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The Choco 10 gold deposit (El Callao, Bolivar State, Venezuela): Petrography, geochemistry and U-Pb geochronology

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ABSTRACT

Located in the El Callao Mining District (Bolivar State), Choco 10 is one of the most important gold deposits in Venezuela. The deposit occurs in the greenstone belt of the Pastora Supergroup, a lithostratigraphic Province of the South American Guyana Shield. The Choco 10 lithostratigraphy is composed of two different formations. The lower El Callao Formation is composed of a Metabasalt Unit, mostly made of tholeiitic basalts, overlain by a Mafic Volcano-Sedimentary Unit, which represents its primary cover. The tholeiitic rocks show a flat, unfractionated REE pattern which is typical of greenstone belt basalts worldwide; the incompatible elements and REE distributions suggest a mid-ocean ridge or back-arc basin setting. Within the tholeiitic series, a transition to more evolved terms is suggested by the occurrence of rocks of andesitic composition mostly in the upper part of the same formation. The overlying Felsic Volcano-Sedimentary Unit, probably pertaining to the Cicapra Formation, is a relatively heterogeneous rock series largely composed of volcanioclastic rocks deriving from an acidic calc-alkaline source, as confirmed by the geochemical data. SHRIMP analyses on zircons from these rocks show consistent magmatic ages of 2143 ± 6 to 2145 ± 5 Ma. This unit contains a gabbroic sill-like body (Metagabbro Unit), composed of medium-grained amphibole gabbro, which yields an age (2142 ± 2 Ma) that is indistinguishable from that of the main body. Both formations are affected by a greenschist-facies metamorphic overprint and different deformation phases. At 2117 ± 3 Ma, the formations have been intruded by a trondhjemite that displays fractionated REE and incompatible elements patterns typical of calc-alkaline rocks. Gold has been introduced into the rock sequence in different stages; the main mineralization is related to highly focused flow of $\mathrm{H_2O-CO_2}$, low salinity fluids to give quartz + ankerite ± albite ± pyrite veins, surrounded by strong sericite + carbonate + pyrite + quartz alteration. Gold concentrations are controlled by both structural setting and fluid-rock interaction processes. The gold metallogeny at El Callao is related to the world-scale metallogenic event of Paleoproterozoic age, which is responsible of important orogenic gold ores formation in the once adjacent Amazonian and West Africa cratons. Even in absence of direct dating of the hydrothermal phases, our precise geochronological dating – together with the geological and petrographic data – constrains the onset of deformation (i.e., the beginning of the Trans-Amazonian deformation) and the subsequent main mineralization phase to the time span comprised between 2142-2144 Ma (age of gabbro and calc-alkaline tuffs) and 2117 Ma (emplacement of the trondhjemite). On a regional scale these data suggest eastward younging of deformation and mineralization within the context of the Trans-Amazonian tectonism.
1. Introduction

The El Callao Gold Mining District is the most prolific gold producing area in Venezuela, with an average of 6 million oz of gold over the last 150 years. The richest gold mines between 1870 and 1896 were El Callao and Chile mines that produced 1,500,000 and 440,000 oz of gold, respectively. Mostly starting from 1990, several mining companies carried out aggressive exploration efforts in the area, which led to the discovery of highly significant gold resources.

In spite of these discoveries, over the last decades, relatively few studies on the gold metallogeny of the district have been published; the most notable exceptions being Blanchet and Chauvet (2000), Hildebrand (2005), Ham et al. (2007) and Velásquez et al. (2011). The only geochronological study regarding the Pastora greenstone belt of Venezuela was instead performed by Day et al. (1995) on zircons of the felsic volcanic and subvolcanic rocks that yielded an age of 2131 ± 10 Ma.

The article presents new petrographic, geochemical and geochronological data obtained within the El Callao Gold Mining District. These data are discussed: i) to characterize the lithostratigraphic sequence of the area; ii) to evaluate the tectonic setting and possible source of these rocks; iii) to discuss about the relationships between the different hydrothermal veins crosscutting the rocks; iii) to consider the relationships between the gold mineralization and the pervasive hydrothermal alteration that affects the rocks. Throughout the article, we put our attention also on the emplacement ages of the main magmatic rocks and the relationships between these bodies and the gold metallogeny, in order to better understand the whole geological setting of this important gold-producing district.

2. Regional geological setting

The El Callao Gold Mining District is located in the Bolivar State (Venezuela), in the northern part of the Guyana Shield of South America (Fig. 1). The Guyana Shield consists of two major terranes, separated by the NE-SW trending Guri Fault (Sidder and Mendoza, 1995): the Imataca Complex, to the north, mainly composed of orogenic Archean terranes (~3.7-3.4 Ga; Montgomery, 1979), and the Paleoproterozoic sequences of the Granitoid-Greenstone Belts to the south. These latter comprise three geological provinces (Velásquez et al., 2011, with refs.): 1) the Pastora Province, a Trans-Amazonian Paleoproterozoic (~2.2-2.0 Ga; Gruau et al., 1985) granitoid-greenstone terranes; 2) the Cuchivero Province (~1.8–1.5 Ga; Mendoza, 2000); and 3) the Roraima Province (~1.7 Ga; Menéndez, 1994) (Fig. 2).

The El Callao Gold Mining District lies inside the Guasipati-El Callao Greenstone Belt (GCGB) hosted in the Pastora Province. The GCGB consists of volcanic, volcano-sedimentary and sedimentary formations intruded, during the Trans-Amazonian Orogeny (2.3-1.8 Ga), by granitoid plutons (Supamó Complex), diabases (Velásquez et al., 2011, with refs.) and minor gabbroic bodies (e.g., the “Laguna Dike”). Little is known about the lithostratigraphy of the GCGB, but mainly based on major-element data, Menéndez (1994) recognized, among the lower units, an important geochemical evolution of the Carichapo Group volcanics from komatiitic basalts (Cicapra Formation) trough Mg-rich (Florida Formation) and Fe-rich tholeiitic basalts (El Callao Formation). The same authors interpreted the GCGB series to comprise (from bottom to top): 1) the Carichapo Group; 2) the Yuruari Formation (2.13 Ga; U-Pb age, on zircon from dacites: Day et al., 1995); 3) the Caballape Formation, unconformably overlying the other formations (Figs. 3A1, 3A2).

3. The Choco 10 deposit

The Choco 10 gold deposit is located 15 km south-west of the El Callao village, about 200 km to the south of Ciudad Guayana. In this area aggressive exploration campaigns were
Figure 1. Regional geology of the northern Guyana Shield (modified after Voicu et al., 2001). The inset at left shows the areal extent of the Guyana and Guaporé Shields in South America and the probable position of the collision front tentatively correlated with the Grenvillian orogeny to the West. The rectangle shows the location of the El Callao Gold Mining District where the study area is located.

