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Modeling of the large Miocene epithermal and porphyry gold deposits of the Cauca Metallogenic Belt of Colombia using Monte Carlo simulations

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ABSTRACT

The Cauca Metallogenic Belt (CMB) is an inter-Andean area located along the Cauca-Romeral fault zone of Colombia. The CMB comprises a group of twelve Late Miocene magmatic-hydrothermal Au-Ag-Cu mineral deposits positioned between the Western and Central Cordillera of Colombia. In addition to being a widely developed region in exploration and exploitation with known Au endowments of over 1,700 tons, this area represents an exceptional metallogenetic laboratory for modeling an archetype Andean mineralization from a calc-alkaline source with high Sr/Y ratios. Efficiency processes such as ion and halogen transport, oxygen fugacity, and sulfur content have been extensively studied in magmatic-hydrothermal deposits with a geochemical approach. However, the quantification and modeling of these efficiency processes are currently debated. Through multiple iterations using Monte Carlo simulations (N > 2 million), the authors modeled those reservoirs corresponding to the CMB's upper crust. In this way, a high flux of dacitic magma of 0.007 km^3/year and efficiencies of 1–2% showed that gold endowments bear heavily with magmatic and hydrothermal Au deposits of the CMB. Outcomes including Au endowments up to 1,000 tons can be obtained for reservoirs below 400 km^3 of hydrous melt in brief mineralization intervals between 40 to 120 ka, whereas volumes of 400 to 800 km^3 are obtained in a 120 to 200 ka range. In contrast, the hypothetical reservoirs for the lower and middle crust of the CMB, through a basaltic calc-alkaline magma flux between 0.0007 and 0.0011 km^3/year, the efficiency of ~0.7%, and pressures below 5 kbar, showed sufficient available content of exsolvable H_2O and gold to feed the reservoirs in the upper crust of the CMB or to generate gold deposits from them, but in longer time intervals (>1 Ma).

Keywords: Modeling; Monte Carlo simulations; Northern Andes; Miocene magmatism; Cauca Metallogenic Belt.

Modelado de los grandes depósitos Miocenos de tipo epitermal y pórfido de oro del Cinturón Metalogénico del Cauca de Colombia usando simulaciones Monte Carlo

RESUMEN

El Cinturón Metalogénico del Cauca (CMC) es un área interandina ubicada a lo largo de la zona de falla Cauca-Romeral de Colombia. El CMC está compuesto por un grupo de doce depósitos magmático-hidrotermal de Au-Ag-Cu del Mioceno Tardío, ubicados entre la Cordillera Occidental y Central de Colombia. Además de ser una región ampliamente desarrollada en exploración y explotación mineral, con dotaciones de Au conocidas de más de 1700 toneladas, el CMC representa un laboratorio metalogenético excepcional para modelar mineralizaciones de tipo andino a partir de una fuente calco-alcalina con altas razones de Sr/Y. A pesar que los procesos de eficiencia en depósitos magmático-hidrotermal han sido ampliamente estudiados con un enfoque geoquímico, como el transporte de iones y halógenos, la fugacidad de oxígeno y el contenido de azufre, entre otros, la cuantificación y modelado de estos procesos de eficiencia han sido debatidos actualmente. A través de múltiples iteraciones usando simulaciones de Monte Carlo (N>2 millones), modelamos reservorios que corresponden a la corteza superior del CMC. Nuestros resultados aplicando un alto flujo de magma dacítico de 0.007 km^3/año y eficiencias entre 1-2%, mostraron que las dotaciones modeladas de oro corresponden fuertemente a las cantidades de Au reportadas de los depósitos magmático-hidrotermal del CMC. Con dicho modelado se pueden obtener dotaciones de Au de hasta 1000 toneladas para reservorios inferiores de 400 km^3 de magma hidratado en breves intervalos de mineralización entre 40 y 120 ka, mientras que se obtienen volúmenes de 400 a 800 km^3 con un periodo de mineralización entre 120 a 200 ka. Por el contrario, los reservorios modelados para la corteza inferior y media del CMC, a través de un flujo de magma basáltico calco-alcalino entre 0,0007 y 0,0011 km^3/año, una eficiencia de ~0,7% y presiones menores a 5 kbar, mostraron suficiente contenido de H_2O soluble y oro disponible para alimentar los reservorios en la corteza superior del CMC, o para generar depósitos de oro a partir de ellos, pero en intervalos de tiempo más largos (> 1 Ma).

Palabras clave: Modelado; Simulaciones de Monte Carlo; Andes del norte; Magmatismo Mioceno; Cinturón Metalogénico del Cauca.

