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Multiscale petrotectonic control of gold mineralization in the El Bagre-Nechí districts (Antioquia and Bolivar, Colombia): a review and a new model.

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ABSTRACT

Existing data and new observations indicate that gold mineralization in quartz veinlets and hypogene sulphides in the El Bagre and Nechí districts is closely related to the Carboniferous granitic plutonism of the El Carmen stock and its analogue in the Nechí area. The ore bodies, with irregular, pinch and swell geometries of variable thickness, tend to be preferentially located in flexures where the dilatant character of the controlling fractures increases. They are arranged in echelon patterns along NNW-trending kilometric corridors, preferentially subparallel to the contacts of the intrusive with its metamorphic country rock. This arrangement favours the influence of thermal volumetric contraction during late magmatic emplacement as a complementary mechanism controlling the distribution of mineralizing fluids. Since most of the mineralized bodies develop a mantiform geometry (with gentle to almost subhorizontal dips) sub-parallel to the intrusive-host contact, they define a spatial relationship that is difficult to reconcile with an exclusively subvertical transcurrent environment attributed to the Otú fault. A substantial involvement of petrotectonic control combined with differential thermal contraction-expansion phenomena of the granitic host rocks is suggested to dominate over the pre-existing structural model of fracture-related emplacement of the vetiform bodies in a transcurrent context. The traditional and exclusive spatial relationship proposed for this mineralization with the activity of the Otú fault, associated with the Andean deformation, needs to be reconsidered as it produces temporal inconsistencies. This alternative model favours the location of unexplored sectors with high potential to define remaining primary gold targets.

Keywords: auriferous mineralization, 4D spatial control, metallogeny, Central Cordillera.

RESUMEN

Control petrotectónico multiescalar de la mineralización de oro en los distritos El Bagre y Nechí (Antioquia y Bolívar, Colombia): una revisión y un nuevo modelo.

Los datos y observaciones disponibles determinan que la mineralización aurífera en ganga de cuarzo y sulfuros hipógenos en los distritos de El Bagre y Nechí está estrechamente relacionada con el plutonismo granítico del Carbonífero del Stock de El Carmen y su análogo Stock Nechí. Los cuerpos mineralizados biextensivos con geometrías irregulares y arrosariadas de espesor variable tienden a localizarse preferentemente en flexuras donde aumenta el carácter dilatante de las fracturas controlantes. Se disponen escalonadamente a lo largo de corredores kilométricos NNW preferentemente subparalelos a los contactos del intrusivo con su el basamento metamórfico encajonante. Esta disposición favorece la influencia de la contracción térmica volumétrica durante el emplazamiento magmático tardío como mecanismo complementario que controla la distribución de los fluidos mineralizantes. Dado que la mayoría de los cuerpos mineralizados se disponen con buzamientos suaves a casi subhorizontales y subparalelos al contacto intrusivo-encajante, determinan una relación espacial difícil de vincular con un ambiente transcurrente exclusivamente subvertical atribuido a la Falla Otú. Se sugiere una implicación sustancial de un control petrotectónico combinado con fenómenos de contracción-expansión térmica diferencial de las rocas graníticas hospedantes que domina sobre el modelo estructural preexistente de emplazamiento relacionado con fracturas de los cuerpos vetiformes en un contexto transcurrente. La tradicional y exclusiva relación espacial sugerida para esta mineralización con la actividad de la falla Otú vinculada con la deformación andina necesita ser reconsiderada, ya que produce inconsistencias temporales. Este modelo alternativo favorece la localización de sectores inexplorados con alto potencial para determinar objetivos auríferos primarios remanentes.

Palabras clave: mineralización aurífera, control espacial 4D, metalogenia, Cordillera Central.

INTRODUCTION

The gold deposits in the El Bagre and Nechí districts are located in the Central Cordillera of Colombia, in the northern part of the prolific and traditional Antioquia region, including the northeastern area of Antioquia and the southern part of Bolívar departments (López et al. 2018). The region is characterized by a relatively flat topography and a significant edaphic cover that limits the visibility of its scarce outcrops (Fig. 1). It hosts numerous lode deposits (e.g., Segovia-Remedios, Gramalote, La Floresta), which are found within igneous formations from various magmatic events spanning the Jurassic to Paleogene, and are associated with metamorphic and sedimentary rocks. This region is considered to have the highest gold potential in Colombia, as well as the largest gold placers along the Nechí and Cauca rivers, along with some isolated disseminated gold mineralizations (Salinas et al. 1999, Cediel et al. 2003, Arias and López 2019).

The gold deposits of El Bagre and Nechí have traditionally been linked to the same Andean metallogenic event, with strong structural control exerted by the Otú Fault transcurrent corridor, and are classified as orogenic gold deposits (Leal-Mejía et al. 2008, Londoño-Herrera et al. 2009, Leal-Mejía 2011). However, Naranjo-Sierra and Alvarán-Echeverri (2020) identified a magmatic event in the El Bagre district dating to the Carboniferous (ca. 333-310 Ma), based on zircon U-Pb dating of sodium-rich biotitic leucotonalites from the El Carmen Stock. This age contrasts sharply with the Middle to Late Jurassic (167-154 Ma) age of the Segovia Batholith, which has long been associated with the formation of these deposits. In the Nechí district, Gómez and Montes (2020) attribute the intrusive rocks to the Permo-Triassic period. Recent mapping by Gómez and Montes (2020) of the anatectic granitic body in Nechí suggests a Permian age, although radiometric dating has not been provided. As a result, this study considers the Nechí granitic body to be of Permian age, though with some uncertainty.

