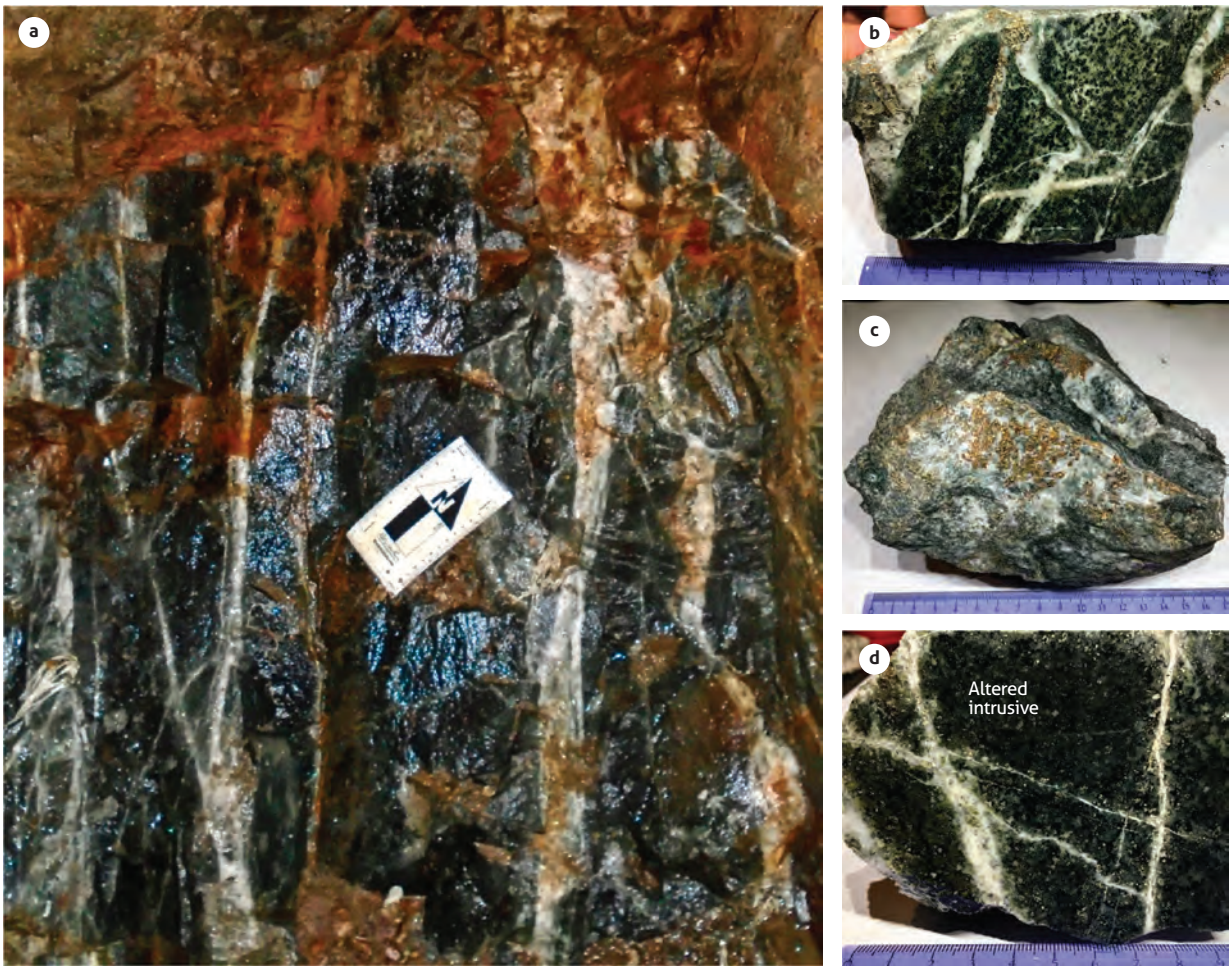
Figure 15. La Cascada mineralized structure
a) Sheeted quartz veins. b-d) Altered intrusions cut by quartz veins with stockwork assemblages. c) Host rock cut by quartz veins with a high content of sulfides.
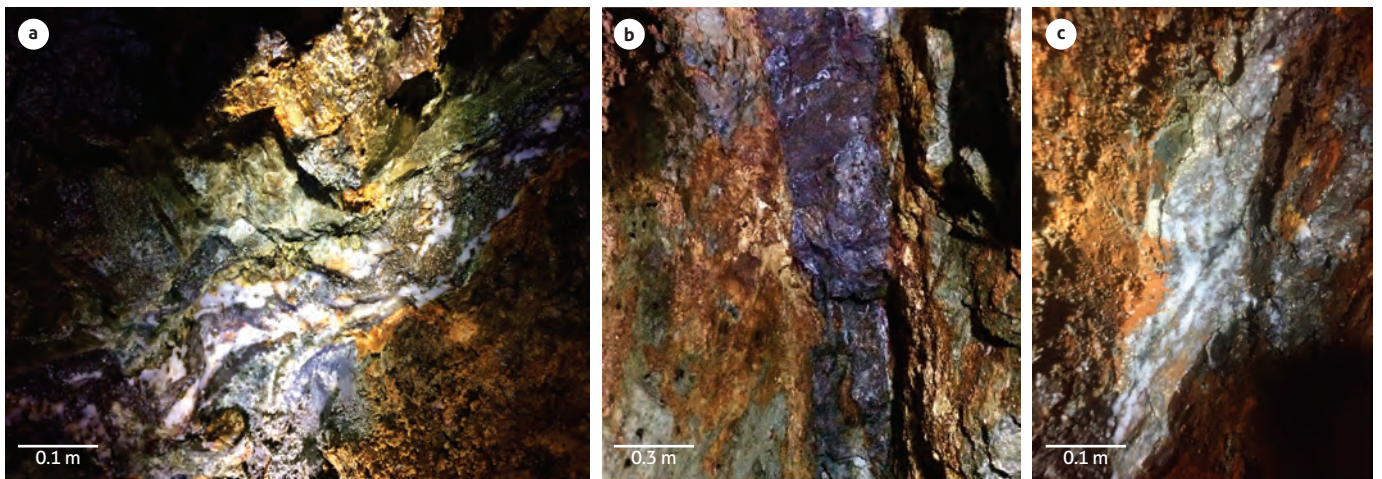