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Introduction

Colombia has the most extended history of gold production and exploitation in South America, which dates back to pre-Columbian goldsmithing to the extraction of porphyry and epithermal gold and silver deposits in the present day (Martinón-Torres & Uribe-Villegas, 2017; Scott & Seeley, 1983). Even though Colombia ranks as the 20th largest gold producer globally, with 46.3 tons of gold mined in 2019 (GoldHub, 2020), proven reserves are above 50 Au Moz (Celada et al., 2016). A considerable proportion of such reserves are found in the unexploited and recently discovered La Colosa and Nuevo Chaquiro porphyry deposits, with 881 and 176 Au tons, respectively (Bartos et al., 2017; Celada et al., 2016; Naranjo et al., 2018). These deposits are part of twelve Late Miocene mineral districts located in the Cauca Metallogenic Belt (CMB), a strip comprising numerous Au-Ag-Cu-Mo satellite deposits between the Central and Western Andean Cordillera of Colombia (Fig. 1). The CMB deposits display the typical characteristics of Andean metallogenetic systems, including calc-alkaline magmatism of intermediate composition and high Sr/Y ratios. These attributes make the CMB a natural laboratory for modeling gold endowments in porphyry and epithermal systems associated with arc environments.

Recent studies have used Monte Carlo simulations to model and predict sensitive parameters in the gold endowments associated with Au-Cu porphyry deposits (Chiaradia, 2020; Chiaradia & Caricchi, 2017). The simulation works on four main parameters: (1) melt productivity; (2) the H_2O concentrations in solution, in excess and exsolvable; (3) the amounts of gold in the exsolvable water, and (4) the precipitation efficiency (Au efficiency = $(X_{inicial} - X_{final}) / X_{inicial}$). A database of the world's largest gold and copper deposits and their modeling has shown that Au endowments are predominantly controlled by magma volumes, duration of the magmatic-hydrothermal activity, and precipitation efficiency. Nevertheless, Monte Carlo simulations can provide new petrogenetic information for a genetically related chain of Au deposits, compared to a large group of deposits scattered around the world, even if they have similar Au endowments and share similar geochemical characteristics. Therefore, to reduce uncertainties and have better statistical approximations, it is possible to refine some parameters such as melt productivity, H_2O concentrations, and precipitation efficiency tied to spatially and temporally consistent input data. Thus, the CMB provides an unprecedented opportunity to model and study the Au endowment mechanism of a group of spatially and temporally related hydrothermal gold deposits. This research work aims to analyze the trigger mechanism in the formation of magmatic-hydrothermal gold deposits in the CMB of Colombia by using Monte Carlo modeling.

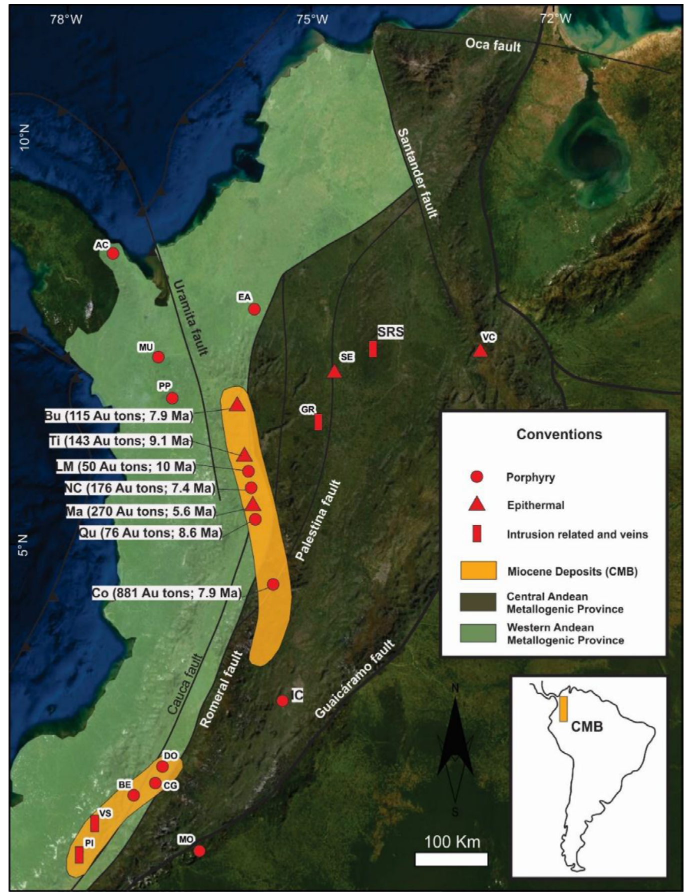

Figure 1. A simplified geological map of the magmatic-hydrothermal deposits and the geodynamic context of the Colombian territory, according to the metallogenetic map of the National Mining Service of Colombia (Celada et al., 2016). Abbreviations of porphyry and epithermal gold deposits: AC Acandí, BE Berruecos, Bu Buriticá, CMB Cauca Metallogenic Belt, Co La Colosa, CG Cerro Gordo, DO Dominical, EA El Águila, GR Gramalote, IC Infierno-Chillí, LM La Mina, Ma Marmato, MO Mocoa, MU Murindó, NC Nuevo Chaquiro, PI Piedrancha Batholith, PP Pantanos-Pegadorcito, Qu Quinchía, SE Segovia-Remedios, SRS Santa Rosa del Sur, Ti Titiribí (Cerro Vetas), VC Vetas California, VS El Vergel Stock.