Figure 2. Geological provinces of the Guyana Craton, Venezuela (modified from Siddar and Mendoza, 1995; Velásquez et al., 2011).
Figure 3. A1) Geological setting of the El Callao Gold Mining District with the different prospects and mines (modified from Viljoen, 2000 and Shaw, 2003). Choco 10 and Choco 4 deposits are emphasized. A2) Lithostratigraphic sequence of the Guasipati-El Callao Greenstone Belt (Northern part) (modified from Menéndez, 1994; Shaw, 2003; Makepeace, 2010 and Velásquez et al., 2011). Symbols for A1 and A2: GA= metagabbro; EC= El Callao Formation; CR= Cicapra Formation; YU= Yuruari Formation; CA= Caballape Formation; SU= Supamo Complex granitoids; B) Simplified geological map of Rosika-Coacia-Pisolita-Villa Balazo-Karolina zones in the Choco 10 deposit (modified from Ham et al., 2007). C) Simplified geological cross-section (A-B trace on the previous Fig. 3B), showing the structural architecture of the sequence dominated by folds (modified from Makepeace, 2010). The Choco 10 deposit is located in a NE-plunging synclinal hinge zone.
carried out, initially mostly by Corporaciòn Venezolana de Guyana (CVG) and Promiven (1990-1996) and subsequently by Bolivar Gold Corp. and Gold Fields Ltd. (2002-2006). These exploration campaigns led to the discovery of important gold resources in the Choco 10 prospect, where four main ore zones - Coacia, Pisolita, Rosika and Villa Balazo-Karolina - were recognized (Fig. 3B). Open pit gold production started in March 2006 in the Pisolita, Coacia and Rosika deposits focused on the oxidized ore, the fresh rock being overlain by a 30 to 70 m thick saprolite caused by tropical weathering. Starting from the end of 2007 the deposit is owned by Rusoro Ltd. The data reported in this paper are based on field and, mostly, drill cores observations performed during the 2003-2006 exploration programs carried out at Choco 10 by Bolivar Gold Corp. and Gold Fields Ltd.; some data from the adjacent Choco 4 prospect are also included (Fig. 3A).

3.1. Lithostratigraphic and structural framework

Detailed core-logging shows that the Choco 10 property occurs within an ENE to E-trending supracrustal lithostratigraphy dominantly composed of the El Callao and Cicapra Formations, which are intruded by a gabbroic body and felsic plutonic bodies. Based on geological observations, the following lithostratigraphic sequence was reconstructed (from bottom to top):

1. **El Callao Formation**: deformed greenschist-facies basaltic flows including pillow metabasalt, occurring in the southern and western parts of Choco 10. This formation is intruded by a porphyritic trondhjemite body of the Supamo Complex and is overlain by the Cicapra Formation with a stratigraphic contact;

2. **Cicapra Formation**: fine to coarse grained layered volcanoclastic deposits and chaotic breccias. This formation crops out as a N-S to E-W trending band in the eastern portion of the area and is, in turn, overlain by a metamorphic gabbro body;

3. **Metagabbro**: this medium-grained metagabbro with greenschist-facies overprint passing to fine-grained, strongly sheared metagabbro at the base of the unit, occurs in the eastern sector of Choco 10.

From a structural point of view, Choco 10 is located in a NE-plunging synclinal hinge zone (Fig. 3C). Two main foliations have been recognized in the area: (i) a penetrative schistosity to slaty cleavage S1, mostly sub-parallel to bedding (S0), which represents the axial plane foliation of rarely preserved F1 folds; (ii) a NE striking, SE dipping crenulation cleavage S2, which is axial planar to northeast trending, northward asymmetric shallow to moderate plunging similar-type folds (Coughlin, 2005; Ham et al., 2007). A S3 NNE to N-S striking, steeply dipping crenulation cleavage occurs within discrete shear zones (these could be linked to the F3 deformatve event of Coughlin, 2005) where it rotates S2 (Ham et al., 2007). In addition, a rare post-F3 NW striking kink-like crenulation is also reported by Ham et al. (2007).

3.2. Petrography

Based on the petrographic study of over 200 thin-polished sections, we recognise a more detailed lithostratigraphic sequence at Choco 10, consisting of (from base to top): El Callao Formation, Cicapra Formation, Supamo Complex and a gabbroic body (Fig. 4).

**Metabasalt Unit (MBU)**, El Callao Formation. The MBU consists of pillow metabasalts, foliated metabasites and andesitic rocks. The pillow metabasalts (Fig. 5A) are characterized by a greenschist facies assemblage consisting of magnesiohornblende”/”actinolite” (Leake et al., 1997 p. 227-228) + epidote + albite + chlorite; quartz, magnetite, titanite ± rutile and ilmenite-(Ce) occur in minor amounts. Ilmenite is the only relic of the primary
assemblage. The outer pillow rim is variably enriched in chlorite, epidote, quartz, magnetite and titanite and locally also contains some pyroxene (diopside-hedenbergite s.s.) and garnet (grossular-andradite s.s.).

Along high-strain domains parallel to the regional foliation planes the pillow metabasalts are transformed into foliated metabasites. In these domains shearing is commonly accompanied by circulation of hydrothermal fluids and associated metasomatism: the typical foliated metabasite is composed of alternating, sub-millimetre thick chlorite + sericite + magnetite + rutile and quartz + albite + calcite ± ankerite layers, which could represent transposed veinlets (Fig. 5B). Where strong shearing occurs chlorite is locally overgrown by biotite.

The top of the unit is composed of volcanic clasts embedded by jasper cement (Figs. 5C, 5D). The clasts are composed of basalt and more leucocratic “andesitic rocks” showing microporphryritic texture consisting of elongated albitized plagioclase phenocrysts set in a very fine-grained groundmass of epidote + chlorite + magnetite ± hematite ± quartz ± pyrite (+ accessory monazite and xenotime-(Y)). Based on the mineralogy, petrography and geochemical composition we conclude that these rocks derived from a relatively evolved protolith.

_Mafic Volcano-Sedimentary Unit (MVSU), El Callao Formation._

The overlying MVSU includes volcanoclastic deposits and breccias with mafic composition, volcano-sedimentary mylonites rich in sericite and siliceous metasediments; its composition, and the lack of evident tectonic contacts, suggest that it represents the primary cover of the basaltic unit. The MVSU can be subdivided into three portions:

1) Lower part: sequence of pyroclastic rocks, including ash, crystal and lapilli tuffs (Fig. 5E). The ash tuffs are composed of micron-sized quartz, sericite (after plagioclase), chlorite, calcite and accessory rutile, monazite, pyrite and chalcopyrite. The crystal tuffs show a clast-supported texture characterized by coarse-grained, rounded albite and quartz within a quartz + calcite + albite + chlorite + sericite + rutile matrix (± zircon ± monazite ± chalcopyrite ± pyrite) matrix.

2) Central part: sericite-rich metavolcanosedimentary rocks commonly affected by a (syn-Df?) mylonitic deformation accompanied by strong fluid circulation. These rocks are in fact characterized by interbedded, millimetre-thick quartz + sericite + chlorite ± calcite ± magnetite and muscovite/sericite + rutile + magnetite or pyrite layers. Un-oriented tourmaline occurs as well.

3) Upper part: volcaniclastic rocks of mafic to intermediate composition. They include clast-to matrix-supported mafic breccias with chert and basaltic s.l. clasts embedded in a mafic matrix at the base, and rocks made of coarse-grained quartz, albite, magnetite and leucoxene clasts embedded in a chlorite + rutile + quartz ± calcite ± sericite ± epidote ± tourmaline ± chalcopyrite matrix at the top. The latter probably represent crystal tuffs of mafic to intermediate composition. These rocks are commonly strongly foliated along horizons of deformation, like due to intense hydrothermal fluids circulation.

**Felsic Volcano-Sedimentary Unit (FVSU), Cicapra Formation.**

The contact between the MGU and the FVSU is strongly sheared and characterized by high carbonate content attributed to hydrothermal fluid circulation. The FVSU, which was mostly studied in the Rosika area, can be subdivided into three portions:

1) Lower part: sequence of pyroclastic rocks, including ash, crystal and lapilli tuffs (Fig. 5E). The ash tuffs are composed of micron-sized quartz, sericite (after plagioclase), chlorite, calcite and accessory rutile, monazite, pyrite and chalcopyrite. The crystal tuffs show a clast-supported texture characterized by coarse-grained, rounded albite and quartz within a quartz + calcite + albite + chlorite + sericite + rutile matrix (± zircon ± monazite ± chalcopyrite ± pyrite) matrix. Albite and quartz show elongated shape and
**Figure 4.** Lithostratigraphic sequence and the crosscutting hydrothermal veins (with related alteration) present within the Choco 10 deposit based on geological, petrographic and geochronological studies (modified from Padoan, 2007 and Makepeace, 2010). A short petrographic description for the lithostratigraphy, the hydrothermal veins and the mineralized zones (gold-bearing veins and alteration pattern) is reported inside the tables.
can be oriented both parallel and at a low angle relative to the contact with the ash tuffs. The lapilli tuffs show a matrix-supported structure with rounded clasts of highly variable size that may be mono-mineralic quartz or altered albite or polymineralic (quartz + chlorite + magnetite ± rutile or chlorite + calcite ± muscovite ± albite intergrowths). The matrix is composed of quartz + chlorite + sericite ± rutile ± pyrite ± chalcopyrite ± epidote, with accessory apatite, zircon, monazite, barite and celestine. Inside the tuffs some “ignimbritic” crystal tuffs occur, characterized by clasts with star-like shape consisting of chlorite + quartz + sericite + rutile ± magnetite and quartz.