Models of the structural control of the vein emplacement of the La Ye mine (El Bagre district) and adjacent veins incorporate the involvement of a transcurrent tectonic context (Naranjo-Sierra et al. 2016, Naranjo-Sierra and Alvarán-Echeverri 2018, 2020, Naranjo-Sierra 2019, Naranjo-Sierra et al. 2021, Salgado-González et al. 2021). However, the detailed spatial descriptions of the ore bodies lack evidence from kinematic indicators or insights into the influence of the thermomechanical behavior of the intrusive host rocks.

This new model reassesses the spatiotemporal relationships between mineralization and the stress fields responsible for creating the spaces exploited by the mineralizing fluids. Additionally, it introduces a novel petrotechnical perspective by incorporating the role of magmatic bodies in generating dilatant conditions, which arise from volumetric changes due to thermal contraction during their final consolidation. The concept of dilatancy (from the Latin *dilatare*, meaning 'to widen') refers to the physical process by which volume changes occur through either contraction or expansion. When this change results in the creation of more space than initially existed, it is termed positive dilatancy (+), while the opposite — when the space is reduced — is termed negative dilatancy (-). In this context, thermal contraction in endogenous systems is the inverse of thermal expansion, which Skinner (1966) defines as the change in volume and shape of a system due to temperature variation. These thermal fluctuations lead to phenomena that generate contraction, which is contemporaneous with dilatancy and epigenetic mineralization. The subsequent loss of fluid pressure, caused by the boiling of residual fluid fractions, facilitates the release of gaseous phases, typically enriched in incompatible mineralizing elements.

For this reason, this new model incorporates the contribution of this mechanism, which was not considered in previous models that focused solely on a singular tectonic aspect related to the stress field associated with the Otú fault. However, the spatial arrangement of the main bodies on the pre-Mesozoic igneous dome and near their contacts with the surrounding metamorphic rocks has led to the formulation and consolidation of this new hypothesis, emphasizing their 4D (spatial and temporal) control.

From both a conceptual and metallogenetic perspective,

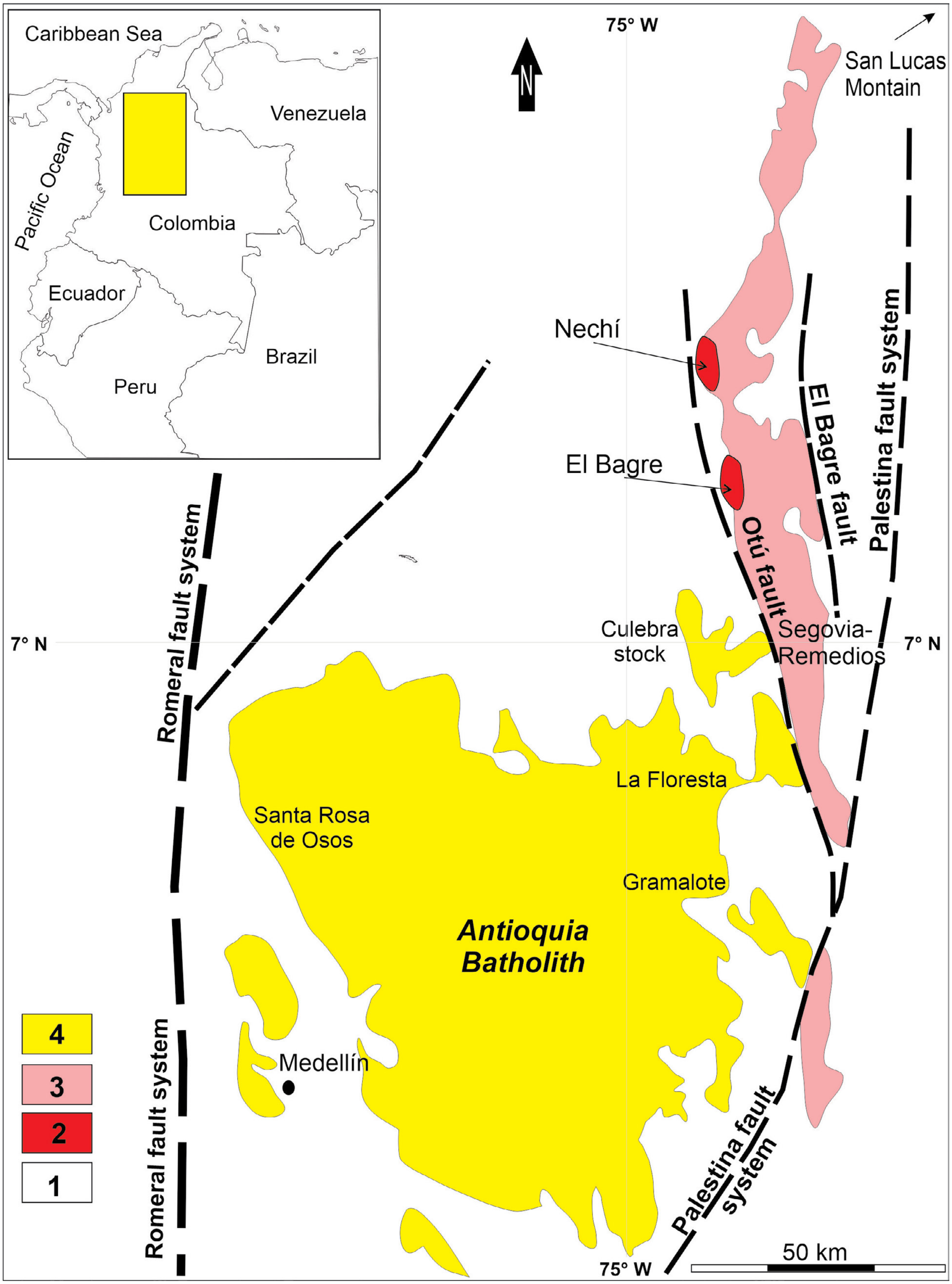

Figure 1: Schematic regional location of the El Bagre and Nechí districts and their relationship with the Antioquia and Segovia batholiths. 1: Undifferentiated basement and unconsolidated alluvial and colluvial cover. 2: El Carmen and Nechí stocks (Carboniferous-Permian?). 3: Segovia Batholith (Jurassic). 4: Antioquia Batholith.

the proposed new emplacement model is highly relevant not only for guiding future exploration efforts but also for predicting previously undiscovered resources. The primary objective of this work is to provide a petrotectonic perspective that enhances the understanding of the syngenetic and post-genetic structural controls of the mineralization in the El Bagre and Nechí mining districts, thereby supporting the exploration of remaining resources in the area.