Figure 16. Mineralizing fluids related to cooling of Morrogacho stock
a-b-c) Subordinated N-NW structures in the Pizarro-Media Cuesta area. a-c) Quartz veins and veinlets with sulfide content and local brecciation of the host rock.
b) Hydrothermally altered host rock cut by veins with pyrrhotite content.
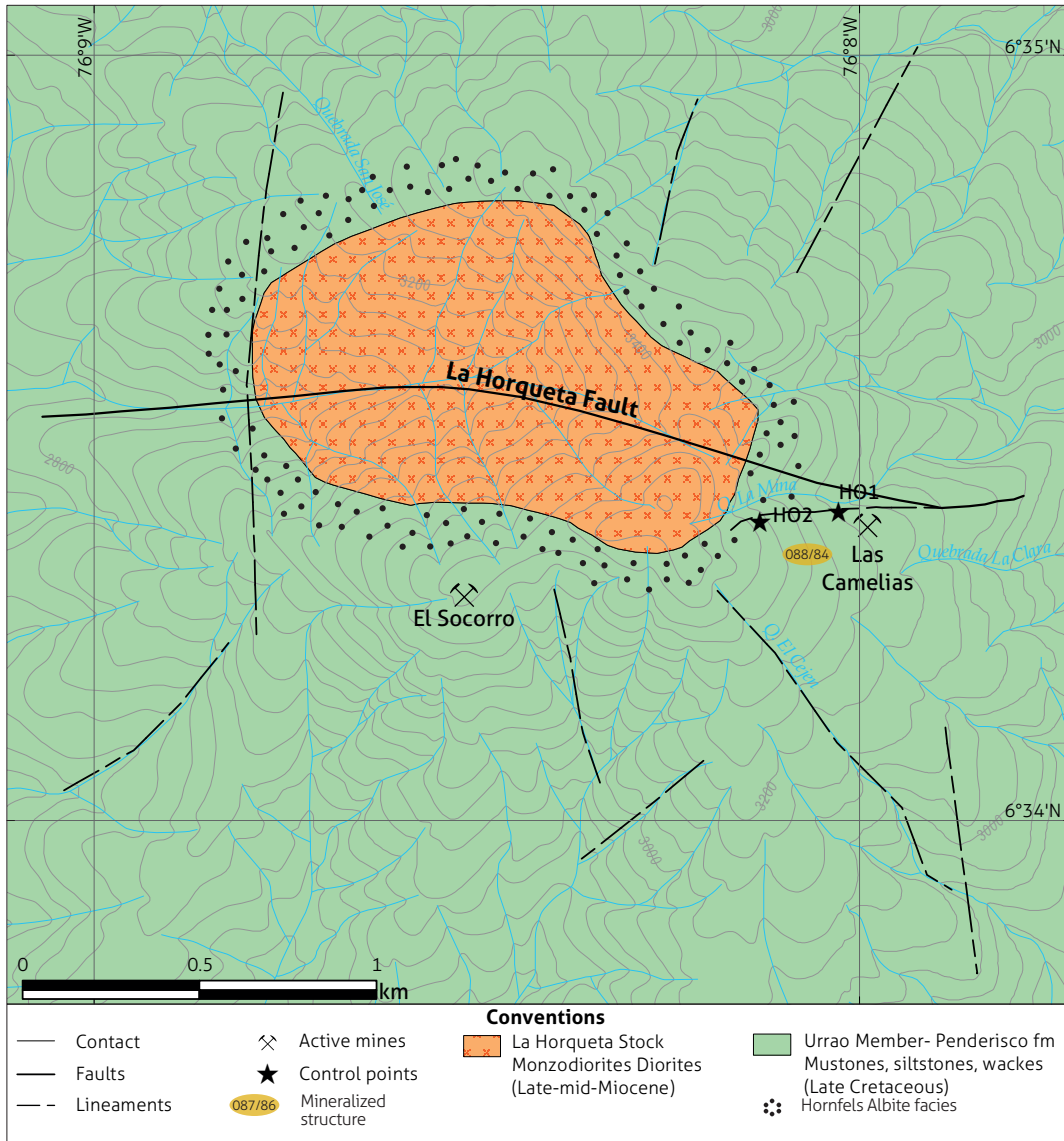
Figure 17. Geological map of the La Horqueta stock with the main mineralized structures
Modified from González and Londoño (2002).

in the pluton are located mainly in the surrounding contact aureole, mineralizations are related to a corridor formed by the La Horqueta Fault inside the plutonic body. The present information is described according to the characteristics of mineralized structures found in the Las Camelias mine, which is a historically productive mine in the Abriaquí area located in the contact aureole of the pluton.

Near the La Horqueta stock, the Urrao sedimentary sequence reflects high tectonic activity, which is evident due to the presence of folds and minor faults. Important exhumation

was inferred because of altitude and the prominence of the igneous body since the stock was formed in the late to mid-Miocene. Steeply slope-resistant cliffs of hornfels units as roof zones on top, combined with the steeply dipping E-striking La Horqueta fault, have created an irregular V-shaped peak that gives this mountain its name. This fault exhibits characteristics associated with the cooling and emplacement history of the intrusive and lately associated with the formation of a mineralized corridor that generated hydrothermal veins and faults in the area.
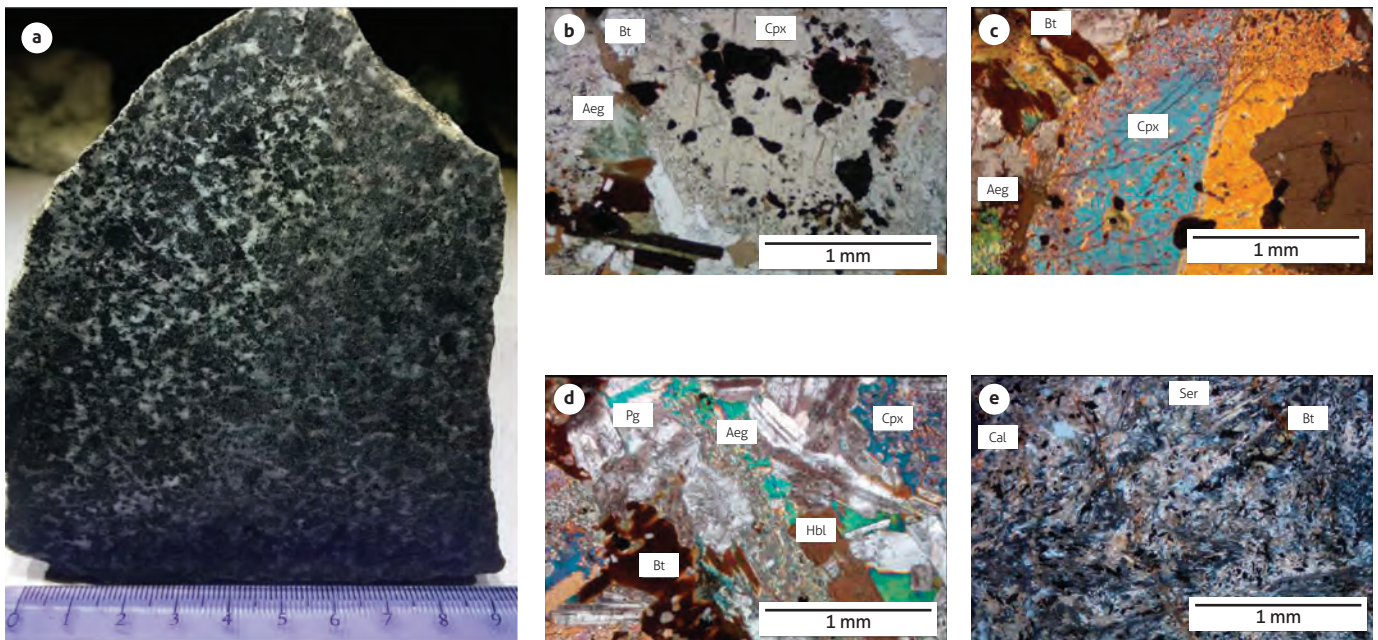
Figure 18. La Horqueta diorite at Las Camelias mineralized structure
a) Hand-sample. b) Presence of opaque minerals as inclusions in the pyroxene crystals. c) Twinned clinopyroxene. d) Plagioclase, hornblende and clinopyroxene crystals. e) Hydrothermal alteration in the presence of sericite and carbonate. Pg: Plagioclase, Aeg: Aegirine, Cpx: Clinopyroxene, Bt: Biotite, Hbl: Hornblende, Ser: Sericite, Cal: Carbonate.

The La Horqueta stock is a phaneritic, intermediate composition pluton with holocrystalline texture and coarse- to medium-sized grains, and it is classified as a diorite with a high content of pyroxene. The pluton is represented by a single intrusive phase that is composed of plagioclase of the andesine series (60%), clinopyroxene of augite-aegirine type (22%), biotite (13%) orthopyroxene (5%), and fewer amounts of k-feldspar, quartz and hornblende (Figure 18). Coarse-grained biotite could be found to be mainly related to hydrothermal processes in addition to sericite and carbonates (Figure 18e). Opaque minerals occur as disseminated pyrite and magnetite constituting up to 10% of the samples locally and are mainly associated with pyroxene crystals (Figure 18b). Some pyroxene crystals show skeletal texture. The emplacement of the stock generated a thermal aureole (Figure 17) that created a zone of hornfels with chlorite-albite facies at least 1 km wide, and country rocks are mainly E-striking with vertical dips and represented by fine-grained siltstone and mudstone strata of the Urrao member.