2) Central part: deformed pyroclastic rocks, characterized by alternating, micron-sized layers of quartz + calcite (± ankerite) + albite ± sericite ± pyrite and muscovite + chlorite + rutile. Coarse grained albite is partially or completely altered by sericite. Pyrite is rich in chalcopyrite, pyrrhotite, galena ± sphalerite, cobaltite and covellite inclusions and is surrounded by quartz ± chlorite ± muscovite and calcite strain fringes. Accessories include zircon, apatite and monazite. These rocks are interlayered with mafic volcaniclastic rocks composed of chlorite + rutile + quartz + magnetite + albite (altered by calcite ± sericite) and skeleton leucoxene clasts in a chlorite + calcite + quartz + magnetite + rutile + pyrite ± chalcopyrite ± pyrrhotite ± zircon matrix.

They pass upwards to microcrystalline, strongly altered volcano-sedimentary rocks composed of quartz + ankerite ± calcite + muscovite (overgrown by chlorite) + pyrite ± chalcopyrite + rutile, with accessory zircon and apatite.

3) Upper part: tabular hydrothermal breccia (up to 60 m -thick and at least 100 m -long) body composed of millimetre- to centimetre-sized angular, strongly altered clasts generally consisting of a granoblastic intergrowth of quartz ± ankerite ± rutile ± pyrite ± albite (Fig. 5F). Pyrite contains inclusions of chalcopyrite, galena, minor pyrrhotite and sphalerite; rare cobaltite and covellite and locally tellurides (mainly melonite, NiTe2). The breccia ranges from clast- to matrix-supported and the hydrothermal matrix consists of medium- to fine-grained quartz + albite + ankerite intergrowths.

**Metagabbro Unit (MGU)**

The FVSU is overlain by a metagabbro body (Fig. 5G), which ranges from coarse- to fine-grained (particularly at its borders) and is mostly composed of a metamorphic assemblage: magnesiohornblende/”actinolite” (Leake et al., 1997 p. 227-228) + albite + epidote + leucoxene + chlorite + zircon + pyrite + chalcopyrite. Primary graphic structures between plagioclase and quartz, cores of Fe-rich amphibole (ferrohornblende and/or ferro-edenite/edenite) are relics of the magmatic assemblage. Plagioclase is strongly albitized (An85) and altered pervasively by sericite and calcite. Within the undeformed metagabbro cm- to dm-thick mylonitic bands occur, particularly towards the lower contact. Approaching the contact the metagabbro becomes strongly sheared and amphibole is re-oriented parallel to the foliation and partially to totally replaced by chlorite; relict leucoxene crystals are plastically folded and fragmented. At the same time, a strong increase in carbonate, quartz, albite and sericite is observed. At the very contact with the underlying unit the rock is composed of strongly elongated domains of: a) chlorite intergrowths (after amphibole), b) leucoxene relics and c) quartz + carbonate + albite + sericite. Growth of very fine grained brownish biotite is also observed, in the chlorite-rich domains and in the outer portions of the quartz + carbonate + albite + sericite intergrowths.

**Trondhjemite Plutonic Body (TPB), Supamo Complex.**

The TPB is intruded in the MBU and its contact is sharp and crosscuts the foliation of the host metabasite. At the contact the
Figure 5. Macroscopic features of selected rock-types from Choco 10 (drill core samples). A) Outer rim of a pillow metabasalt (MBU, El Callao Formation). The inter-pillow matrix is mostly composed of calcite and magnetite. B) Quartz + ankerite + albite veins folded by the D2 deformation. Enrichments in pyrite (and gold) occur in the strongly bleached and sheared metabasite host. C) Mafic breccia composed of basaltic clasts embedded in a jasper matrix (MVSU, El Callao Formation). D) Strong pyrite (and gold) enrichments at the contact between quartz + ankerite + albite ± pyrite veinlets and red jasper at top of the MBU (El Callao Formation). E) Finely interbedded ash and crystal tuffs in the FVSU (Cicapra Formation). F) Matrix-supported hydrothermal breccia in the FVSU (Cicapra Formation). Dark spots are pyrite enrichments. G) Medium-grained isotropic metagabbro (MGU). H) Basaltic xenolith enclosed in a very fine-grained trondhjemite. The xenolith is foliated and bleached, due to a strong sericite + ankerite + quartz + pyrite alteration.
metamorphic overprint produces white mica overgrowing albite. The plutonic body is strongly leucocratic (content of mafic minerals <10%) and shows a porphyritic to locally fine-grained equigranular texture composed of plagioclase (altered in sericite ± calcite) and quartz phenocrysts embedded in a very fine-grained albite + quartz + sericite/muscovite + carbonate groundmass. Locally quartz and albite of the groundmass form a micrographic texture. In the central part of the plutonic body, the oscillatory zoned plagioclase is oligoclase in the core (An$_{16-20}$) and albite (An$_{10}$) in the outer rim. Mafic phases are represented by rare biotite, almost completely replaced by chlorite + rutile + magnetite + epidote and, during a later alteration stage, also by muscovite. In the upper part of the trondhjemite body, the plagioclase is albite and the primary biotite is replaced by muscovite + rutile + magnetite ± carbonate. Accessory phases are given by ilmenite (mostly replaced by rutile), magnetite, apatite, barite, monazite-(Ce) and zircon. Scanty pyrite, chalcopyrite and galena disseminations are related to quartz – albite – ankerite veinlets.

The trondhjemite body is not affected by any metamorphic overprint and post-dates the first deformation phase(s), as shown by the occurrence of foliated metabasite xenoliths (Fig. 5H). The only evidence of deformation is represented by cataclastic planes, commonly filled with oriented quartz and albite and surrounded by abundant sericite and fine-grained quartz.

3.2.1. Metamorphic overprint

As described above, evidences of a low-grade metamorphic overprint are widespread, though irregularly distributed in the rock sequence. Particularly in the MBU, a greenschist-facies overprinting still enables the recognition of primary textures. This metamorphic overprint predates the main deformation phases and, taking into account the geodynamic setting, is probably related to an ocean-floor alteration. This latter event was followed by at least two phases of deformation documented both within the MBU and in the overlying sequence; greenschist-facies metamorphic minerals (particularly, chlorite and albite) grew along the S$_1$ foliation. The occurrence of these phases in strongly foliated domains, within and also well above the MBU, is related to a regional metamorphism post-dating the ocean-floor alteration.

Geothermobarometry of amphibole-bearing assemblages in the metabasite of the MBU (following the method of Okamoto and Toriumi, 2001; 2004) suggests conditions of very low P (<1 to 2 kbar) and T = 370-500°C ) for the oceanic alteration (Padoan, 2007). For the MGU, geothermobarometry on the magmatic amphibole gives P-T emplacement estimates of around 2 kbar and 750-800°C (adopting the calibrations of Helz, 1973 and Anderson and Smith, 1995); the geothermobarometer of Okamoto and Toriumi (2001; 2004) on metamorphic amphiboles yields P - T conditions ranging from 2-3 kbar, 400-500°C (magnesiohornblende) and 0.6-2 kbar, 370-410°C (“actinolite”, Leake et al., 1997 p. 227-228) (Padoan, 2007), which are taken as the P-T conditions of the orogenic metamorphism.