GEOLOGICAL SETTING

The northeastern region of Antioquia marks the northernmost extension of the Central Cordillera of Colombia and is home to the country's largest gold-bearing district, encompassing both hypogene and epigenic deposits (Shaw 2000, Sillitoe 2008, Arias and López 2019). Regionally, the area is characterized by a basement composed of Neoproterozoic to Cambrian crystalline rocks of green schist facies, Carboniferous felsic plutonic rocks, Triassic-Jurassic intermediate magmatic

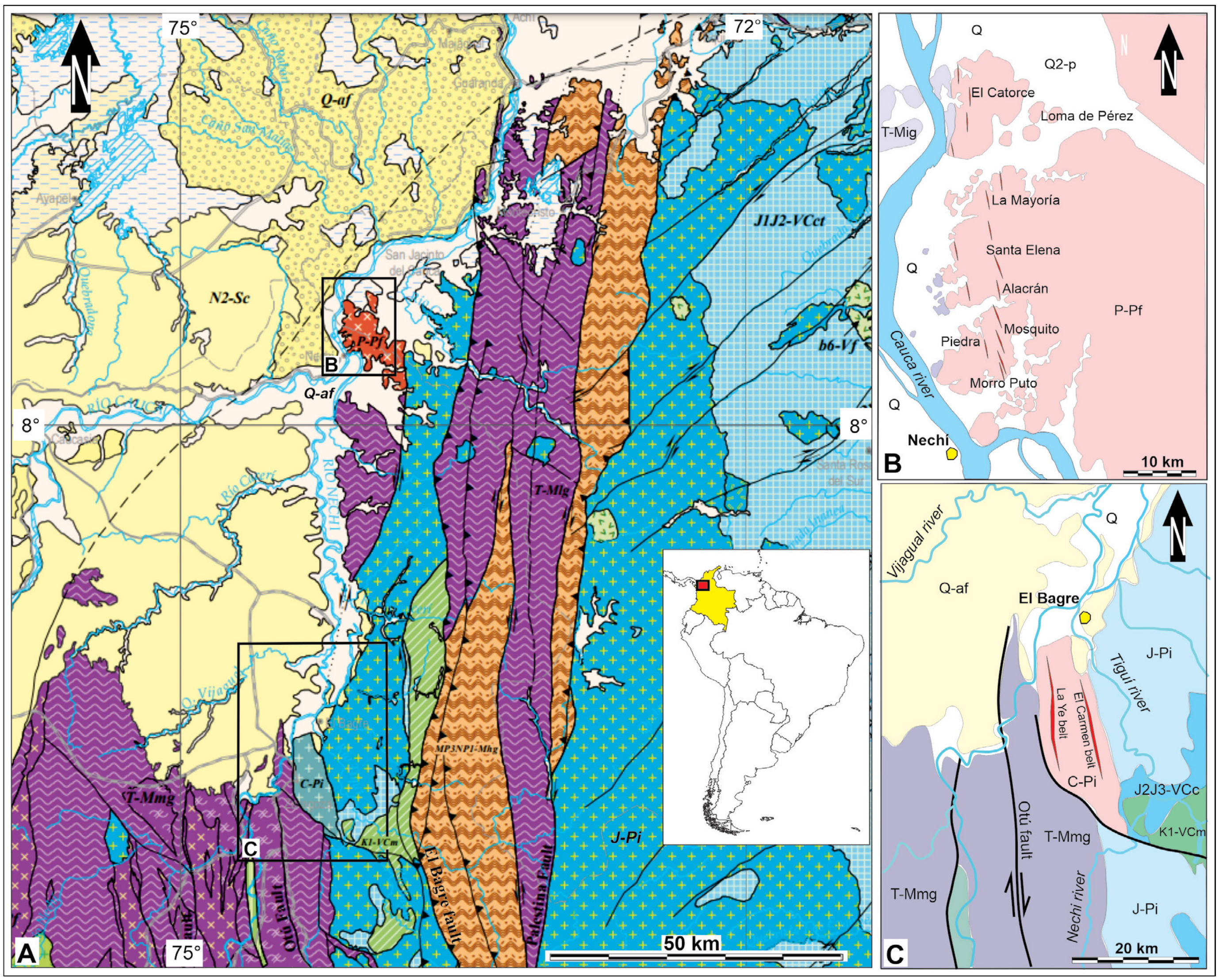

Figure 2: A: Location of the Nechí (B) and El Bagre (C) sectors (black squares) on a portion of the 1:500,000 scale Geological Map of Colombia (Gómez and Montes 2020). MP3NPI-Mhg: Neoproterozoic quartz feldspathic gneisses, migmatites, granulites, amphibolites, orthogneisses, quartzites, and marbles. T-Mig: graphitic quartz– muscovitic, chloritic schists. T-Mmg: amphibolic schists, phyllites, quartzites, marbles, and serpentinites. C-Pi (El Carmen stock): Carboniferous-Permian diorites, granodiorites, quartz diorites, and tonalites. P-Pf (Nechí stock): Carboniferous-Permian anatectic granites, quartz– feldspar gneisses, migmatitic gneisses, amphibolites, and granulites. J-Pi (Segovia Batholith): Jurassic granodiorites that vary from syenogranites to tonalites and from quartz-monzonites to quartz-monzodiorites. J1J2-VCet, J2J3.VCc (Segovia Batholith): Jurassic sandstones, siltstones, and limestones intercalated with tuffs, breccias, agglomerates, and rhyolitic to andesitic lavas. K1-VCm: Aptian basalts, and andesites intercalated with lithic muddy sandstones, carbonaceous mudstones, feldspathic sandstones, limestones, and siliceous siltstones. N2-Sc: Pliocene conglomerates and conglomeratic lithic sandstones intercalated with claystones, siltstones, and peats. Q-af: Pleistocene dissected alluvial fan. Q2-p: Holocene paludal deposits.

rocks, and Cretaceous acidic magmatic rocks, as well as Meso-Cenozoic sedimentary sequences preserved as relics along submeridian depressions (Gómez and Montes 2020).