5.1.3.1 Las Camelias mine
Mineralized structures in the Las Camelias mine are located east of La Horqueta stock, near a fault structure with an E-striking steeply dipping to the S-strike. Mineralization consists of a trend of at least Three subparallel vertically S-dipping veins with E-trending strikes of at least 300 m. Veins are narrow, with thicknesses of approximately 0.1 m-0.2 m and rarely wider. Spacing between the subparallel veins varies from 5 m-20 m (Figure 19). Vein infilling occurs mainly along joints and shear planes with evidence of kinetic movement due to the presence of slickensides with steps along the vein margins that indicate E-right-lateral movement. Mineralization exhibits coarse sulfides and is mainly hosted in hornfels of the contact aureole; nonetheless, principal veins show continuity into the pluton, where the width decreases with no deflection in the strike.

Associated with the shear veins, it is possible to observe local zones that develop a proximate halo of chlorite alteration, with minor carbonate and sericite. In some parts of the mine, a thin late-stage barren quartz veinlet with oxidized pyrite and malachite cuts the dioritic pluton and mineralization. Open space filling textures appear in the veins as drusical cavities with coarse sulfides and oriented pyramidal quartz crystals.

Mineralization consists of quartz and calcite as gangue. The first stage permits crystallization of pyrite and arsenopyrite, which is later remobilized in the second stage of mineralization.
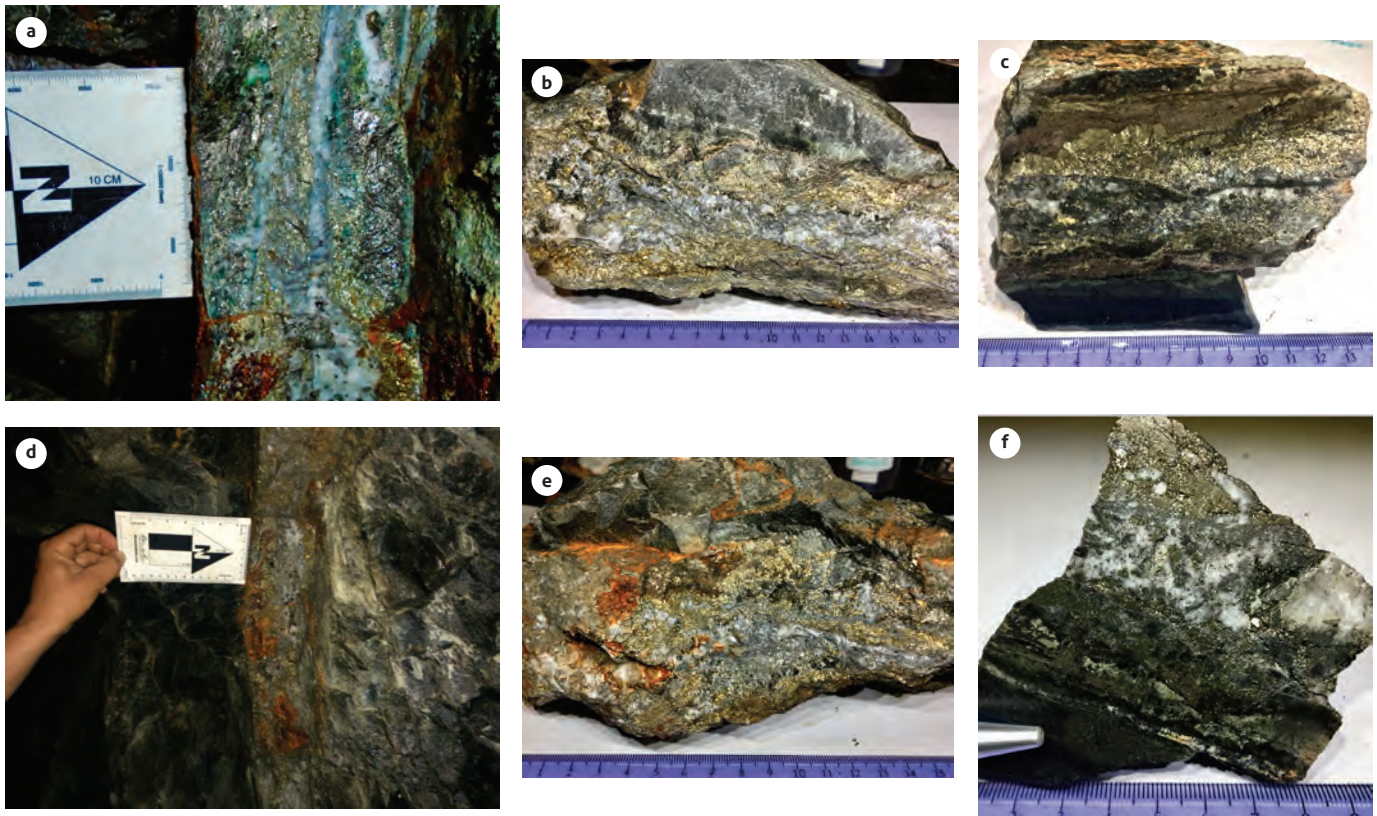
Figure 19. Las Camelias mineralized structure. Subparallel veins with the presence of pyrite, chalcopyrite, arsenopyrite, sphalerite and galena. Host rock corresponds to hornfels with mudstone protolite
a and d) Late quartz-pyrite veins. b-c-e-f) Hand samples of mineralized country rocks and veins with high contents of sulfides and chloritic alteration.
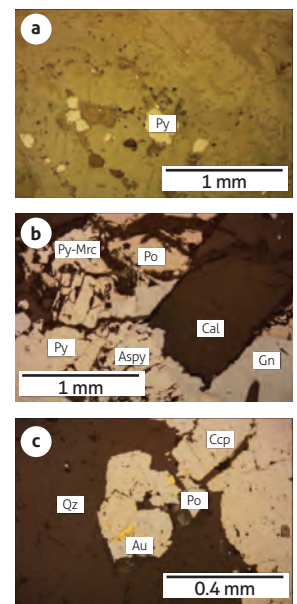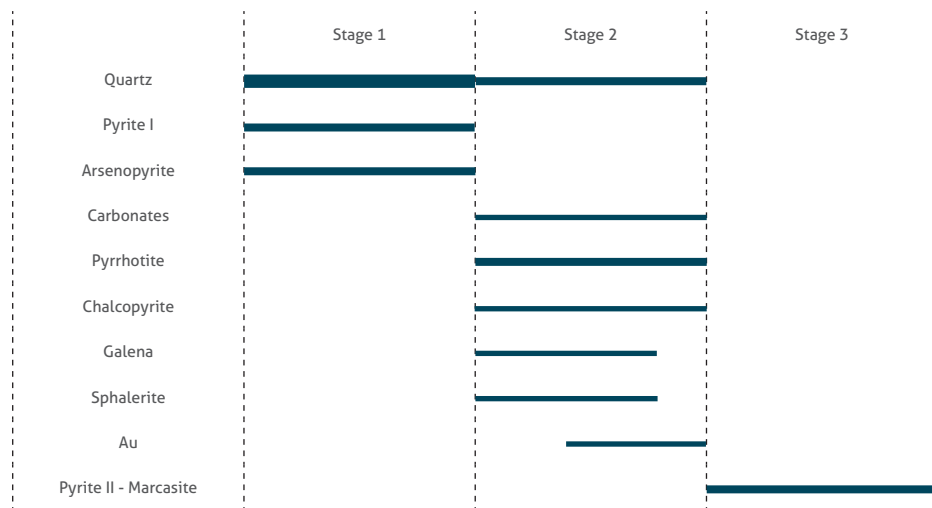

Figure 20. Paragenesis of the Las Camelias mineralized structure
a) Disseminated pyrite content. b) Pyrrhotite and galena with carbonate. c) Gold related to pyrrhotite event. Py: Pyrite, Mrc: Marcasite, Gn: Galena, Aspy: Arsenopyrite, Ccp: Chalcopyrite, Po: Pyrrhotite, Qz: Quartz, Cal: Carbonate, Au: Gold.