The intensity of the orogenic metamorphic overprint is related to the local deformation regime, as deformation and fluid infiltration enhance recrystallization. This is shown within the strongly deformed parts of the mylonitic metagabbro. Where deformation is extreme and accompanied by fluid circulation, chlorite develops widely; even some biotite occurs, overgrowing chlorite, suggesting a thermal regime close to the upper limit of the greenschist-facies conditions at least locally.

4. Hydrothermal veins and alteration

The whole sequence was deeply affected by hydrothermal circulation, testified by different
types of hydrothermal veins and related alteration. Based on petrography and crosscutting relationships, the following main vein types have been identified (older to younger) (Fig. 4):
1) quartz + calcite + magnetite veinlets. These veinlets occur in the mafic breccias and pillow metabasalts of the El Callao Formation and only produce a weak magnetite + sericite ± chlorite ± quartz alteration in the host rock. They may crosscut, or are crosscut by, the epidote-bearing veins and surely represent early veins, possibly related to pre-metamorphic exhalative activity.
2) epidote-bearing veins. These veins are found within the MGU and the mafic rocks of the MBU. They are metamorphic veins which can be composed of Fe-rich epidote only or, in the mafic breccias of the MVSU, of quartz + calcite + Fe-rich epidote + pyrite ± sericite ± albite, enveloped by a pyrite + calcite + chlorite + sericite + Fe-rich epidote alteration. Though generally not mineralized, these veinlets may contain scattered gold.
3) quartz + ankerite ± albite ± pyrite veins. These are the main gold-bearing veins and are described in detail in the following section, together with the spatially associated quartz + calcite veins.
4) quartz + calcite ± chlorite veins. These veins are spatially associated to the outer envelope of the mineralized zones and are described below.
5) quartz + chlorite veins. These are late, discontinuous and not mineralized veins that occur along microfractures crosscutting the D₁ and D₂ deformation planes in all rock types.
6) veins in the trondhjemite body. Some veinlets have been occasionally found in the trondhjemite body. Their mutual relationships and their chronologic relationships with the vein systems mentioned above are not obvious. As the trondhjemite contains foliated xenoliths of metabasite which are affected by a strong sericite - carbonate - pyrite alteration (Fig. 5H), these veins probably post-date all other systems, possibly apart from the late quartz + chlorite veins:

a. quartz + albite + ankerite ± barite veins, which produce a weak sericite + calcite + pyrite ± albite ± barite alteration. Some gold enrichments locally occur in the altered wallrock, associated with pyrite enrichments;
b. quartz ± galena ± calcite veins, which develop some calcite ± sericite alteration;
c. rare Ba-rich celestine veinlets.

4.1. The mineralized zones: gold-bearing veins and alteration pattern
Within the Rosika – Coacia ore zones (Fig. 3B), mineralization is related to hydrothermal veins and breccia bodies which occur along up to some tens of metres-thick, N-S trending zones dipping 40 to 65° east, i.e. broadly parallel to the main lithological contacts, in the northern limb of the Coacia syncline. Mineralization may occur through the whole lithostratigraphic sequence, though the MGU is only locally mineralized and the main concentrations are within the FVSU, at its lower contact and at top of the MBU. At Villa Balazo - Karolina, where the stratigraphy is dominantly composed of foliated metabasite, the mineralization occurs along a series of south-east dipping veins, with a trend corresponding to the axial plane of district scale D₂ folds. At Pisolita the mineralization occurs within the MBU and seems to be related (based on limited drilling) to a series of sub-horizontal veins.
Like in many other orogenic gold deposits worldwide (e.g., Phillips, 1986, with refs.), at Choco 10 the gold lodes occur within ore zones displaying peculiar structural and vein/alteration features, which are better recognized within the mafic rocks of the El Callao Formation, due to the rock composition and rheology. Approaching the mineralization, three main alteration zones (“chlorite”, “carbonate” and “pyrite zone” adopting the terminology of White et al., 2003) can be generally distinguished (Fig. 4).
In the outer “chlorite zone” (corresponding to the “distal alteration” of Eilu et al., 2001), a first change is given, in the mafic rocks, by the disappearance of “actinolite” (Leake et al.,
1997 p. 227-228) and epidote and increase of chlorite, quartz and calcite, associated with quartz + calcite ± chlorite veinlets; albite is stable. In both veins and altered rock, sulphides are represented by scattered pyrite and no gold enrichments are observed. There is no change in strain at the transition between unaltered host rock and distal alteration zone; a strain increase is, instead, observed through the zone, the inner part of which is generally composed of moderately to intensely foliated rocks (Fig. 6A), with chlorite and often also the quartz + calcite ± chlorite veinlets aligned parallel to the regional foliation.

A drastic change is seen passing to the intermediate “carbonate zone” (broadly corresponding to the inner part of the “intermediate zone” of Eilu et al., 2001), where abundant Ca-Fe-Mg carbonate (ankerite) occurs associated with K-mica (sericite), the latter overgrowing and completely replacing chlorite inward (Fig. 6B); the quartz content generally also increases. Whereas in the distal zone the primary rock texture is mostly preserved, it is generally destroyed in the intermediate zone. Ilmenite or titanite are generally replaced by rutile. The carbonate zone is commonly marked by high strain intensity, with muscovite/sericite overgrowing chlorite along the regional foliation. Such alteration is related to quartz + ankerite ± albite ± pyrite veins, which are the main gold-bearing veins.

The same vein and alteration assemblages are observed within the inner “pyrite zone” (“proximal zone” of Eilu et al., 2001). The difference is given by the increase of alteration intensity, quantity of veins and pyrite content (highly variable, up to 10-15%). The wallrock is completely transformed to a fine-grained granoblastic intergrowth of quartz, ankerite, sericite/muscovite and pyrite (Fig. 6F); tourmaline and very fine grained biotite may also occur in the basaltic rocks and metagabbro.

A similar alteration and veining pattern is also observed in the other rock types, even if it is less evident due to the rock composition: particularly, in the FVSU the outer alteration envelope is scarcely evident, whereas a drastic change is seen in the inner, mineralized alteration zone, characterized by strong carbonate – quartz – sericite – pyrite alteration and flooding of quartz + ankerite ± albite ± pyrite veins.

Within both the carbonate and pyrite zones the quartz + ankerite ± albite ± pyrite veins, few millimetres to several decimetres thick, are mostly parallel to the regional foliation, even if some occur which clearly crosscut it at low angle; they are deformed (Figs. 5B, 6C, 6D). The mineral abundance in the veins is variable; albite is commonly abundant (Fig. 6D) but it is missing in some veins; ankerite-only veins also occur. Pyrite rarely exceeds few units % and commonly contains small inclusions of chalcopyrite, pyrrhotite, galena. Ankerite is commonly rimmed by calcite, which also forms secondary patches. Drill cores observations suggest that such variation in vein composition reflects local changes rather than different vein generations.

Gold is spatially related to the quartz + ankerite ± albite ± pyrite veins. The highest concentrations occur in the inner pyrite zone, associated with pyrite enrichments within the vein or, more commonly, in the quartz + ankerite + sericite/muscovite + pyrite-altered wallrock (Fig. 6F). In both cases gold is in pyrite, as inclusion and along microfractures (Fig. 6H). In minor cases gold is associated with quartz or carbonate.

Within siliceous rock-types (red jasper and chert, particularly at Coacia) the outer alteration zones are thinner and the auriferous veins are enveloped by strong pyrite (and gold) enrichments, where pyrite clearly overgrows the abundant magnetite and/or hematite (Figs. 5D, 6G).