The crystalline basement is composed of variably deformed, often schistose greenstone facies, including mafic, ultramafic, and felsic volcanic rocks, serpentinites, peridotites, dunites, gabbros, diorites, greywackes, shales, limestones, quartzites, granite-greenstone belts, and felsic and intermediate intrusions (González 2001, Arias and López 2019).

In the geological map of the Department of Antioquia by González (2001), the Jurassic intrusive rocks are grouped under the name Segovia Batholith, originally described by Feininger et al. (1972). This batholith consists of medium to coarse-grained phaneritic rocks, ranging from biotite diorites to quartz-diorites, with local compositional variations toward quartz monzonites, granodiorites, and gabbros (Malo-González 2020). In some areas, the rocks exhibit a slightly banded or distinctly gneissic appearance (Villagómez et al. 2011). Additionally, Leal Mejía (2011), based on petrographic, mineralogical, geochemical, and geochronological data from various Antioquia Batholith samples, suggests that the batholith is composed of four well-defined magmatic pulses. The first three pulses are dated to the Late Cretaceous (96-92 Ma, 89-82 Ma, and 81-72 Ma, respectively), while the fourth pulse is dated to the Paleocene (60-58 Ma). The batholith intruded into Triassic migmatites and schists. Its composition varies from hornblende-biotite tonalite to granodiorite, with lateral variations including gabbro and granite. Common minerals include hornblende, quartz, plagioclase, K-feldspar, biotite, and amphibole, with trace amounts of epidote, chlorite, and sphene. Due to extensive weathering (in some areas, saprolite thickness reaches up to 200 m), outcrops are scarce and mainly confined to riverbeds.

Duque-Trujillo et al. (2019) conclude that the Antioquia batholith was intruded by successive pulses from ca. 97 to 58 Ma in an arc-related setting. The initial pulses are related to syn-collisional tectonics, during the early interaction between the Farallón plate and NW South America. The final pulses, that record Eocene ages, are related to a post-collisional setting, similar to that recorded in other plutons of the Paleogene magmatic arc of the Central Cordillera coincident with the Peruvian Phase of the Andean Tectonics (Cobbold et al. 2007).

The exposed area of the Segovia Batholith is structurally controlled by two major regional faults: the Otú Fault to the west and the El Bagre fault to the east, both located west of the Palestine Fault System. The outcrops present important regolithic developments which are variably covered by Neogene siliciclastic sediments and alluvial deposits of the Nechí river (Fig. 2). Tectonically, the studied area is dominated by the trace of the Otú Fault, which near Zaragoza runs N-S to N30ºW. It is traditionally interpreted as the Otú fault with sinistral displacement, although due to the lack of concrete structural evidence it is also interpreted as a low-angle fault with west vergence (Álvarez Galíndez et al. 2007).

Table 1: U-Pb ages of samples from the Segovia Batholith and El Carmen Stock (taken from Ibáñez-Mejía et al. 2007, Leal-Mejía 2011, Leal-Mejia et al. 2019).

Lithology	Geological unit	Locality	AAge (Ma)	Methodology
Diorite	Segovia Batholith	Morro Puto	166.5 + 2.3/-2.5	LA-MC-ICP-MS
Granodiorite (pan concentrate)	Segovia Batholith	Los Chorros (El Bagre)	164.6 ± 2.4	LA-MC-ICP-MS
Granodiorite	Segovia Batholith	Segovia-Remedios	158.7 ± 2.0	LA-MC-ICP-MS
Saprolite (pan concentrate)	Segovia Batholith	Segovia-Remedios	160.7 + 2.4/-2.3	LA-MC-ICP-MS
Saprolite (pan concentrate)	Segovia Batholith	Segovia-Remedios	159.0 ± 2.4	LA-MC-ICP-MS
Quartz-diorite	Segovia Batholith	El Cairo - Normandía	162.7 ± 2.6	LA-MC-ICP-MS
Granodiorite	Segovia Batholith	El Dorado	163.1 ± 2.8	LA-MC-ICP-MS
Diorite (saprolite)	El Carmen Stock Host rock	El Bagre El Cordero creek	333.1 + 4.7/-4.8	LA-MC-ICP-MS
Diorite (saprolite)	El Carmen Stock Host rock	Los Mangos El Bagre	326.0 + 5.6/-5.1	LA-MC-ICP-MS
Biotite leucotonalite	El Carmen Stock host rock vein	El Carmen drill core	317 ± 10	SHRIMP
Biotite leucotonalite (saprolite)	El Carmen Stock host rock vein	El Carmen sector football field	322.5 ± 5.6	LA-MC-ICP-MS
Biotite leucotonalite	El Carmen Stock host rock vein	El Bagre La Ye Mine	310.6 + 5.3/-5.2	LA-MC-ICP-MS
Biotite leucotonalite	El Carmen Stock host rock vein	El Bagre La Ye Mine	313.6 + 4.8/-5.6	LA-MC-ICP-MS