This second stage is a compound pyrrhotite and chalcopyrite assemblage with the posterior crystallization of sphalerite and galena, with high contents of carbonates and quartz. Gold grains present sizes of 0.1 mm and are related to pyrrhotite inside brecciated crystals or near their rims (Figure 20). At the final stage of mineralization, pyrrhotite is replaced by pyrite and marcasite. Pyrrhotite is the most common mineral in the ore. The sulfide content averages 10% but can reach up to 80%, with massive pyrrhotite and chalcopyrite crystals concentrated towards the borders of the veins, and no dissemination or very poor brecciation occurs in Las Camelias.

5.2 Mineral chemistry of ore minerals

Mineral chemistry analyses were carried out to analyze the mineral content, composition of the sulfide and gold grain signature and fineness in mines belonging from each of the intrusive centers of the El Cerro Igneous Complex: Tajo Abierto (Morrogacho polyphase stock), Las Camelias (La Horqueta stock) and El Apique (Cerro Frontino polyphase stock) mineralized structures. The results of the gold chemistry plotted in a ternary diagram indicate three families of electrum based on the spectra of the gold grains (Figure 21):
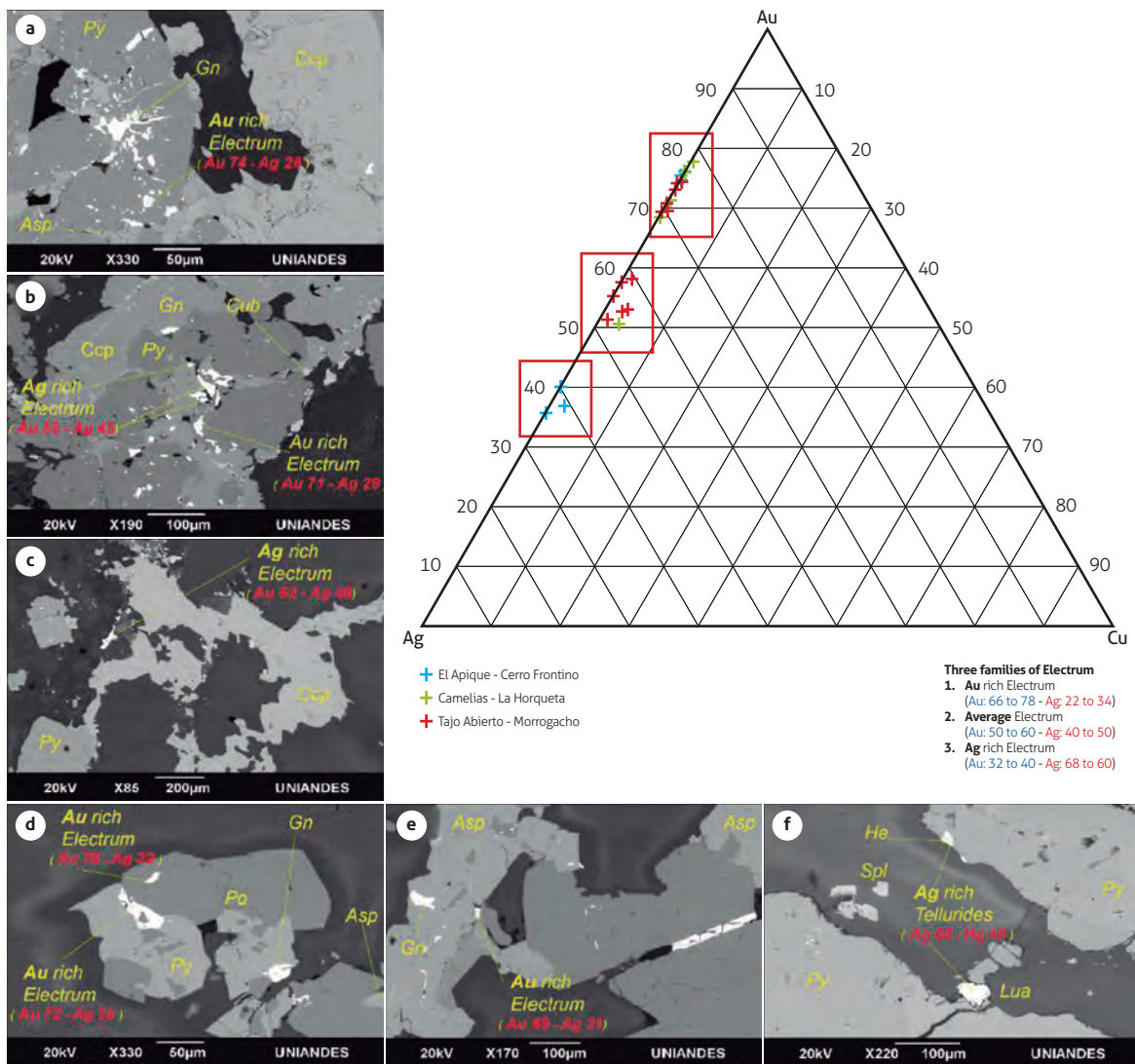

Figure 21. Ternary plot for calculating the gold signature from the Au-Ag-Cu ratio using SEM compositions
Notice the three different families of electrum and tellurides that exist in the area. a-b-c) Tajo Abierto Mineralized structure. d-e) Las Camelias mineralized structure. f) El Apique mineralized structure. Py: Pyrite, Po: Pyrrhotite, Asp: Arsenopyrite, Gn: Galena, Ccp: Chalcopyrite, He: Hessite, Cub: Cuboargirite, Spl: Sphalerite.

» Gold-rich electrum: electrum grains with 66%-78% Au and 22%-34% Ag with sizes ranging from 15 μm to 100 μm. These grains occur in borders of arsenopyrite, chalcopyrite and pyrrhotite crystals and in paragenesis with galena along fractures. Samples of all the mineralized structures present grains of this family, but these are mainly related to Las Camelias and Tajo Abierto mineralized structures.

» Average electrum: electrum grains with 50%-60% Au and 50%-40% Ag. These grains are found in Las Camelias and Tajo Abierto mineralized structures but are mainly related to second.

» Silver-rich electrum: electrum grains with 32%-40% Au and 68%-60% Ag with sizes ranging from 10 μm to 70 μm. These grains are located in the borders of chalcopyrite crystals. The El Apique mineralized structure is the only one with this family of silver-rich electrum grains, which occur as mercury alloys and silver tellurides.

According to the SEM results, vein-type gold fineness in the district ranges between 50% and 80%. The average size of gold grains is between 20 μm and 100 μm; the minimum size is approximately 10 μm; and the maximum size can reach hundreds of micrometers in the form of visible gold. These coarse-grained gold specimens are commonly found in the northern El Cerro Frontino stock at the San Diego-La Cuadrazón and El Apique mines and in the high-grade gold structures of the Morrogacho-Popales area. Gold grains are commonly found as electrum associated with the rims of grains (or within) in chalcopyrite, pyrrhotite, galena, arsenopyrite, native gold grains and silver tellurides, close sulfosalts and

mercury-gold-silver alloys, specimens that include cuboargirite, imeterite, stützite, petzite, luangeite, hessite and calaverite, with consistent Bi, Te and Sb contents. Gold is mainly refractory, hosted within sulfides and rarely present as free grains in quartz or carbonates; conversely, it is found filling fractures within sulfides, with tabular, semicircular and elongated shapes and occasionally with a circular shape.

6. DISCUSSION

6.1 Geochemical comparison, Frontino-Morrogacho arc and Middle Cauca Belt (MCB)

After the emplacement of the El Cerro Igneous Complex intrusive suite, Frontino arc magmatism ended and plutonism shifted eastwards, where arc migration was associated with the genesis of the Middle Cauca Belt (MCB) (Leal-Mejía et al., 2019; Shaw et al., 2019). In the present study, we present a geochemical comparison between both arcs according to lithogeochemical data of the intrusions in the El Cerro Igneous Complex, presented in the Cordillera Occidental project of the Servicio Geológico Colombiano (Rodríguez and Zapata, 2012; Rodríguez-García and Bermúdez-Cordero, 2015) (Annex 1), and lithogeochemical data from MCB intrusions: Buriticá andesite and La Colosa cluster (Gil-Rodríguez, 2010; Lesage et al., 2013) (Annexes 2 and 3).