As already mentioned, an important hydrothermal breccia, that is commonly strongly mineralized, occurs within the FVSÜ, as a tabular body. It is parallel to S0/S1 and represents a strongly altered and brecciated rock unit. The extensive alteration does not allow unambiguous recognition of the protolith. The gold mostly occurs as
Figure 6. Microscropic relationships between veins, alteration and deformation (A-F: transmitted, G-H: reflected light).

A) Inner part of the “chlorite zone”: the metabasite is strongly deformed and transformed into a very fine-grained schist mostly composed of chlorite with minor quartz (white spots) and calcite. Black is pyrite. Plane polarized light. B) “Carbonate zone”: in broadly the same rock-type of Fig. 6a where chlorite is completely transformed to sericite, intergrown with fine-grained carbonate (mostly ankerite). Strongly deformed rutile and some pyrite also occur. C and D): strongly deformed quartz + albite + ankerite veins. In C) the microvein is folded by the D2 deformation; the wallrock is completely altered to a quartz + sericite + carbonate + pyrite (+ very fine-grained rutile) assemblage. Gold occurs associated with pyrite. Plane polarized light. In D) is shown a hydrothermal vein strongly enriched in albite. Crossed polars. E) Calc-alkaline tuff strongly affected by quartz + ankerite + sericite alteration, which overgrows the S1 foliation. Plane polarized light. F) Typical aspect of a strongly mineralized domain: independently from its primary composition, the wallrock is completely transformed to a fine-grained granoblastic intergrowth of quartz + ankerite + sericite + pyrite ± albite. Crossed polars. G) Pyrite overgrowing magnetite (light grey) in Fe-rich chert affected by hydrothermal alteration. Strongly pyritized portions like these are commonly highly enriched in gold (H). Symbols for mineral as reported by Kretz (1983): Ab = albite, Ank = ankerite; Mt = magnetite; Py = pyrite; Qtz = quartz; Rt = rutile.
inclusions within pyrite enrichments in the clasts.

Concerning the relationships between mineralization and structural evolution, the following observations are made: a) both veins and hydrothermal breccias are sub-parallel to S1/S0; b) in some cases veins which are folded by F2 effectively cross-cut S1 (Fig. 5B) and are not obviously folded by F1 folds; c) in some instances sericite-pyrite alteration is seen to replace the S1 compositional layering (Fig. 6E); d) at-least in the Villa Balazo-Karolina trend, mineralization in a spatial sense is strongly related to F2 hinge zones and the ore shoots appear to follow the average dip of S2. Coughlin (2005) proposed that gold mineralization at Choco 10 was emplaced either late in D1 or early in D2 and was mechanically and chemically concentrated in F2 hinge zones progressively during D2.

According to Ham et al. (2007), though the geometry of mineralization is strongly controlled by S2, at least locally some mineralized veins cut both S1 (at a high angle) and S2 (at a low angle), suggesting that at least one phase of mineralization has occurred post D2. This overprinting of D2 fabrics is attributed to D3, though D3 shear zones show minor displacement and are difficult to recognize in drill cores.

Our observations, mostly based on the Coacija and Rosika ore zones, fit well with the conclusions of Coughlin (2005). Some gold mobilization occurred, as also shown by the local occurrence of (minor) gold enrichments in cataclasite post-dating the main veins.

A detailed characterization of the fluid of the gold-bearing veins is difficult, due to the amount of deformation. A reconnaissance fluid inclusions study (Padoan, 2007) has shown that early inclusions of possible primary origin in quartz and ankerite of the gold-bearing veins are composed, at room T, of two liquids (LH2O and LCO2) and vapour; the FCAR ratio (it represents the CO2 liquid volume/total inclusion volume ratio) is variable, probably as a result of post-entrapment modifications. Based on microthermometric data, the fluid is mainly composed of a low salinity (4-5% NaCleq) H2O-CO2 fluid (with possibly minor amounts of CH4 and/or N2, as suggested by CO2 melting over a temperatures interval). The total homogenization temperatures of the fluid inclusions (Th) are mostly in the range 250-290°C. Although these data must be taken with caution, they closely match the typical characters of the fluids of the orogenic lode deposits worldwide (Ridley and Diamond, 2000, with refs).

Different generations of secondary, biphase (L + V) fluid inclusions occur, probably representing dominantly aqueous fluids.

5. Geochemistry

Representative samples of the Choco 10 (and, in part, Choco 4, N of Choco 10: Fig. 3A1) rock types were analysed for major, trace and REE elements (Appendix A1). To obtain the primary compositions, we selected samples least affected by hydrothermal alteration; some secondary carbonate and/or sericite (± quartz) however occur even in several of these samples. Therefore some values (particularly CaO, K2O and LOI) may not always reflect the primary rock content. For metagabbro and pillowed metabasalt both massive and deformed samples have been analyzed, in order to check compositional modifications related to shearing. The analytical technique is described in Appendix A2.

In addition to the magmatic rocks (metagabbro and sheared metagabbro, MGU; pillow metabasalt-foliated metabasite and andesitic rocks, MBU; trondhjemite, TPB), also volcaniclastic rocks (ash, crystal and lapilli tuffs, FVSU; mafic tuffs and mafic breccia, MVSU) have been investigated because their geochemical features can be useful for establishing correlations with the associated igneous rocks.

The Zr/TiO2 – SiO2 diagram (Fig. 7) suggests the occurrence of two magmatic series:
tholeiitic (MBU, MVSU and MGU) and calc-alkaline (TPB and FVSU). Particularly the pillow basalt, metabasite, andesite and metagabbro samples fall, with few exceptions possibly related to hydrothermal alteration, in the subalkaline basalt field, overlapping the El Callao basalts of Velásquez et al. (2011). Instead, the trondhjemitic rocks fall in the dacite-rhyodacite field, with a compositional gap between ca. 57 and 66 wt% SiO₂. Among the “andesitic rocks”, two samples still plot within the subalkaline basalt field and the third one in the andesite field. Depending on the classification adopted as well as a consequence of the effects of alteration, these rocks may plot in different fields, from basalt to basaltic andesite, andesite or trachyandesite. Among the volcaniclastic rocks, the mafic tuffs also fall in the subalkaline basalt field, while the tuffs from the FVSU span a wide compositional range, as expected due to their “mixed” nature. The mafic breccia shows a high SiO₂ content due to the occurrence of a quartz-rich matrix. The occurrence of two distinct magmatic series is also shown in the AFM diagram (Fig. 8):

a) Tholeiitic rocks. Metagabbro/sheared metagabbro and pillow metabasalts/foliated metabasite overlap the compositional field of the El Callao basalts of Velásquez et al. (2011) and the tholeiitic basaltic rocks from the Guyana Shield (Guyana: Voicu et al., 1997; French Guyana: Lafrance et al., 1999). The very high FeO_tot/MgO ratio (accompanied by a strong CaO enrichment) of a pillow metabasalt sample (CH10-11; Appendix A1) is due to the occurrence, at microscopic scale, of some calcite + quartz + magnetite matrix. Mafic tuffs also fall in the field of the basaltic rocks. The andesitic rocks plot in a separate field, farther from the M apex; compared to the basalts they are characterized by higher SiO₂, Al₂O₃ and Na₂O and lower MgO and CaO contents (Appendix A1), which suggest derivation from a more differentiated protolith. The exact position of the mafic breccia sample is probably not significant because of the intense alteration. It is interesting to note, however, that it plots close to the andesitic samples, in agreement with the petrographic data and geological setting (at top of the El Callao Formation). Most samples display a low K₂O content (< 0.5 wt%; low-K tholeiitic), a higher content being generally due to the occurrence of some sericite alteration.