THE EL BAGRE AND NECHÍ GEOLOGICAL FRAMEWORK

The geological setting of the area around El Bagre District is dominated by a metamorphic basement composed of Precambrian and Palaeozoic magmatic gneissic acidic rocks with biotite, hornblende, quartz-feldspar and actinolite-chlorite and muscovite schists (Restrepo et al. 2010, Moreno-Sánchez et al. 2020). In turn, it is intruded by diorite to quartz-diorite rocks of the Late Jurassic Segovia Batholith (Cediel and Cáceres 2000, Ordóñez et al. 2007; Londoño-Herrera et al. 2009, Gómez and Montes 2020). Álvarez (1983) proposed the name of Segovia Batholith to group all Jurassic intrusive rocks outcropping in the northern Cordillera Central east of the Otú Fault, including both the eastern and western bodies described by Bogotá and Aluja (1981). New Carboniferous-aged magmatism (ca. 330 - 310 Ma) represents a previously undocumented period of magmatic activity in Colombia of a calc-alkaline meta-aluminous nature, related to a volumetrically minor intrusion, restricted to the El Carmen - El Cordero Stock near El Bagre in the lower Nechí River basin (Naranjo-Sierra et al. 2016).

The gold potential is determined by the presence of primary mineralization in quartz veins and placer deposits by its erosion concentrated in the fluvial courses. Both metallogenic types sustain a nourished and persistent production since pre-Hispanic times, especially the secondary ones. The Plio-Quaternary alluvium of the Cauca, Nechí and Tiguí rivers and adjacent sectors of the mountainous foothills and their current terraces and plains, contribute to the largest gold production in Colombia (Arias and López 2019). Reserves were calculated for 520,000,000 m^3, with a tenor of 104 mg/m^3, with an approximate volume of 1,600,000 ounces of gold in alluvial deposits of ancient channels with thicknesses up to 35 m, mainly in the Nechí and Tiguí rivers (Grupo Mineros S.A. 2016).

Many authors (Berger 1992, Shaw et al. 2010, Leal-Mejía 2011, Arias and López 2011, among others) consider the gold-bearing deposits in the studied region as massive and persistent gold-bearing quartz bodies and veinlets with minor amounts of sulphides that cut a wide variety of host rocks (especially regionally metamorphosed volcanic rocks and volcanic sediments). They are located along major regional fault corridors where their related splays correspond to types of Mother Lode veins, Archean gold veins, mesothermal quartz-gold veins, low sulphur gold and quartz veins, gold veins or orogenic gold deposits (Groves et al. 2018, Goldfarb et al. 2005).

According to Echeverri-Castañeda et al. (2009) and Arias and López (2019), the ore mineralogy in both districts consists of native gold, pyrite, arsenopyrite, galena, sphalerite, chalcopyrite, pyrrhotite, tellurides, scheelite, cosalite, tetrahedrite, stibnite, molybdenite, gersdorffite, bismuthinite and tetradymite in quartz, carbonates, albite, fuchsite, sericite, fluorite, muscovite, chlorite, tourmaline, and in quartz, calcite, sericite and graphite gangue. Adjacent to the veins (usually less than 1 m) silicification, pyritization and potassium metasomatism are recognized; carbonate alteration also occurs, with ferric dolomite veining extending for tens of meters from the veins. Other veins reflect the composition of the host-rock, e.g.: talc and Fe-bearing magnesite in ultramafic rocks, ankerite and chlorite in mafic volcanic rocks, -graphite, sericite, albite and pyrite in felsic to intermediate intrusions-.

The veins are located in faults and multiscale fracture systems related to the deformational events linked to the cortical evolution of the Central Cordillera. Over a distance of more than 2 km, mineralization has a vertical extension and lacks of pronounced zoning (Leal-Mejía 2011). Gold deposition occurred in tabular veins and quartz veins with massive and banded textures with stepwise patterns in cortical levels at depths of 6 to 12 km, at pressures between 1 and 3 kb and temperatures between 200 and 400 °C (Arias and López 2019).

Geochemical anomalies of the veins are dominated by elevated Au, Ag, As, Sb, K, Li, Bi, W, Te, and B ± (Cd, Cu, Pb, Zn and Hg) in rocks and soils, and Au in active stream sediments. The paragenetic association is of medium to high temperatures (between 250ºC and 312ºC) recognized from the homogenization of fluid inclusions and emplaced in intrusive and/or metamorphic host rocks (Arias and López 2019).

El Bagre Sector

In the El Bagre mining district, the intrusive rocks of the El Carmen Stock are prominent, exhibiting a characteristic leucocratic aspect that is distinctly different from the typical hornblende-biotite-diorite to quartz-diorite facies of the Segovia Batholith. In addition, U-Pb (zircon) magmatic crystallization ages obtained for the leucotonalites of the El Carmen stock and associated diorite yielded Carboniferous ages ranging from ca. 334-310 Ma (Table 1, from Leal-Mejía 2011).

The primary mineralization are gold-bearing seams with pyrite, galena, sphalerite in quartz gangue. The mineralization is located east of the Otú fault, which has a general direction N25° W, where the host rock is the El Carmen Stock (previously considered “Batolito Segovia”, in Rodríguez and Pernet 1983, Ash and Alldrick 1996). The vein biextensive type mineralization (following the terminology of García 1981) is mostly exploited by underground mining works of small to medium scale (Mineros S.A. 2016) and artisanal character. The area is characterized by a flat topography with development of intense weathering and saprolite cover (Fig. 3 A and B). Two main mineralized veins are recognized: the La Ye and El Carmen veins surrounded by several smaller satellite veins. In this sector of El Bagre, several structurally controlled mineralized vein systems are recognized, hosted within the Carboniferous leucogranites of the El Carmen Stock that intrudes the early Palaeozoic metamorphic basement (Fig. 3C) and is cut by a series of medium-grained basic and aphanitic acidic dykes (Fig. 3D).