According to the alumina saturation index (Shand, 1943), the El Cerro Igneous Complex intrusive suite corresponds to the metaluminous series (Figure 22a), which is consistent with the mineralogy of the intrusives. The elemental behavior of the El Cerro Igneous Complex intrusions exhibits a shoshonitic
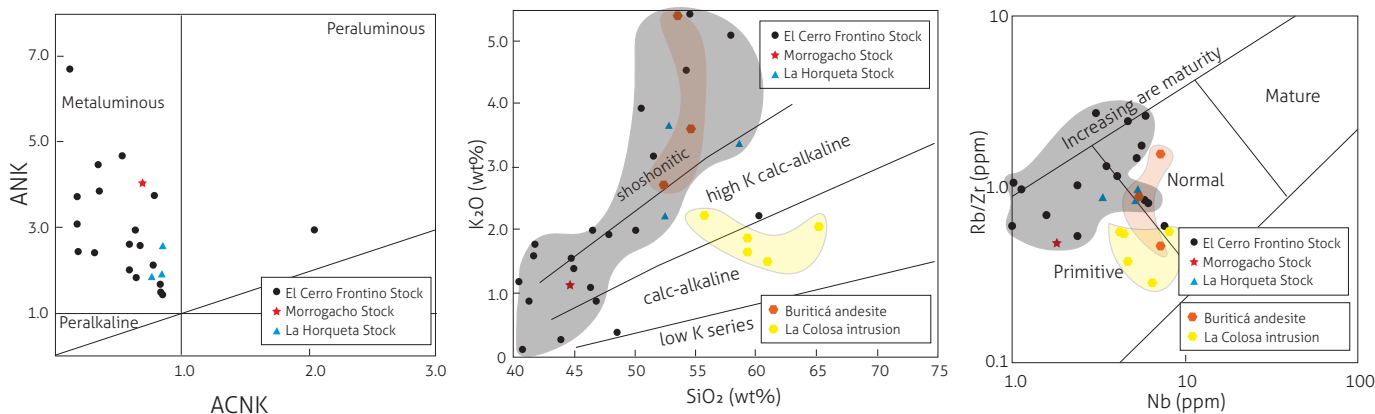

Figure 22. a) Alumina saturation index after Shand (1943). b) Relationship between SiO$_2$ and K$_2$O content-Peccerillo and Taylor (1976). c) Arc maturity discrimination diagram after (Brown, 1984)
Geochemical data from Gil-Rodríguez (2010); Rodríguez and Zapata (2012); Lesage et al. (2013), and Rodríguez-García and Bermúdez-Cordero (2015).

to high-K calc-alkaline geochemical signature, which marks a high content of K in the parental magma, which is evident locally by the high content of biotite (Figure 22b). Furthermore, detailed petrographic studies show late magmatic K metasomatism along the Cerro Frontino intrusive, which can also be associated with K enrichment. This alteration is reflected in the replacement of augite and diopside by hornblende and euhedral Fe-rich biotite (Escobar and Tejada, 1992; Shaw et al., 2019), with alteration haloes along the veinlet margins marked by the coarsening of biotite and by calc-silicate mineral assemblage. Late hydrothermal effects include local replacement of biotite by chlorite and epidote (Escobar and Tejada, 1992; Shaw et al., 2019). Similarly, Buriticá andesite plots in the shoshonitic series with a sample close to the high-K calc-alkaline series, which is related to an increase in K- content due to potassic hydrothermal alteration (Lesage et al., 2013)Colombia. It is hosted by the late Miocene Buriticá andesite porphyry, a shallow-level pluton dated at 7.41 ± 0.40 Ma (2σ, MSWD = 2.30; 40Ar/39Ar on hornblende. The porphyry intrusion of the La Colosa deposit shows a decrease in K_2O content in comparison to Buriticá and El Cerro Igneous Complex suite intrusions (Figure 22b). Maturity discrimination diagrams display Rb/Zr and Nb compositions related to a primitive to mature arc that is associated with the presence of an initial stage of plutonism in the volcanic arc formed after the Baudó terrane collision (Figure 22c).

Multielemental trace element composition diagrams were used to compare Frontino arc intrusions with some porphyry intrusive samples of the early, intermediate and late units of the La Colosa deposit presented by Gil-Rodríguez (2010) and por-

phyritic intrusions of the Buriticá Andesite. REE normalized diagrams show a great similarity between the middle Cauca belt and El Cerro Igneous Complex, in certain patterns (Figure 23a). There is enrichment in LREEs with respect to HREEs, which is shown in the decreasing slope with generally flat HREE values, indicating enrichment in LREEs and fractionation of the intrusion that is consistent with the fertile intrusive bodies in both arcs, as expected (Figure 23b). The plotted REE data show that these magmatic arcs were formed as a response to a main tectonic event of Baudó terrain accretion, as they share general REE characteristics. Conversely, spider diagrams show a clear impoverishment, with negative anomalies of Ba, Rb, Th, U, Zr, Nb and Ta in the El Cerro Igneous complex in comparison to the Middle Cauca Belt intrusive suites. These discrepancies could be related to the more evolved composition in the magmatic arc environment, with possible crustal contamination higher in the middle Cauca Belt due to U, Th, and Pb anomalies.

In this way, the El Cerro Igneous Complex in relation to the MCB is a less developed and undifferentiated magmatic arc that formed from a more mafic and impoverished source with less crustal contamination (negative Th, U, Zr, Nb and Ta anomalies). Frontino arc magmatism preceded the formation of the Middle Cauca Belt for at least 3 Ma, when the axis of the magmatic arc migrated eastwards towards the Romeral shear zone. Although the general geochemical signatures of both arcs are similar, the El Cerro Igneous Complex intrusions have formed in a postcollisional extensional regime with different slab conditions than those associated with the MCB (Leal-Mejía et al., 2019; Shaw et al., 2019).
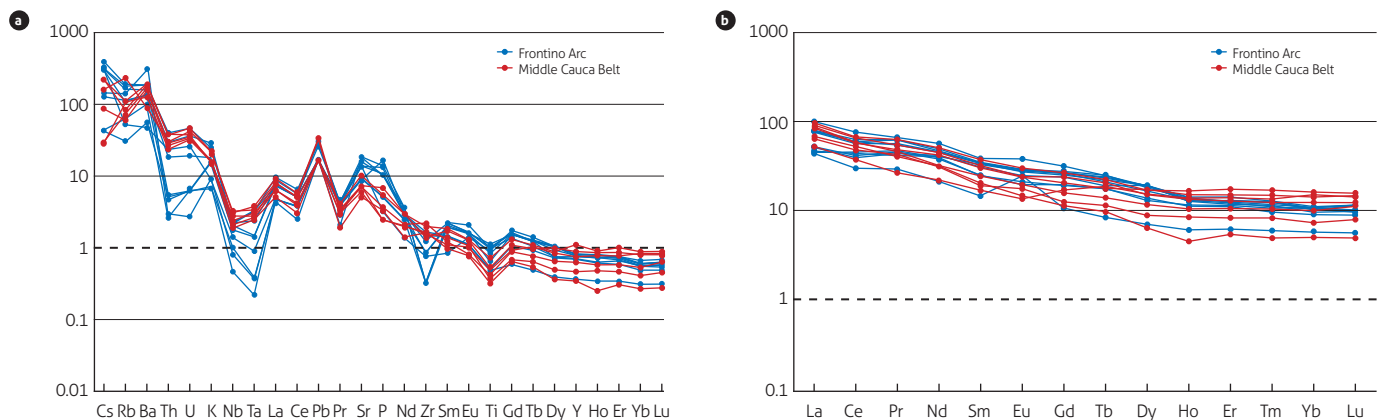

Figure 23. Spider and rare earth element (REE) discrimination diagrams normalized to N-MORB and chondrite, respectively (Sun and McDonough, 1989) Geochemical information from Rodríguez-García and Bermúdez-Cordero (2015); Rodríguez and Zapata (2012); Lesage et al. (2013) and Gil-Rodríguez (2010).