The rationale of the model

Data collection

Geochronological, chemical (Sr/Y ratios and alkalinity), and gold endowment information were obtained mainly by the metallogenetic map of Colombia (Celada et al., 2016), previous studies, and repositories of master and doctoral theses on seven primary gold deposits and provinces in the CMB (Supplementary Information A). The information corresponding to the ore duration (Ma) was made based on geochronological data of granitogenesis and syn- to post-ore porphyry and epithermal U-Pb, Ar-Ar and Re-Os dating (Bissig et al., 2017; Celada et al., 2016; Lesage et al., 2013; Naranjo et al., 2018). There is an information gap for the northern and southernmost zones of the CMB, which needs to be studied in detail in the future. However, the central zone is well detailed to model the Au endowments for the primary deposits in the CMB (Supplementary Information A).

Monte Carlo simulation

The Monte Carlo simulation was carried out in the RStudio program (https://rstudio.com), with more than 2 million iterations, to ensure reproducibility and replicability. The algorithm was based on Chiaradia (2020) and Chiaradia & Caricchi (2017), according to the model and mass balance of Annen et al. (2006) and Annen (2009). The simulation works with four main parameters, using concatenated equations (detailed in the attached Supplementary Information B), as follows: (1) melt productivity, defined as the hybrid melt produced in the crust; (2) the H_2O concentrations in solution, in excess and exsolvable at pressure of saturation; (3) the amounts of gold in the exsolvable water, at the pressure of saturation within the crust, and (4) the precipitation efficiency, defined as the ratio of gold precipitated regarding the initial gold content in the fluid (Gold efficiency [%] = $(m_{Au\ initial} - m_{Au\ final}) / m_{Au\ initial}$), where m is the molality in the initial and final fluid (Sanchez-Alfaro et al., 2016). The values and intervals used for each parameter to model hypothetical reservoirs of the lower, middle, and the upper crust of the CMB are explained in Table 1.

For reservoirs of the upper crust in archetypal gold deposits of the world, injection rates of 10^{-2} m/year with radii greater than 7.5 km have been proposed to explain the volume of super-eruptions (> 450 km^3) (Chang et al., 2007; Mason et al., 2004; Sparks et al., 2005). However, the present work models smaller-scale plutons and plugs (<40km^2), for which a rate of 10^{-2} m/year with a smaller radius is proposed, plus injection time intervals between 40,000 – 200,000 years and random pressures at which magma accumulation occurs between 0.3 - 3 kbar, corresponding to crustal depths of ~1 to ~10 km (Sanchez-Alfaro et al., 2016).

Table 1. Input parameters used for Monte Carlo simulations for two different magma fluxes (low magma flux between 0.0007 and 0.0011 km^3/year and high magma flux of 0.007 km3/year) to predict diverse scenarios of gold endowments in the Late Miocene lower, middle and upper crust of Colombia.

Parameters analyzed for reservoirs in the lower and middle crust of the CMB	**Parameters analyzed for reservoirs in the upper crust of the CMB**
• Time: 0 - 5 Ma (Annen et al., 2006) • Pressure: 1.5 - 9 kbar (Annen et al., 2006) • H_2O in parent magma: 2 - 4% (Plank et al., 2013) • H_2O in crustal rocks: 0.2 - 1% (Chiaradia & Caricchi, 2017) • The fluid-melt partition coefficient of gold: Random between 10-100 (Simon et al., 2005) • The gold content in calc-alkaline magmas: 6 – 9 ppb (Moss et al., 2001) • Au Efficiency: Random between 0.5 – 1%	• Time: 40,000 – 200,000 years (Annen, 2009) • Pressure: 0.3 - 3 kbar (Sanchez-Alfaro et al., 2016) • H_2O in parent magma: 2 - 4% (Plank et al., 2013) • H_2O in crustal rocks: 0.2 - 1% (Chiaradia & Caricchi, 2017) • Fluid-melt partition coefficient of gold: Random between 10 - 100 (Simon et al., 2005) • Gold content in calc-alkaline magmas: 6 – 9 ppb (Moss et al., 2001) • Au Efficiency: Random between 1 – 2%

Results

State of the art in the CMB

The CMB, located throughout the vast Cauca-Romeral fault systems (Fig. 1), between the Western and Central Andean Cordillera of Colombia (Cediel et al., 2003; Pulido, 2003; Restrepo & Toussaint, 2020; Velásquez et al., 2019), is an inter-Andean area of ~620 km long by 50 km wide hosting several Late Miocene porphyries, epithermal and intrusion-related deposits of gold, silver, and copper plus molybdenum, which has south continuity to Miocene porphyry and epithermal deposits in Ecuador (Schütte et al., 2012). The geology and tectonics of the CMB were studied at first by Grosse, 1926, in which he drew the cartography and mapped the artisanal mines of the region. Based on this classic work, researchers conceptualized the economic geology associated with the Cauca-Romeral fault system. The CMB comprises seven large deposits (> 1 Au Moz) in the central area, defined by (Sillitoe, 2008) as the Middle Cauca Belt and also five poorly explored zones to the south with numerous associated satellite deposits (Fig. 1), for which no geochemical information was available until now. The CMB also continues north to the Andean foothills, with a tradition of ancestral alluvial gold mining (OCDE, 2016), but also with no basic geochemical or geochronological information available. The main deposits include La Colosa (28.3 Au Moz), Quinchia (2.4 Au Moz), Marmato (8.7 Au Moz), Nuevo Chaquiro (5.6 Au Moz), La Mina (1.62 Au Moz), Titiribí-Cerro Vetas (4.6 Au Moz) and Buriticá (3 Au Moz) (Bartos et al., 2017; Bissig et al., 2017a; Lesage et al., 2013; Naranjo et al., 2018; Tassinari et al., 2008). These deposits and their associated plutons have been dated by the Colombian National Mining Agency giving ages between 5.6 and 10 Ma (Celada et al., 2016).