Londoño et al. (2009) highlighted the marked structural control of the La Ye and El Carmen vein-type mineralization, as well as the displacement associated with dextral reverse faults, which they interpreted to facilitate the emplacement of post-mineral dykes along a northeast-southwest direction. The structural evidence led these authors to propose an orogenic gold deposit model for this vein-type mineralization, without discarding other types of gold mineralization. They are potentially associated with different intrusive facies grouped in the Segovia Batholith as shown in the geological maps at regional and departmental scale.

Salgado-González et al. (2021) describe the La Ye mine (with 6 production levels down to 200 m depth) with mineralized veins striking N15°W/64°SW and dipping from 48°SW (at the southern end) and 76°SW (at the northern end) in blocks bounded by four main fault zones (locally named the Ciénaga-Grande, Lápida, Naranjal and La Ye faults).

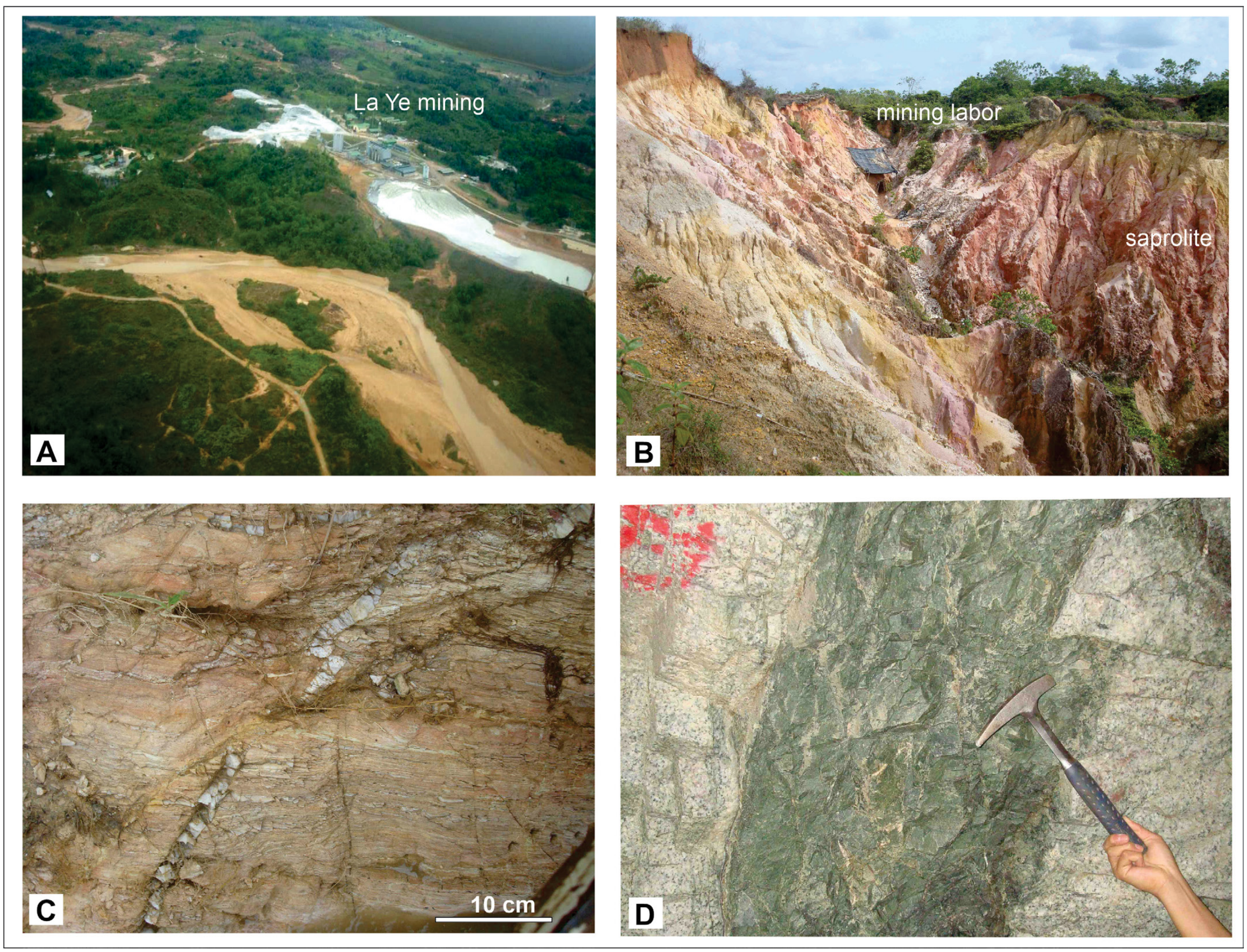

Figure 3. A: Aerial view of La Ye mine. B: View of the important saprolitic development on the magmatic units of the El Bagre District exploited by artisanal miners for the extraction of gold through informal workings. C: Details of the veins developed in rocks of the metamorphic basement on the left margin of the Cauca River. Note the spatial relationships between concordant and discordant veins and the late faulting that cuts them. D: Dolerite dyke in Cordero Mine Level 1 (El Bagre District), discordant with respect to the magmatic foliation and then, in turn, affected by brittle discontinuity planes that cause slight displacements at their edges.