6.2 Metallogenic characteristics and deposit classification

Mineralizations in the El Cerro Igneous Complex are present as a series of shear-related veins, subparallel planar-sheeted quartz extension veins, and quartz-carbonate tabular-shaped extension veins spanning from a few centimeters to several meters in width. The metallic signature consists of Au + Ag + Cu + Zn + Pb + As (± Te ± Bi ± Sb ± Hg ± W) assemblages. Mineralization occurs as breccias in shear zones with important sulfide contents, massive milky quartz extension veins filling fractures as arrays, and rarely as stockworks. The mineralogy consists of quartz and calcite as gangue with pyrrhotite, pyrite, chalcopyrite, Fe-rich sphalerite, galena and arsenopyrite, and it includes more than two mineralization stages. General features of the mineralogy indicate common assemblages; however, mineralization in the El Cerro igneous complex corresponds to fine- to coarse-grained gold and electrum grains.

The most common hydrothermal alteration is chloritization proximate to the back of the veins in discrete selvages. Additionally, there are high quantities of sericite, carbonate, pyrite, and illite and a replacement of coarser biotite by chlorite and rare epidote in the margin of the veins. Extension veins are hosted in the intrusives and fault-shear veins in the country rocks. The contact aureole of the intrusives developed albite-chlorite-pyroxene-hornblende hornfels. The alteration of the distal sector in the thermal aureole occurs as interstitial silica dominant-grain recrystallization of the sedimentary country rocks. The presence of skarn mineralizations in the El Cerro Frontino stock with high tungsten concentrations has been described in the La Loaiza area (Molina and Molina, 1984; Escobar and Tejada, 1992). Dikes and breccias with low sulfide and gold contents occur along the El Cerro Frontino stock related to differentiation processes during intrusion.

Mineralized structures of the Frontino-Morrogacho district have preferential E-strikes, dominant subvertical (60°-90°) to rarely subhorizontal (20°-50°) S-dipping angles, and secondary N- and NW-striking, steeply to vertically E-dipping structures in the Media Cuesta-Pizarro area. Subhorizontal structures allowed the fluid percolation of the subvertical structures in zones such as El Apique, and the E-striking vertical and subvertical dip of the stratigraphic bedding in the country rocks allows it, which is coincident with the trend of mineralization and should contribute to the formation of debility planes along the strata. The presence of these structures corresponds to the main fractures and alignments of the intrusives in the El Cerro Igneous Complex, which are related to pre-syn-mineral structural processes associated with the cooling of the plutons. There is a consistent similarity in the vein and fault orientations over the complex with a general E-strike for extension veining and ENE-, N- and NW-strikes in oblique fault and shear-related veins, indicating E-W shortening at the time of mineralization (Figure 24).

Sheeted and tabular auriferous extension veins in the complex show no displacement, with unstrained orthogonally growing pyramidal quartz crystals in the vein borders indicating a position of the minimum principal stress σ_3 with a subhorizontal broadly N-S extension orientation (Stephens et al., 2004). Intermediate σ_2 and maximum σ_1 are broadly E-W oriented with vertical orientations, which coincides with thinned zones of the intrusions. Veins do not have any evident deflection across the pluton-country rock transition, showing consistent stress trajectories. Consequently, the emplacement and crystallization of the stocks occurred at the time of vein formation. A ductile-brittle transition in the formation of the veins is evidenced by tensile failure in the bulk rock resulting in the formation of σ_1 parallel to E-striking extension veins and orthogonal to pure σ_3 extension (Sibson, 1992). N- and NW-trending fault veins are thought to be misoriented with respect to σ_1 and are likely developed related to N-S regional trending structures that formed pre- or early synmagmatic. However, increased fluid pressure after plutonic suite boiling could generate re-failure episodes of the N- and NW-structures found in Pizarro and Media Cuesta (Figure 25).

Plutons were emplaced during the collision of the Baudó terrane and record less oxidized and more alkaline signatures than those found in the intrusions of the Middle Cauca Belt in a deeper epizonal environment. According to the mineralogical and structural characteristics, the Frontino-Morrogacho gold district could be classified as an intrusion-related gold system (IRGS) (Lang and Baker, 2001; Hart, 2007). Intrusives associated with IRGs are emplaced in an extensional postcollisional regime in the form of isolated, cylindrical-shaped and elongated plutons that reflect structural controls during emplacement (Mair et al., 2006; Hart, 2007). Hydrothermal processes in the systems are related to the cooling history of the plutons with exsolved fluids circulating near a brittle cupola-carapace in the roofs of plutons, allowing the fluid to focus in the apex, such as in the Tajo Abierto Mine. At the El Cerro Igneous Complex, intrusions occur as cylindrical-shaped isolated stocks with steep sides and domed or cupola-like roofs where fluid focusing is

enhanced due to the pluton geometry (Hart, 2007). Furthermore, sharp shoulders in igneous bodies are related to structural and rheological contrast that enhances the development of fluid focusing structures (Stephens et al., 2004).

The presence of carbonates and pyrrhotite in the mineralization and chlorite-sericite-carbonate-pyrite alteration assemblages in discrete margins of the veins indicates a considerably reduced fluid with neutral to alkaline pH and high CO_2 con-
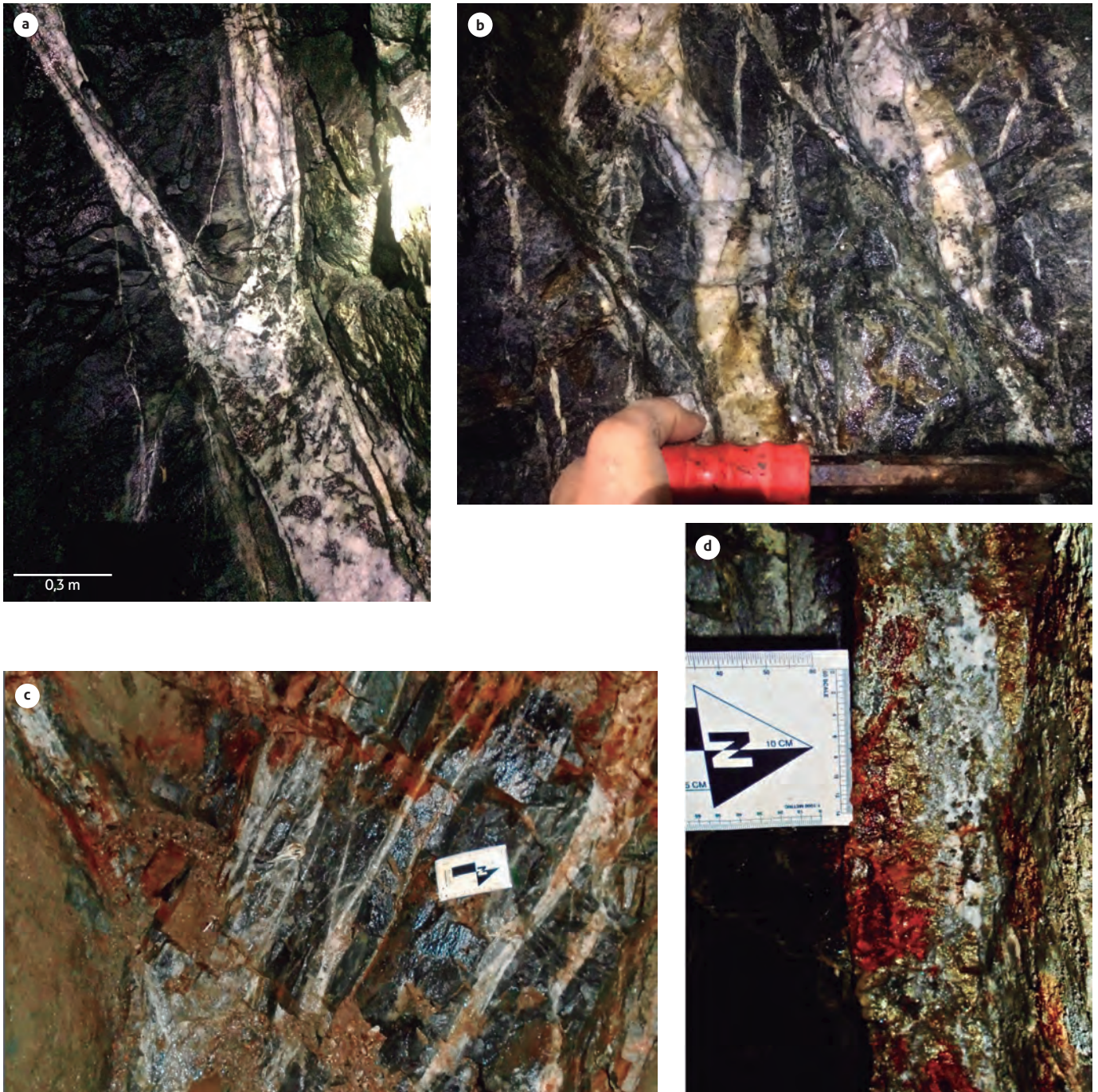