The magmatic rocks associated with deposits of the CMB display calc-alkaline andesitic to dacitic compositions, porphyritic textures and adakitic-like signatures, with high Sr/Y ratios mainly between 40-60 (Fig. 2b), except for the La Colosa deposit, which shows an average value of 26.8 (Gil-Rodríguez, 2010). The mineralization style of the Middle Cauca Belt varies in a south-north sense, where La Colosa is gold-dominant without copper and displays veinlets and bands of low grade (0.92 g/t) (Naranjo et al., 2018), whereas the Titiribí, La Mina and Quinchía deposits are low-grade gold-copper (<0.8 g/t) (Bissig et al., 2017b). Nuevo Chaquiro along with El Roble (~13.8 Ma) are copper-dominant porphyry deposits (Bartos et al., 2017). The Buriticá epithermal deposit shows thick (>30 cm) mineralized high-grade veins of gold-dominant (10.4 g/t) and silver, distributed in two main E-W vein systems (www.continentalgold.com), called Veta Sur and Yaraguá. The Marmato Au deposit is prominent in the area, due to its mining traditions for more than 100 years of gold exploitation, with veins and bands of 0.9 g/t (Tassinari et al., 2008).

In general, the basement of the mineral deposits associated with the Western Cordillera consist mainly of andesitic flows, tuffs, agglomerates and sandstones of the Late Miocene Combia formation (6 - 10 Ma; Jaramillo et al., 2019; Weber et al., 2020) and marine volcano-sedimentary sequences of the Late Cretaceous Barroso formation (Rodríguez & Zapata, 2013). Otherwise, the basement of the deposits towards the Central Cordillera consist mainly of black schists and micaceous metapelites of Triassic-Jurassic age from the Cajamarca Complex (240-230 Ma & 157-146 Ma; Blanco-Quintero et al., 2014; Vinasco et al., 2006) and the Early Cretaceous volcano-sedimentary rocks of marine origin from the Quebradagrande Complex (Nivia et al., 2006).

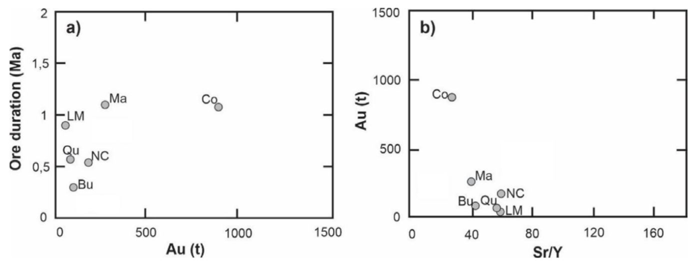

Figure 2. (a) Total ore duration (Ma) vs. Au (tons) for the CMB magmatic-hydrothermal deposits (>1 Au Moz). (b) Gold endowment (tons) vs. Sr/Y ratio. Abbreviations of porphyry and epithermal gold deposits: Bu Buriticá, Co La Colosa, LM La Mina, Ma Marmato, NC Nuevo Chaquiro, Qu Quinchía.

Monte Carlo simulation for Au endowments from the CMB

Low magma flux

Monte Carlo simulations with 3 million iterations, returned 1,919,000 plotted results. A group of endowments gave negative results, but they were not taken into account because a negative Au endowment has no geological significance. Results for a low magma flux between 0.0007 and 0.0011 km^3/year, yielded a wide spectrum of Au endowments, varying between 0 - 48,000 Au tons, with a mean of 8,277 tons and a median of 5,719 tons (Fig. 3a). These endowments are well above our case study (the CMB endowment interval is marked between the 2 red lines in Figs. 3a-d). Nonetheless, for injection time between 0 and 2 Ma, there is a volume of hydrous melt of up to 500 km^3 with an Au endowment spectrum similar to those of the CMB (Fig 3b). For time intervals greater than 2 Ma there is no correlation with the CMB. The pressure at which magma accumulation occurs is sensitive up to 5 kbars (Fig. 3c), after this value and up to 9 kbars there is no good correlation as is shown for the injection time. Finally, the results for the efficiency parameter are very random between 0 – 0.7%, and associates values of Au tons and volume of hydrous melt of 0 - 20,000 and 0 - 1,500 km^3 respectively. For an efficiency between 0.7 to 1%, the results are no longer random and a group of separate fields are observed (Fig. 3d).