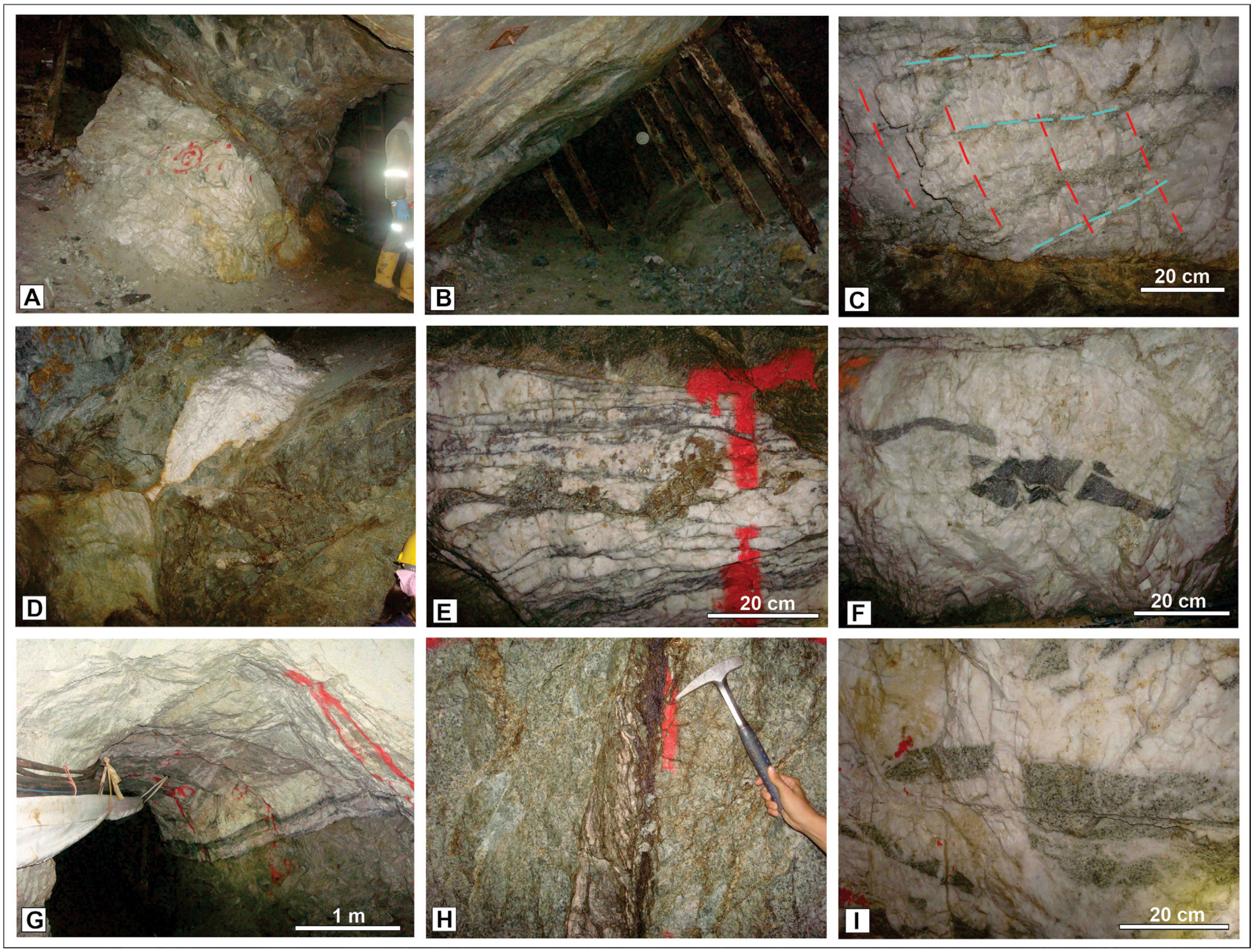

Figure 4. Photographs of the quartz veins in the underground workings of the La Ye mine in the El Bagre district. A: Sigmoidal vein reaching five meters thick (Level 2). B: Mantiform vein with banding (Level 2). C: Detail of ribbon banded vein with late brecciated quartz texture superimposed (red lines) on the previous ductile texture (green lines) (Level 2). D: Anastomosed vein (Level 2). E: Vein with abundant sulphides in bands of coarse granular aggregates arranged in central sectors (Level 2). Mina Cordero. F: Fragments of the wall rock included in the vein (Level 1). G: Mantiform vein with ribbon-like banding (Level 1). H: Subvertical vein with ductile shearing structure represented by sigmoidal quartz lenses and orthogneissified sectors of the crystalline lode (Level 1). I: Detail of the bands with partial digestion of the host rock blocks (Level 1).

The Ciénaga-Grande fault is located along a N20°W/52°SW corridor where veins with an average width of 1 m are hosted in the leucogranites of the Carboniferous El Carmen Stock (Londoño-Herrera et al. 2009). The vein mineralogy is composed of quartz + pyrite + galena accompanied by minor amounts of chalcopyrite and scarce sphalerite. Macroscopically, electrum particles (1 to 3 mm) associated with galena are observed. Internal reports from Mineros S.A. cited by Londoño-Herrera et al. (2009) indicate the presence of lead tellurides (altaite) and a paragenetic sequence with pyrite as the earliest mineral species, followed by galena and chalcopyrite.

The most frequent disposition of the Los Mangos mineralization is mantiform (dipping between 40 and 50º), preferentially concordant with its intrusive contact and with variable thickness (pinched and swollen) that oscillate between 1 and 3 meters (Fig. 4). In some cases, it can be seen that in the central portions the veins are made up of sulphides (pyrite, galena) in ribbon-like milky quartz gangue associated with mylonitic bands that also usually show sulfide impregnation (Fig. 4).

The El Carmen vein is disposed N5°E/45°E with an average strike length of 1.2 meters. Diamond drill core (Mineros S.A.) of El Carmen shows pre-mineral and post-mineral dykes cutting the leucogranites. As in La Ye mine, the mineralization of the veins is composed of quartz + pyrite with minor amounts of galena and chalcopyrite. Coarse-grained electrum is observed in small fractures (Londoño-Herrera et al. 2009). The alteration of the host rock is similar to that observed at La Ye, with chlorite and epidote partially replacing micas and plagioclase, respectively. Sericite is also observed as aggregates within the vein and on the vein edges (Londoño-Herrera et al. 2009). In level 1 of the Cordero Mine, the presence of centimetric muscovite booklets forming part of the quartz veins could be appreciated.