b) Calc-alkaline rocks. Trondhjemitic rocks plot in a restricted field close to the A apex, whereas the tuffs from the FVSU span a wide compositional range within the calc-alkaline series field, with one sample (CH10-27) plotting in the tholeiitic field. Three trondhjemite samples are characterized by high SiO₂ and Na₂O (avg. 70.4 and 6.1 wt%, respectively) and low K₂O and FeO_tot+MgO (0.9 and 2.6 wt%, respectively); sample CH04-30 is instead enriched in K₂O (and depleted in Na₂O) as a result of sericitization. The high Al₂O₃ (avg. 14 wt%) content and the fractionated heavy rare earth elements are typical of ‘high-Al₂O₃’ trondhjemite not generated in oceanic setting (Arth, 1979). These two distinct magmatic series show different REE-pattern (Fig. 9; Appendix A1) compared to chondrite-normalized values:

a) Tholeiitic rocks. The pillow metabasalt and foliated metabasite samples (Figs. 9A, 9B) show flat REE-patterns (La_N/Sm_N = 0.54-0.60; La_N/Yb_N = 0.64-0.80) with no Eu anomaly (Eu/Eu* = 0.99-1.13; only a foliated sample shows a slightly negative anomaly of 0.78) which are very similar to the basalts of Velásquez et al. (2011), and in part overlap those of Guyana (Voicu et al., 1997) and of French Guyana (Vanderhaeghe et al., 1998). The same pattern is also shown by the mafic tuff samples, whilst the mafic breccia, which also shows a flat trend, is more REE-enriched and characterized by strong Eu anomaly (Eu/Eu* = 1.77) (Fig. 9b).
Figure 7. SiO$_2$ vs (Zr/TiO$_2$)*0.0001 classification diagram (Winchester and Floyd, 1977). The grey stars symbols are the analysed El Callao basalts (El Callao Formation) reported by Velásquez et al. (2011).

Figure 8. AFM diagram (Irvine and Baragar, 1971; symbols as in Fig. 7). Compositions are compared to those from: Omai mine (Guyana: Voicu et al., 1997), Cayenne Region (northern French Guyana) and Central Guyana (Vanderhaeghe et al., 1998) and St. Elie mine (French Guyana: Lafrance et al., 1999). The grey stars symbols are the analysed El Callao basalts (El Callao Formation) reported by Velásquez et al. (2011).
Figure 9. Chondrite-normalized REE patterns of investigated samples (McDonough and Sun, 1995). Compositions are compared to the same as Fig. 8.
Figure 10. N-MORB-normalized incompatible element diagrams (Sun and MacDonough, 1989). Compositions are compared to the same as Fig. 8. Note that Cs values are not given by the other authors.
b) Among the andesitic rocks, two samples display a flat pattern similar to the basaltic rocks but with a marked La-Ce enrichment, like some tholeiitic and andesitic rocks from French Guyana (Lafrance et al., 1999). All the gabbro samples show a relatively flat pattern, with a weak LREE enrichment (LaN/YbN = 2.5-3.4) and generally a small negative Eu anomaly (Eu/Eu* = 0.79-0.89; only a sheared metagabbro sample shows a slightly positive anomaly of 1.16) (Fig. 9C).

c) Calc-alkaline rocks. The trondhjemite samples display a fractionated REE pattern with strong LREE/HREE enrichments (LaN/YbN = 30-63) and moderate Eu troughs (Fig. 9D) very similar to other plutonic bodies in the Guyana Shield (Voicu et al., 1997; Vanderhaeghe et al., 1998; Lafrance et al., 1999). Our samples are characterized by high La/Sm (8.5-13), La/Ta (41-83) and low Zr/Th (8.5-22) ratios, as typical of sialic crust. In spite of the scattering of the major elements geochemistry the tuff samples show highly REE and incompatible element patterns consistent with their pyroclastic character; strongly reworked material, in fact, would result in much more variable patterns. The chondrite-normalized REE pattern (Fig. 9E) is similar to that of trondhjemite, being well fractionated and displaying negative anomalies of Eu (weaker than trondhjemite; apart from sample CH04-24). Apart from these small differences, the slope of the tuffs pattern is slightly lower than that of trondhjemites.

On a N-MORB-normalized incompatible element diagrams the tholeiitic and calc-alkaline rocks show different patterns:

a) Tholeiitic rocks. The volcanic tholeiitic rocks (Fig. 10A) show a relatively flat HFSE pattern, with a strong Pb spike and a marked LILE-enrichment; the scattering of K, Ba, Rb and Cs values is likely due, at least in part, to some hydrothermal alteration, their highest content (coupled with a Ti depletion) occurring in a foliated metabasite sample affected by some sericite alteration. A similar pattern is also shown by the andesitic rocks and, even if with some scattering due to the rock heterogeneity and hydrothermal alteration, by the mafic breccia and mafic tuffs (Fig. 10B). All gabbro samples display a highly HFSE pattern with a marked Pb anomaly and variable K, Ba, Rb and Cs contents (Fig. 10C).

b) Calc-alkaline rocks. Trondhjemites show a LILE enrichment and HFSE depletion, with pronounced Pb anomaly and Nb-Ce-P-Ti-Yb troughs (Fig. 10D). Some scattering of LILE data (particularly for Cs, Rb, Ba, K) are likely related to hydrothermal alteration. Similar REE and incompatible element patterns are shown, in the Paleoproterozoic Guyana Shield, by some plutonic rocks of the Central Guyana and, in part, Ile de la Cayenne Complexes (Vanderhaeghe et al., 1998) and the quartz-feldspar porphyries from Omai (though the published analytical data make a thorough comparison difficult; Voicu et al., 1997). The spider diagram for the tuffs samples is remarkably similar to those of trondhjemites (Fig. 10E).

The foliated metabasite and metagabbro samples show the same compositional features of the undeformed protoliths, only differing systematically for higher LOI values mainly due to the high chlorite content; differences in abundance of major elements are not systematic and may represent primary heterogeneities. As clear from Figs. 9 and 10, deformation did not involve mobilization of the REE and incompatible elements, as the corresponding patterns are consistent with those of the undeformed protoliths.

6. Geochronology

Zircon from the trondhjemite, a mixed calc-alkaline ash-crystal lapilli tuff, lapilli tuff and
a metagabbro sample were dated by U-Pb using the SHRIMP (analytical technique in Appendix A4). The selected samples were relatively unaffected by deformation and alteration, in order to obtain their magmatic age. Dating of metabasite and andesitic rocks has not been possible, because these samples did not contain any zircons. From the cathodoluminescence (CL) images (Fig. 11) the zircons do not show evidence of re-crystallization or re-equilibration with the host rock system.

Ash and crystal tuffs
In this sample zircons are clear, light pink, prismatic and isometric (100-150 µm in length). They show a well developed concentric oscillatory zoning typical of magmatic zircon (Fig. 11). U and Th contents are less variable than in other samples (107-299 and 89-199 ppm, respectively) and the $^{232}$Th/$^{238}$U ratio ranges from 0.3 to 0.9 (Appendix A3). Twelve U-Pb analyses on oscillatory zoned zircons are concordant and form a tight cluster with an average $^{207}$Pb/$^{206}$Pb age of 2145 ± 5 Ma (MSWD 0.65; concordia age 2143 ± 5 Ma, Fig. 12), which is interpreted as a magmatic age.

Lapilli tuffs
Zircons are clear, light pink, prismatic and isometric (100-150 µm in length), with well developed oscillatory concentric zoning. These crystals have features similar to the zircons of ash and crystal tuffs (Fig. 11). Their U content is relatively low (85-188 ppm, with one analysis at 204 ppm) and the $^{232}$Th/$^{238}$U ratio ranges from 0.5 to 0.9 (Appendix A3). The obtained $^{207}$Pb/$^{206}$Pb age, based on analyses of 11 zircons, is 2143 ± 6 Ma (MSWD 0.53; concordia age 2139 ± 8 Ma, Fig. 12) which is interpreted as the age of crystallization of the tuffs.