High magma flux

Monte Carlo simulation for a high magma flux was only possible for a maximum number of 2 million iterations. For a larger number of iterations, the computer showed problems to concatenate the equations in Supplementary Information B. The results for a high magma flux exhibit a match with Au endowments of the CMB (also marked between the interval of 2 red lines in Figs. 4a-d). The iterations yielded a mean of 954 Au tons and a median of 760 Au tons, which are within the range of Au endowments in the CMB (Fig. 4a). Parameters such as pressure (at which magma accumulation occurs) and efficiency present random values in almost the whole graphic, although at low pressures and low efficiency, a trend is shown for 0 -1 kbars and 0 - 1.5% for pressure and efficiency respectively (Figs. 4c-d). The injection time on the other hand, shows a clear well-marked response to model the Au endowments, in which it is observed that for 0 - 160 ka, endowments between 0 – 1,000 Au tons and 0 - 600 km^3 of volume of hydrous melt were found (Fig. 4b).

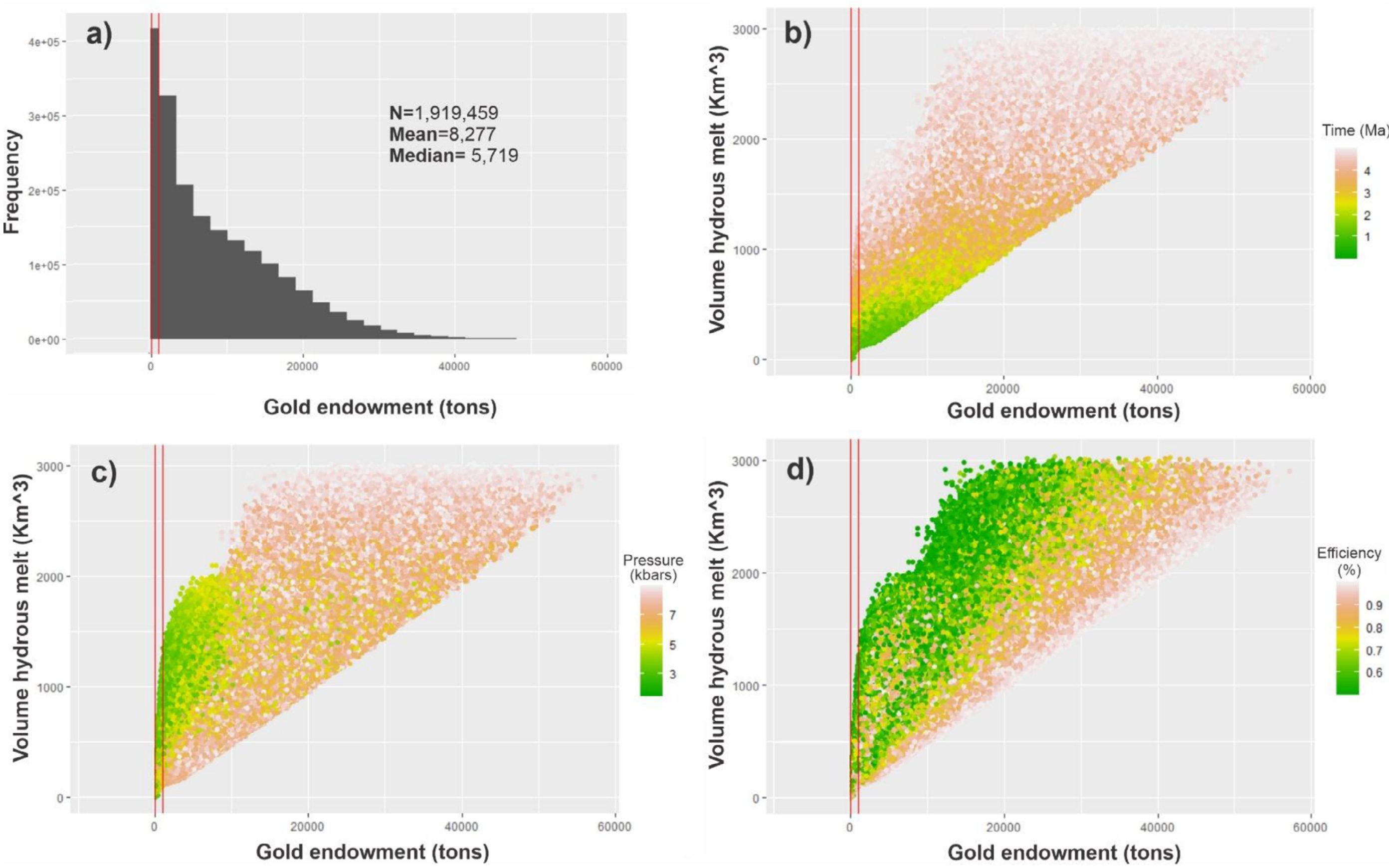

Figure 3. Monte Carlo simulations of gold endowments with three million of iterations, modeling a basaltic magma injection rate of 5 mm/y, through a disk with random values between 6,500 – 8,500 m radius, corresponding to a calc-alkaline magma flux between 0.0007 and 0.0011 km^3/year. (a) frequency diagram of gold endowments with N = 1,919,459; b), c) and d) diagrams associate volume of hydrous melt (km^3) vs. gold endowments (tons), with random iterations of injection time (years), pressure at which magma accumulation occurs (kbars) and gold efficiency (%), respectively. The vertical red lines between 0 and 1,000 Au tons correspond to the range of gold endowments in Colombia.