Figure 24. Principal arrangements of high-grade gold veins in the Frontino-Morrogacho gold district
a) Extensional vein bifurcation in Los Hoyos mine. b) Nest of veins and veinlets in Los Hoyos mine. c) Multimeter-wide horse-tail splay of sheeted veins in Morrogacho-Popales. d). Massive sulfide vein hosted in hornfels in La Horqueta.
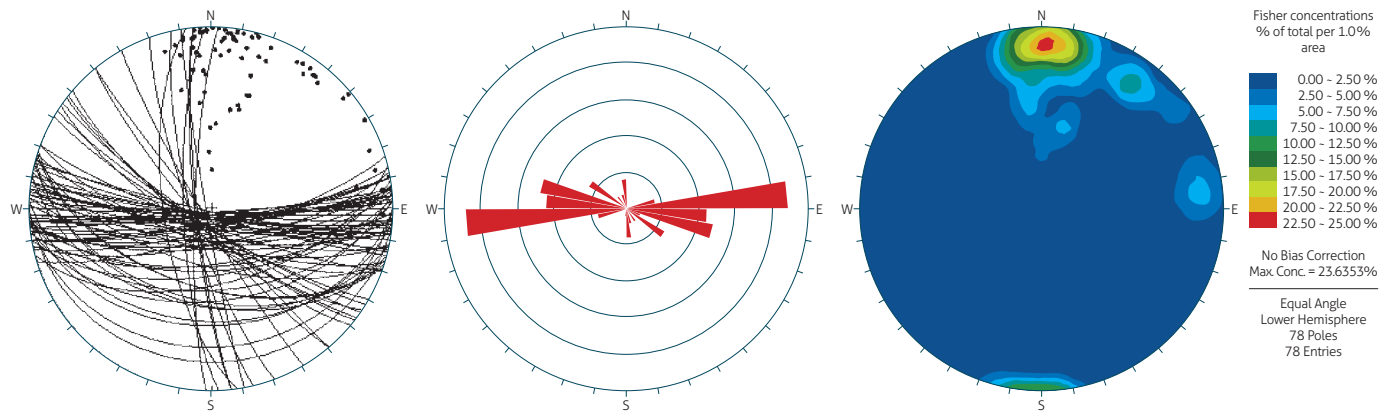
Figure 25. Main structural characteristics for the mineralized structures of Frontino-Morrogacho gold district, according to the structural attitude of 78 mineralized veins. Horsetail with main structural orientations of the veins

tent, in which Au(HS)$_2$ was probably the ligand and transport media (Mikucki, 1998; Goldfarb et al., 2004). The metal assemblage shows the presence of gold with As, Te and Bi with general low- to high-grade gold and sulfide contents less than 10% on average. The gold-silver ratio is variable from 10:1 and 1:1.

Concentric metal zoning was found as Au-Cu ± Bi ± Te extensional sheeted veins in the center and shoulders of the intrusions, As-Au assemblages mainly in the contact aureole, and Au-Ag-Pb-Zn mineralizations in peripheral-distal fault vein structures, such as those observed in the El Mocho mine, peripherally located in the Morrogacho stock. In this way, the Frontino-Morrogacho district shows some characteristics related to the reduced (ilmenite-series) intrusion-related gold systems, although it is associated with magnetite-bearing plutons with magmatic pyrite, indicating oxidizing conditions of the redox state (Ishihara, 1981; Hart, 2007).
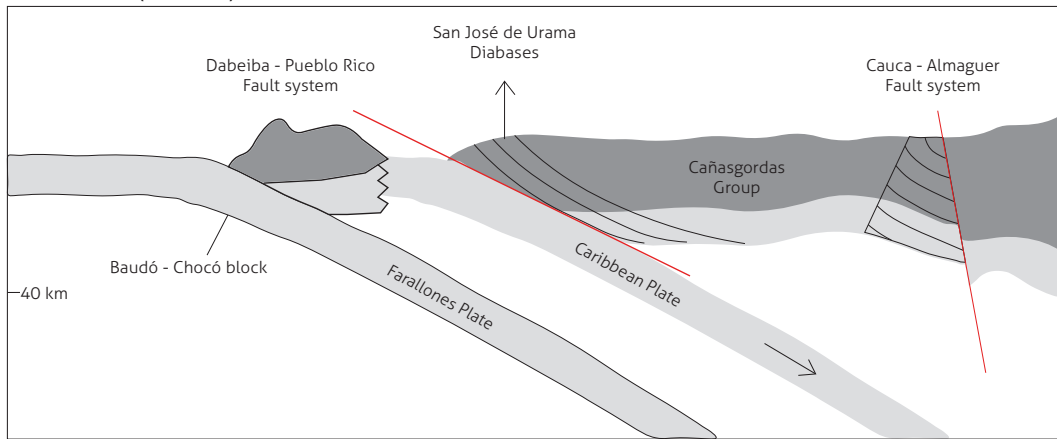
6.3 Evolution of the El Cerro Igneous Complex
The magmatic and tectonic evolution of the El Cerro Igneous Complex is associated with late- to mid-Miocene erratic subduction-related magmatism due to the approximation of the Baudó terrane at 11-12 Ma (Maya, 1992; Cediel and Shaw, 2003). This complex is part of calc-alkaline to shoshonitic geochemical series plutons (Rodríguez and Zapata, 2012), with intermediate to mafic compositions, high pyroxene contents and the presence of secondary biotite as a product of potassic metasomatism. The high-K content of the intrusives is related to a late magmatic K-metasomatism event associated with the cooling of the pluton (Escobar and Tejada, 1992; Shaw et al., 2019), which is considered to be premineralization due to

the textural relationship shown in veins and veinlets in the El Cerro Frontino gabbro. Cerro Frontino and Morrogacho stocks show different intrusion phases that are overprinted. At least two phases of the El Cerro Frontino stock are described in the present study: a mafic initial gabbroic pulse with high pyroxene content and a later dioritic pulse, both hosting mineralized structures. The Morrogacho stock is related to different intermediate- to felsic intrusions with local dioritic dikes and satellite bodies that host mineralized structures, such as Media Cuesta. The presence of these igneous phaneritic bodies represents part of the deepest mid- to late-Miocene magmatic arc, with elevated morphologies due to the high rates of exhumation and erosion that took place since the late Miocene (Villagómez and Spikings, 2013).