Metagabbro
Zircons in the metagabbro are medium in size (100-200 µm), pink, prismatic and euhedral. Many of the grains recovered appear to be fragments of larger (more elongated) crystals. The zircons dated show low CL intensity and thus not clear zoning can be seen; only occasionally traces of oscillatory or gradational zoning is observed, whereas in most cases the crystals are apparently homogeneous and lack any internal structure (Fig. 11). The U content of the zircons is extremely variable (239-1410 ppm), like the Th content (196-1986 ppm) (Appendix A3) resulting in $^{232}$Th/$^{238}$U ratio ranging from 0.85 to 1.5. Such high ratios are commonly observed in magmatic zircon from mafic rocks (e.g. Rubatto and Gebauer, 2000). The U-Pb analyses of 14 zircons are tightly clustered, with an average $^{207}$Pb/$^{206}$Pb age of 2142 ± 2 Ma (MSWD 0.63; concordia age 2140 ± 3 Ma, Fig. 12), which is taken as the crystallization age of the gabbro.

Trondhjemite
The zircon crystals are euhedral, elongated (length up to 300 µm, aspect ratio 2-3.5:1), dark pink in natural light and with a marked oscillatory zoning in CL (Fig. 11). Such concentric zoning is a common feature of zircons from acid igneous rock formed during the crystallization process (e.g. Pidgeon, 1992). U and Th content of the zircons is highly variable, in the range 147-1055 ppm and 33-364 ppm respectively (Appendix A3). The resulting $^{232}$Th/$^{238}$U ratios range from 0.2 to 0.4, values that are typical for zircon from Si-rich magmas. The average $^{207}$Pb/$^{206}$Pb age, obtained from 15 zircons with oscillatory zoning, is 2117 ± 3 Ma (MSWD 0.89). Due to moderated Pb loss the analyses are partly discordant and a concordia age cannot be calculated (Fig. 12). The age of 2117 ± 3 Ma is taken as the age of crystallization of the trondhjemite.

7. Discussion

7.1 Lithostratigraphy of the Choco 10 deposit

The geological, petrographic and geochemical data show that the Choco 10 lithostratigraphy is composed of different formations and rocks types on which we recognized strong
Figure 11. Representative cathodoluminescence images of dated zircons from the ash-crystal tuffs, lapilli tuffs, metagabbro and trondhjemite (scale bars are 100 micron for photos with many zircon crystals, and 50 micron for photos with only one zircon crystal). Inside the single zircon crystal it is possible to better observe the oscillatory concentric zoning (only for zircons of metagabbro this zoning is not good developed).
Figure 12. Concordia diagrams for U-Pb analyses of zircon from ash-crystal tuffs, lapilli tuffs, metagabbro and trondhjemite.
hydrothermal alteration and different hydrothermal veins (Fig. 4).
The El Callao Formation, which crops out at base of the sequence, is composed in its lower part by the Metabasalt Unit (MBU), made of tholeiitic basaltic to andesitic rocks. The tholeiitic rocks show a flat, unfractionated REE pattern which is typical of greenstone belt basalts worldwide; the incompatible elements and REE distributions suggest a mid-ocean ridge or back-arc basin setting, in agreement with the often preserved pillowed nature. It is not also possible to exclude a plateau oceanic setting as proposed by Velásquez et al. (2011) for the El Callao basalts on the base of Nb content (> 3 ppm) and La/Nb ratio (< 1.4). Our pillow basalt samples are characterized by Nb ~ 2 ppm that could suggest a MORB setting (Velásquez et al., 2011 with refs.), but also have low La/Nb ratio < 1.4 (only one sample has 1.7).

The overlying Mafic Volcano-Sedimentary Unit (MVSU), composed of mafic tuffaceous rocks and breccias still showing tholeiitic affinity, metasedimentary rocks and chert, represents its primary stratigraphic cover. Within the tholeiitic series, a transition to more evolved terms is suggested by the occurrence of rocks of andesitic composition mostly in the upper part of the El Callao Formation, often as clasts in the MVSU.

The Felsic Volcano-Sedimentary Unit (FVSU), probably pertaining to the Cicapra Formation, is a relatively heterogeneous rock series that strongly contrasts in composition with the underlying El Callao Formation. The FVSU largely consists of volcaniclastic rocks characterized by abundant albite and quartz clasts of (sub-) volcanic derivation which imply an acidic, calc-alkaline source, as confirmed by the geochemical data. In fact, in spite of the metamorphic overprint and fluid circulation that affected the rock series and probably at least in part modified the rock composition, the minor and trace elements show well defined, coherent calc-alkaline patterns. U-Pb zircon ages of these rocks also show consistent magmatic ages of 2143 ± 6 Ma and 2145 ± 5 Ma.

The nature (stratigraphic or tectonic) of the contact between FVSU and MVSU can only be hypothesized, as its primary features are invariably obscured by strong deformation and alteration associated with fluids circulation. However, the occurrence of primary mafic to intermediate crystal tuffs and andesitic rocks interbedded in the lower part of the FVSU at Rosika suggests a stratigraphic continuum between the two units.

In the Rosika – Coacia area the top unit is represented by a metagabbro body (MGU) probably deriving from an amphibole gabbro emplaced at relatively shallow level, as suggested by the occurrence of quartz-plagioclase micrographic intergrowths and in agreement with geothermobarometric estimates by Padoan (2007) (calculated P-T emplacement conditions: 2 kbar, 750-800°C). Like the basaltic rocks of the El Callao Formation, the metagabbro shows a tholeiitic affinity and displays, however, a more fractionated REE. Along the contact with the underlying unit the metagabbro becomes finer-grained and is locally strongly sheared; though the contact is often deformed and locally even mylonitic. The geochronology data (magmatic age: 2142 ± 2 Ma) indicate that the metagabbro and the underlying volcaniclastic rocks are coeval and thus the contact is broadly primary, probably representing a sill-shaped gabbroic body. In other parts of the El Callao District (e.g., along the Lo Increible trend) gabbro/dolerite sills are a typical component of the Yuruari Formation, which is likely to represent a lateral equivalent of the Cicapra Formation (Shaw, 2003). This latter interpretation is in agreement with the good correspondence between our gabbro dating and the age reported by Day et al. (1995; 2131 ± 10 Ma) for zircons of felsic volcanic and subvolcanic rocks occurring within the Yuruari Formation. In the MBU, the MVSU and the MGU two metamorphic stages are recognized. The first
stage developed under static conditions and perfectly preserves many volcanic/igneous textures and taking into account the geodynamic setting, it is most likely related to an ocean-floor alteration. The second stage includes at least two phases of deformations related to regional greenschist-facies metamorphism: i) schistosity and slate cleavage \( S_1 \), sub-parallel to bedding \( (S_0) \); ii) NE striking, SE dipping crenulations cleavage \( S_2 \) (Coughlin, 2005; Ham et al., 2007).

This sequence is intruded at 2117 ± 3 Ma by a plutonic body of trondhjemitic composition (TPB) and calc-alkaline affinity, which displays fractionated REE and incompatible elements patterns similar to the calc-alkaline volcaniclastic rocks. The trondhjemitic pluton likely represents a differentiated (leucocratic) facies of a body of tonalitic composition such as the calc-alkaline tonalitic plutons of Central Guyana, which show similar geochemical pattern, and the same age (2115 Ma: Vanderhaeghe et al., 1998). The trondhjemite body intrudes the MBU and the MVSU and is undeformed, apart from localized cataclastic planes. As it is not affected by metamorphic recrystallization and contains inclusions of foliated metabasite, its emplacement must post-date the peak metamorphism and at least the \( F_1 \) deformation phase.