Discussion

Magmatic reservoirs in the Andean lower crust of Colombia in the early Miocene

The Monte Carlo simulations in the present work employing 3 million iterations, aimed to determine how the gold endowments were reached from the mantle to the shallow crust. The Late Miocene magmatic rocks located along the Cauca river valley include the volcanic rocks of the Combia Formation and the Cauca shallow volcanic intrusions (Weber et al., 2020). These rocks display calc-alkaline affinity (Jaramillo, 1976) and there is a group of rocks that chemically plots in the adakitic series (Borrero & Toro–Toro, 2016). In the CMB, there are also rocks of tholeiitic and shoshonitic series (Rodríguez & Zapata, 2013), but the analysis of the association of calc-alkaline, tholeiitic and shoshonitic magmas is beyond the scope of this work. However, the literature shows that a strong hypothesis for the association of these three magmatic series could be explained by the Caldas Tear (Vargas & Mann, 2013), which is described as a fracture of the Nazca plate under the South American plate, causing a flat slab, therefore there is an incipient post-collisional magmatism, placing rocks of the calc-alkaline, tholeiitic and shoshonitic series in the same regional context, however future geochronological studies need to be carried out to clarify this association. The calc-alkaline affinity rocks present garnets with rings of plagioclase, hornblende and plagioclase with zoned textures in the Chinchiná, Palestina, Jericó, Tesorito and El Poma areas (Alonso–Perez et al., 2009; Harangi et al., 2001), all of them related to the areas with polymetallic deposits within the CMB. Chemical outcomes showed that the garnet-bearing magmas undergone at least two stages of formation through the evolution of phenocrysts, where garnets were formed from 17–19 km and 950 °C and the rims and sieve textures in plagioclase indicate degasification and chemical/physical disequilibrium (Weber et al., 2020). The previous results show that in the Late Miocene, the lithosphere associated with the CMB underwent enormous magmatic fractionation at the base of the earth's crust in the northern Andes of Colombia that later generates reservoirs in the upper crust.

The results obtained by the Monte Carlo simulation reflect the complex geodynamic context of the CMB, which is attributed to a transtensional basin setting (Weber et al., 2020). Monte Carlo simulations demonstrated that there is a low probability that Au deposits within the CMB are formed directly from the reservoirs generated in the lower and middle crust (Figs 3a-d), mainly because the Monte Carlo simulations show Au endowments generally outside the range of the CMB (Figs. 3 and 5), however, because earlier deposits reveal high early fractionation of garnet and hornblende and total rock chemistry (with high Sr/Y ratios Fig. 2) showing a development of rocks of the adakitic series (Borrero & Toro–Toro, 2016), it is probable that the reservoirs of the lower and middle crust, have fed more felsic reservoirs to the upper crust, forming a more evolved dacitic intermediate reservoirs. Monte Carlo simulations also shows a low probability of triggering hydrothermal gold deposits from basalt magmas formed directly from lower tectonostratigraphic levels (Figs. 3a-d), but at timescales of millions of years (Fig. 5). However, this works for porphyry-type Au deposits, while epithermal deposits are more associated with mineralization stages in windows of thousands years (Sanchez-Alfaro et al., 2016). Finally, Monte Carlo simulations show that the mean values of gold endowments associated with the CMB are associated with reservoirs in the lower and middle crust with dimensions between 500 and 2,000 km^3 (Fig. 5),