The tectonic setting of the El Cerro Igneous Complex emplacement is related to the subduction of the young and hot Nazca Plate during the beginning of the flattening of the slab below the South American Plate in the mid- to late Miocene (Pennington, 1981; Hardy, 1991; van der Hilst and Mann, 1994; Gutscher et al., 2000a). In this setting, the initial volcanism stages presented a calc-alkaline affinity with a later increase in alkalis related to slab melting due to the steepness of the subducted slab (Barberi et al., 1974; Gutscher et al., 2000b). Oblique convergence of the Baudó terrane during the accretion gave place to rotation and fragmentation with uplift and faulting during the stabilization of the arc in a local postcollisional extensional regime (Karig, 1974), in which the El Cerro Igneous Complex plutons were emplaced (Figure 26). The posterior evolution of the arc allowed the enrichment of the intrusions where several alteration and mineralization proces-
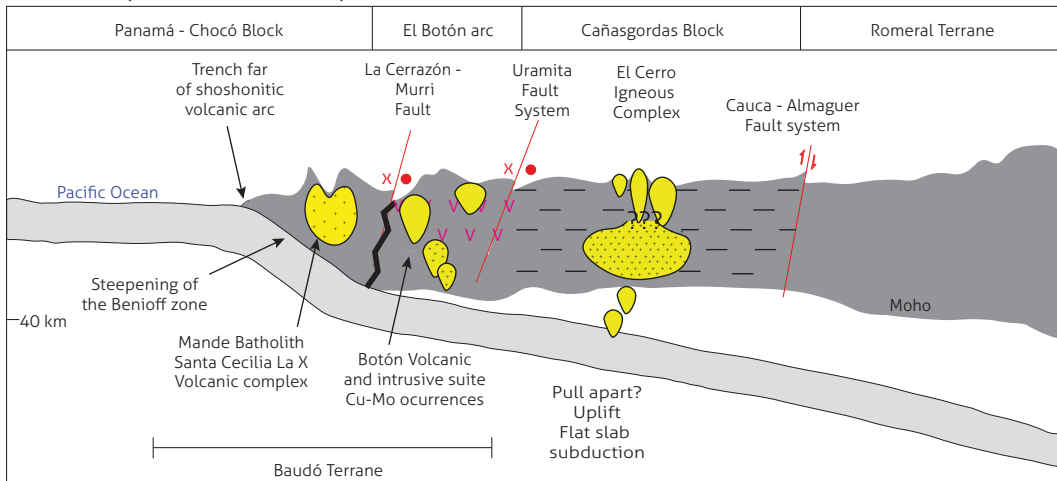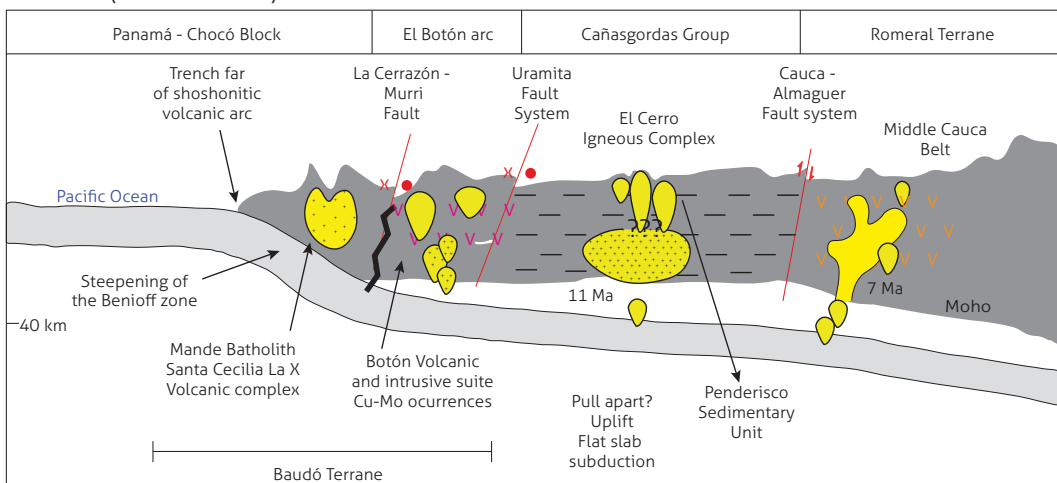
Figure 26. Regional tectonic evolution during the emplacement of the late- to mid-Miocene plutons, and 9-13 Ma emplacement of the El Cerro Igneous Complex with an unknown main magma source

ses occurred and genesis of the Frontino-Morrogacho district took place.

7. Conclusions

The magmatic and structural features of the Frontino-Morrogacho gold district allow us to classify it as an intrusion-related gold system (IRGS), which is spatially associated with the presence of the late- to mid-Miocene El Cerro Igneous Complex. Petrographic, mineral chemistry and field studies suggest the presence of concentric metal zoning in the district with a general Au + Ag + Cu + Zn + Pb + As (± Te ± Bi ± Sb ± Hg ± W) metallic assemblage. The mineralized structures are dominantly E- and steeply S-dipping, with reactivated N- and NW-striking structures in the form of extension veins, shear veins and fault veins and with the presence of extensional duplex and horse tails in broad mineralized zones.

The Frontino-Morrogacho district is an underexplored metallogenic area of late- to mid-Miocene age that holds great potential for the exploration of gold-silver deposits. Corresponding to an independent arc episode that marks the existence of an individual metallogenic belt spreading for at least 300 km, from the south of Chocó Province to the north of Antioquia Province. The presence of multiple unroofed and roofed plutonic suites hosting gold, silver and copper mineralization is commonly observed in the vicinities of the Frontino-Morrogacho gold district in rocks of similar age and characteristics. This type of mineralization is observed in extensional sheeted vein zones in the apex of the San Juan stock, fault veins containing gold-base metal sulfides in shear and breccias peripheral to the Páramo Frontino stock and Cu-Au-Ag porphyry style mineralization associated with intrusive phases of the Carauta stock (Arrubla and Silva-Sánchez, 2019). In the genesis of the Frontino-Morrogacho gold district, there is probably a key role associated with the redox state during the enrichment of Au-Ag in volatile phase separation to produce economic concentrations during the crystallization of the magmas.

The gold content in the Frontino-Morrogacho district is similar in several of the mineralized structures; hence, gold identified in three different families is mainly associated with the presence of pyrrhotite, chalcopyrite, tellurides and alloys with a high presence of Bi and Sb. The first family is characterized by Au-rich electrum with gold contents varying from 66 to 78 Au % wt, the second family presents average electrum with gold contents varying from 50 to 60 Au % wt, and the third family is characterized by Ag-rich electrum and tellurides with gold contents varying from 32 to 40 Au % wt.

An important magmatic relationship exists between the Middle Cauca Belt and the Frontino Arc/Frontino-Morrogacho gold district. Frontino Arc was formed in a low-angle postcollisional environment as a precursor of posterior middle Cauca belt magmatism. In this way, the Frontino-Morrogacho magmatic event is related to an initial stage of plutonism that migrated to the east after the El Cerro Igneous Complex Intrusive event ended at an uncertain age, with magmatic genesis initiating afterwards in a sector of the Middle Cauca Belt. Subsequently, the mineral assemblages and mineralization styles are quite different due to the differences between the geochemical signature of the plutons and the geodynamical setting of both arcs.

Further studies concerning fluid chemistry should include detailed microthermometry and Raman spectroscopy of fluid inclusions to determine the temperature and pressure of the fluid associated with the different events of mineralization. In this way, the fluid salinity and sulfur compositions in the magmatic fluids can be determined. Zircon U/Pb, molybdenite Re-Os, Sm/Nd, and sericite-muscovite Ar-Ar geochronological data analyses will be useful to find the absolute timing relationship between plutonism and mineralization, with Pb, S, H and O isotopic data to determine the source of the mineralization fluids. Stable isotopic oxygen analyses will assist in constraining the magmatic and country rock continuum to establish a possible interaction between fluid phases. Finally, combined pluton thermal metamorphic, pluton crystallization and mineralization ages should aid in identifying the evolution of the mineral process and identifying new targets.

Supplementary Data

Supplementary data for this article can be found online at https://doi.org/10.32685/0120-1425/bol.geol.48.1.2021.500

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