7.2 Tectonic setting and gold mineralization

The petrographic and geochemical data suggest that the formation of volcanic centres with calc-alkaline affinity (i.e., building of a calc-alkaline magmatic arc) on top of the tholeiitic basalts occurred at around 2140-2150 Ma (ash and crystal tuffs: 2145 ± 5 Ma, lapilli tuff: 2143 ± 6 Ma). This is likely related to an early stage of crustal generation of the granite-greenstone belt, as it has been proposed for similar sequence in French Guyana by Vanderhaeghe et al. (1998). The metamorphic overprint that affects all the lithostratigraphic sequence is constrained between ca. 2142 Ma (gabbro emplacement) and 2117 Ma (age of trondhjemite). These deformation events are slightly older than those proposed by Vanderhaeghe et al. (1998). The latter authors reported that the Paleoproterozoic granite-greenstone belts formed during two mechanisms of crustal growth: a first formation of oceanic crust with tholeiitic affinity at 2174 ± 5 Ma, and a following building of calc-alkaline plutonic volcanic complexes at 2144 ± 6 Ma (Ile de Cayenne, northern French Guyana) and at 2115 ± 7 Ma (Central Guyana). After a period of crustal recycling and tectonic accretion, the first deformation event was related to the Trans-Amazonian orogeny during which there was the emplacement of syn-tectonic granites. These plutonic bodies were dated at 2093 ± 8 Ma and 2083 ± 8 Ma.

The petrographic study shows that gold has been introduced into the rock sequence in different stages. An early, minor stage is represented by quartz - carbonate - pyrite ± sericite ± Fe-rich epidote ± albite veinlets, occurring in the deeper portions of the MBU. These veins are responsible, at least in Rosika, of the random gold enrichments observed in massive/pillow basalt, often still present at bottom of hole. The main mineralization is instead related to the structurally controlled circulation of low salinity, \( \text{H}_2\text{O}-\text{CO}_2 \) fluids to give quartz + ankerite ± albite ± pyrite veins (often strongly deformed) surrounded by strong sericite + carbonate + pyrite + quartz alteration. The vein and alteration assemblages, as well as the fluid inclusions typologies, are typical of the orogenic gold deposits worldwide.

In the different rock units, two diverse mechanisms played a role in gold concentration. Within the MBU two factors were important: a) the structural setting: within often undeformed rock blocks, mineralization is associated with sheared portions, which acted as channels of focused fluid flow; and b) the host rock composition: the interaction of the hydrothermal fluids with Fe-bearing phases (like magnetite, often very abundant) promoted pyrite and gold precipitation in the altered wallrocks. Within the MVSU, the chemical control, together...
with the brittle rock behaviour, was probably the dominant process: jaspers and chert show, in fact, an extreme Fe/Fe+Mg ratio, and strong gold enrichments are often seen at rim of the veins, where abundant pyrite overgrows magnetite and/or hematite. A quite different picture is observed in the FVSU, where a lithologic control, in terms of rock competence and permeability, is clear. The upper contact of the unit, within the hydrothermal breccias, commonly shows strong gold enrichment. This is due to focused fluid flow that, in overpressure conditions, created strong brecciation and extreme alteration (and mineralization).

The relative age of mineralization is debated: based on structural evidence (mostly from the Rosika area), Coughlin (2005) suggested that gold mineralization was late D1 and/or syn D2. On the contrary, Ham et al. (2007), though recognizing a strong control by S2, proposed that, particularly at Villa Balazo – Karolina, at least one phase of mineralization was post D2. As already stressed, our observations are in agreement with Coughlin’s (2005) hypothesis. Moreover, our geochronological data constrain the onset of deformation (i.e., the beginning of the Trans-Amazonian deformation and associated metamorphism) to the time span comprised between 2142 ± 2 – 2145 ± 5 Ma (age of gabbro and calc-alkaline tuffs, respectively) and 2117 Ma (emplacement of trondhjemite). The occurrence of foliated and sericite-quartz-carbonate-pyrite altered metabasite inclusions in trondhjemite implies that at least one important mineralization phase must also be older than 2117 Ma. The presence of low grade mineralization (associated to hydrothermal veinlets) within the trondhjemite body suggests that gold was introduced and/or mobilized in the rock sequence also after the intrusion of the trondhjemite. A prolonged period of gold-bearing fluids circulation may also explain (and fit with) the different structural models proposed.

The gold metallogeny at El Callao District is related to the world-wide metallogenic event of Paleoproterozoic age which is responsible for important orogenic gold ores formation in the adjacent crustal blocks of Amazonian and West Africa cratons (e.g. Norcross et al., 2000; Goldfárb et al., 2001). Unfortunately, direct dating of gold hydrothermalism and the regional deformation related to is lacking or highly imprecise in the Guyana Shield. The only two examples are: 1) at Omai (Central Guyana), the age of the Trans-Amazonian deformation is bracketed to between 2120 and 2094 Ma (ages of the volcanics and of the Omai intrusion, respectively) and the age of the (epizonal) Au mineralization between 2094 ± 1 Ma and ca. 2002±5 Ma (age of hydrothermal rutile and titanite, which likely post-date the deposition of gold: Norcross et al., 2000). 2) The age of gold mineralization in French Guyana was determined in Dorlin at 2067 ± 1 Ma (Marcoux and Milési, 1993) and at around 2000 Ma by Voicu et al. (2001) in northern Guyana, like many West Africa late-orogenic gold deposits (2000 ± 17 Ma - Milési et al., 1992; range between 2098-2105 Ma in Ghana – Oberthür et al., 1996; 1998).

Even in the absence of direct dating of the hydrothermal phases, our time constraints imply slightly older ages for the onset of the Trans-Amazonian deformation and the development of the orogenic gold deposits in the El Callao District. Though more radiometric dating would be needed, on a regional scale the available data suggest, younging of deformation and mineralization eastward within the Trans-Amazonian craton.

8. Conclusions

The Choco 10 deposit of the El Callao Gold Mining District is composed mainly of tholeiitic rocks (MBU and MVSU related to the El Callao Formation) characterized by unfractionated REE pattern, as other typical greenstone belt basalts worldwide. These tholeiitic series are covered by more evolved terms: heterogeneous volcaniclastic rocks with calc-alkaline affinity (FVSU; this is related to Cicapra Formation). SHRIMP analyses on zircons from these latter rocks
show consistent magmatic ages of 2143 ± 6 to 2145 ± 5 Ma. The top unit is represented by a gabbroic body (MGU) which yielded broadly the same age (2142 ± 2 Ma). Both formations are overprinted by greenschist-facies metamorphism and were intruded, at 2117 ± 3 Ma, by a trondhjemitic plutonic body. This latter displays fractionated REE and incompatible element pattern, as typical calc-alkaline rocks. Gold mineralization is controlled by both structural setting and fluid-rock interaction processes. The main mineralization is related to highly focused flow of H2O-CO2 low salinity fluids that developed quartz + ankerite ± albite ± pyrite veins, responsible of strong sericite + carbonate + pyrite + quartz alteration.

Based on geological, petrographic and precise geochronological data we have constrained the onset of deformation (i.e., the beginning of the Trans-Amazonian deformation) and the subsequent main mineralization phase to the time span comprised between 2142-2144 Ma (age of gabbro and calc-alkaline tuffs) and 2117 Ma (emplacement of the trondhjemite). On a regional scale these data suggest eastward younging of deformation and mineralization within the context of the Trans-Amazonian tectonism.

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APPENDIX A. SUPPLEMENTARY DATA

Supplementary data associated with this article include: 1) geochemical analyses (A1) and related information on analytical techniques (A2); 2) geochronology analyses (A3) and related information on analytical techniques (A4).

REFERENCES


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