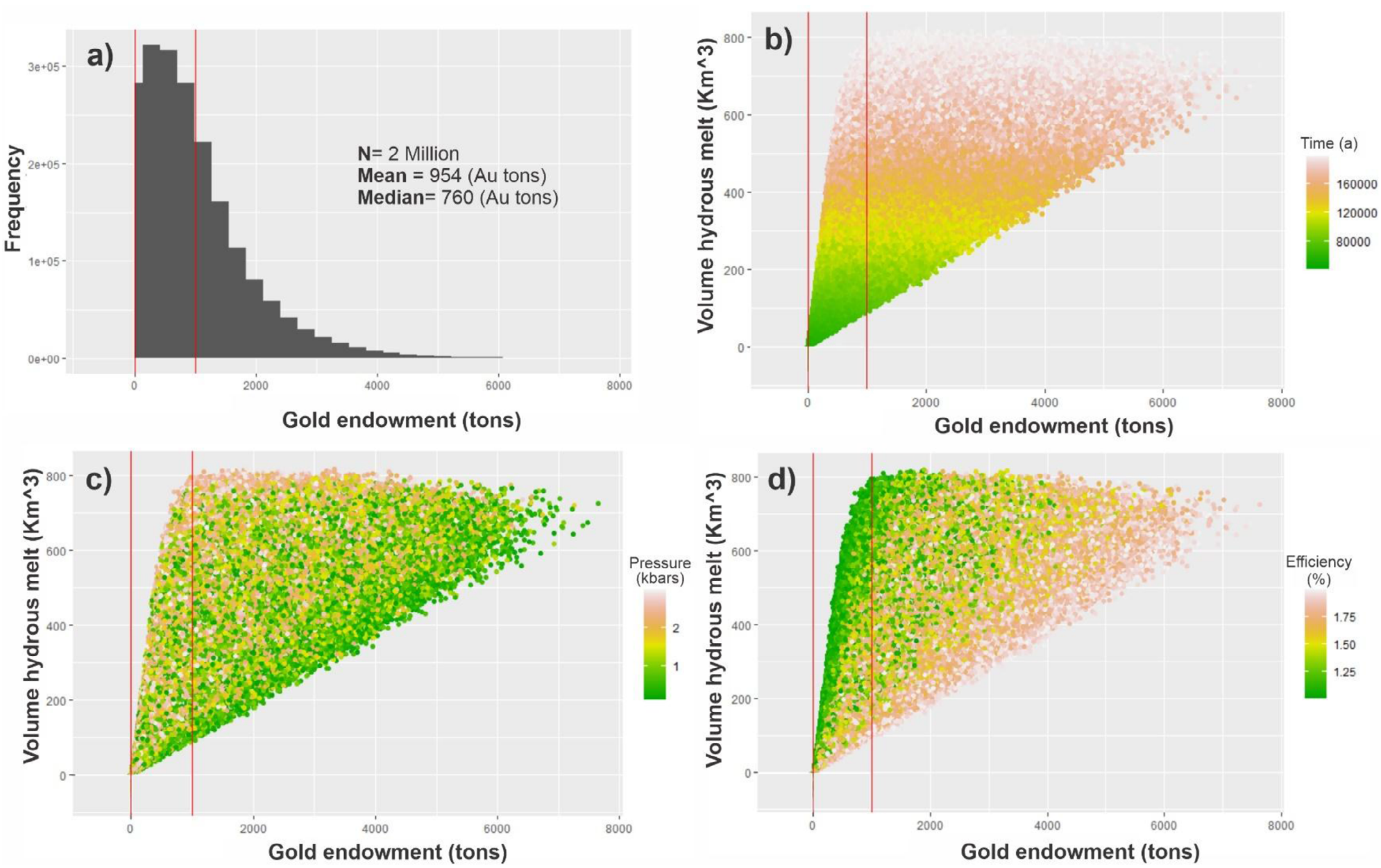

Figure 4. Monte Carlo simulations of gold endowments with two million of iterations, modeling a dacitic magma injection rate of 50 mm/y, through a disk of 6,500 m radius, corresponding to a calc-alkaline magma flux of 0.007 km^3/year. (a) frequency diagram of gold endowments with N = 2,000,000; b), c) and d) diagrams associate volume of hydrous melt (km^3) vs. gold endowments (tons), with random iterations of injection time (years), pressure at which magma accumulation occurs (kbars) and gold efficiency (%), respectively. The vertical red lines between 0 and 1,000 Au tons correspond to the range of gold endowments in Colombia.

values that are above an order of magnitude, compared to reservoirs modeled for the upper crust.

Reservoirs of the upper crust and generation of porphyry and epithermal deposits

The CMB is characterized by having several porphyry and epithermal Au deposits, some of them located less than 30 km apart, along a 100 km long strip, indicating consecutive small-scale reservoirs in the upper crust, due to a previous process of magmatic differentiation in the middle and lower crust (Weber et al., 2020). Considering this, we propose an injection rate of 50 mm/y, through a disk of 6,500 m radius, corresponding with a high magma flux of 0.007 km^3/year, coupled with injection time intervals between 40,000 and 200,000 years for the shallow levels. An injection rate greater than 50 mm/y results in a greater volume of hydrous melt, and would model scenarios outside the CMB range (Fig. 5), which vary between 0 to 1000 Au tons. It is also observed that between 0 to 1,000 tons of Au, mineralization intervals <120 ka can develop in hydrous melt volumes of less than 300 km^3, while longer intervals of mineralization reach a maximum of 800 km^3 (Fig. 5). On the contrary, injection rates of less than 50 mm/y are expected for the lower crust but with larger time intervals (in Ma; Fig. 5) and would mean a transport of hydrous basaltic melt to the crust, with mean values well outside the range of the CMB. Therefore, by means of several interactions using a high magma flux of 0.007 km^3/year, it can be observed that Au endowments match the amount found in the CMB (Fig. 4).

The mineralization style of the epithermal deposits in the CMB are of high-grade vein characteristics, with values of up to 10 g/t, which suggests that the efficiency would have values of tens of %, however the model shows that the obtained efficiencies for epithermal deposits varies between ~1 - 2%, slightly higher than the endowments for porphyry deposits (~0.7%). Thus, it was quantitatively observed that the gold efficiency from epithermal deposits is lower than the expected and slightly higher than porphyry type deposits or that the present method has no way of modeling resetting and flashing processes.

The emplacement of mineralizing hydrothermal fluids can be closely linked to the Cauca-Romeral fault system. While the ore ages vary between 10 - 5.6 Ma, the reactivation of the Cauca-Romeral fault system is ~6.3 Ma (Weber et al., 2020). Thus, the mineralizing processes in the CMB can be associated with pre, sin and post deformation activity underwent in the Cauca Valley in Late Miocene. In the case of the La Colosa porphyry-type gold deposit, it is located along the Palestinian fault, while the deposits of Marmato, Nuevo Chaquiro, La Mina, and Quinchía are associated with the central and western Cauca fault system. Finally, the Buriticá epithermal deposit is closely associated with the Tonuzco fault, of which it is located in the main entrance to the Higabra Mine. Thus, the complex Cauca-Romeral fault system was permeated in the Late Miocene by the water expelled by the hydrated residual magma from the more superficial reservoirs. This complex fault system could have been responsible for generating the seismic activity to generate all the deposits associated with the CMB, as has been modeled in (Sanchez-Alfaro et al., 2016; Sanematsu et al., 2006).

Conclusions

In the present research project, Monte Carlo simulations were used to generate a unique formation model for the huge CMB in the Andes cordillera of Colombia. The results of this work show that for a high dacitic magma flux of 0.007 km^3/year and pressures below 3 kbar, the gold endowments obtained were representative for epithermal and porphyry Au deposits of the region, whose hypothetical models fit an equivalent range up to 1,000 Au tons. For

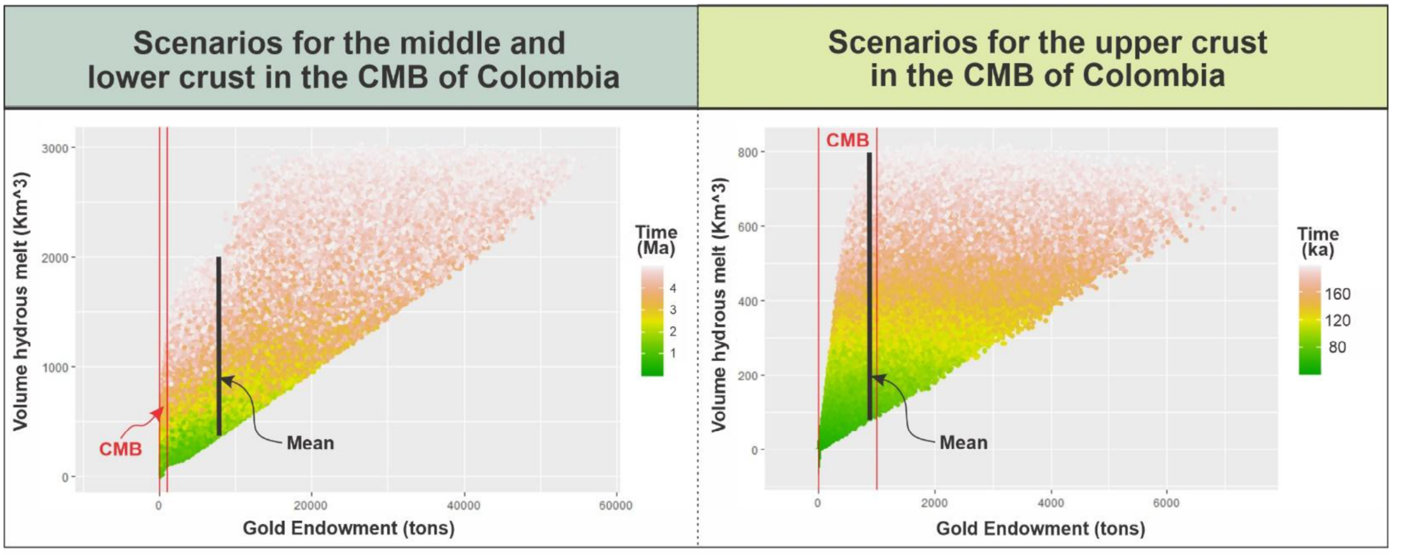

Figure 5. Comparison of Monte Carlo simulations outcomes in the lower and middle crust versus the upper crust of the CMB. The red lines comprise the CMB range and the black line are the mean values of the total iterated scenarios.

time intervals of magma injection <200 ka, the values are associated with epithermal deposits where there is a close interaction of exsolved fluids with the Cauca-Romeral fault system, because of a strong decompression in a transtensional basin setting. Otherwise, the modeling for a low basaltic magma flux between 0.0007 – 0.0011 km^3/year and efficiencies of ~0.7% showed that only for pressures above 5 kbar that correspond to the middle crust, the modeled reservoirs showed sufficient available content of exsolvable H_2O and gold to feed the reservoirs in the upper crust or generate gold deposits from them along the Cauca-Romeral regional fault system, but in longer time intervals.

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Computer code availability

Name of code: MetalData
Developers: F.V. Ruiz, e-mail: fevelasquezru@gmail.com, and Juan Camilo Martinez, e-mail: juan.c.martinez@vanderbilt.edu
Year first available: 2021
program language: R
Program size: 27 KB
Access: https://github.com/fevelasquezru/Modeling-of-the-large-Miocene-epithermal-and-porphyry-gold-deposits-of-Colombia
Experimental software: RStudio.

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