The earliest ductile features are evidenced by massive textures, contacts with metamorphites and diffuse banding (Fig. 4) as well as sigmoidal banded structures typical of ductile shearing (Fig. 4). On the contrary, it is possible to identify brittle deformations superimposed to the previous ones that give the vein a brecciated aspect (Fig. 4).

Salgado-González et al. (2021) describes Into the El Carmen Stock, the Los Mangos mine with five levels, reaching a depth of 90 m. The general trend of the vein is N4°W/34°NE and is cut by seven fault zones that define six east-dipping structural blocks. The vein bands exhibit partial replacement of mafic minerals and plagioclase from the leucogranitic host rock by chlorite and epidote. Sericitic hydrothermal alteration is also observed. A notable feature is the presence of host rock fragments enclosed within the vein that have been completely altered to sericite aggregates. Calcite appears as a late fracture-filling mineral species (Londoño-Herrera et al. 2009).

Nechí Sector

In the eastern area of the Nechí locality, on the right bank of the Cauca River (Fig. 2B), gold-bearing quartz veins are located along an NNE corridor in intrusive rocks, considered by Gómez and Montes (2020) to be of Permo-Triassic age. Also, on an outcrop of metamorphic rocks located at water level on the left bank of the Cauca River, in front of the El Catorce wharf (Fig. 2B), structural unconformable relationships between veins and schistosity-foliation could be appreciated. Field observations indicate that dyke-like structures are arranged

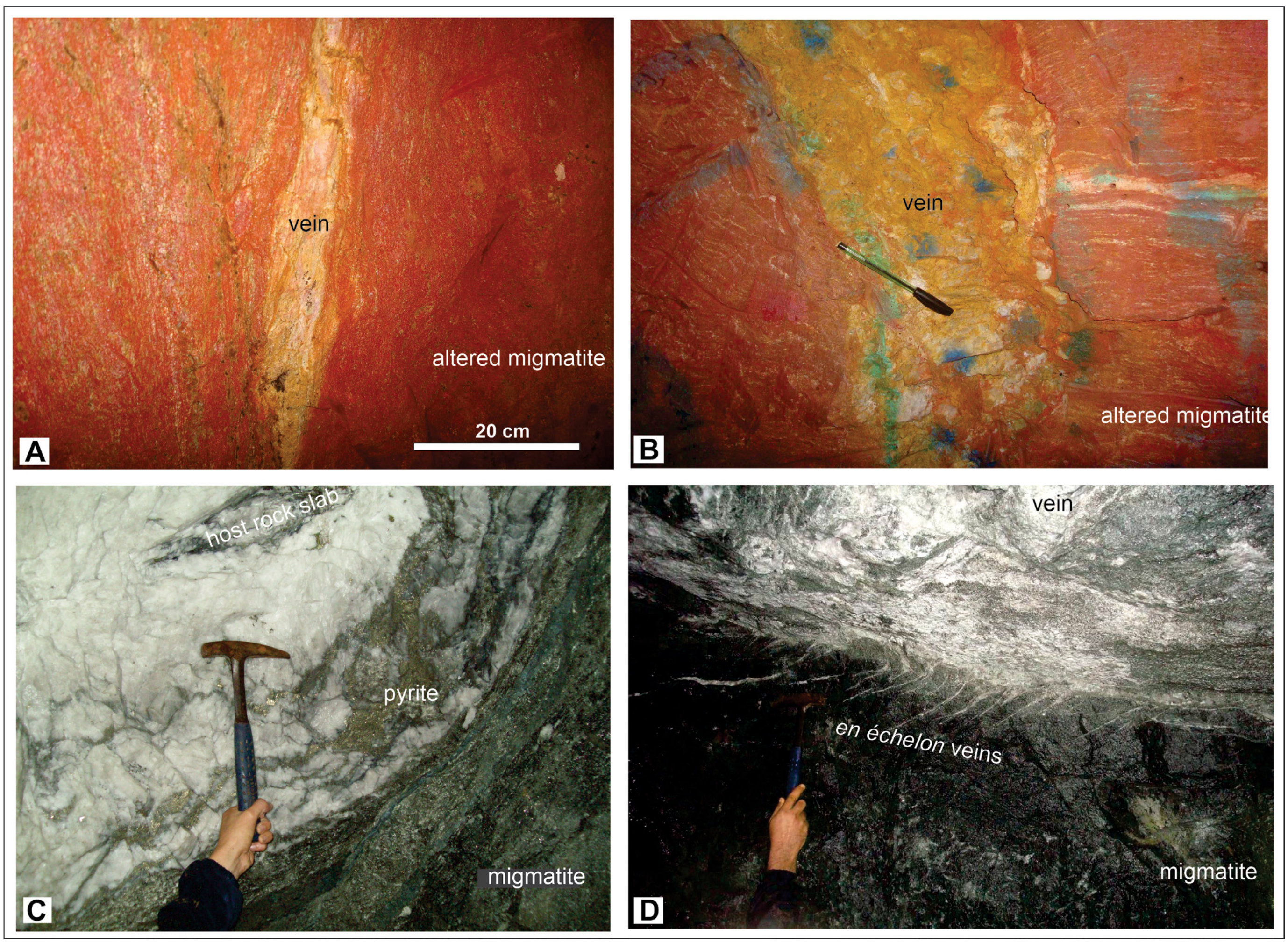

Figure 5. Protographs of the quartz veins in the Nechi District. A: View of the subhorizontal Francisco gallery (Cerro Puto) developed on saprolite, where the relictic anisotropy of the granitic type banding with conspicuous subvertical planar anisotropy can still be recognized. B: Idem showing subtabular discordant vein. C: Lenticular concordant vein top with lenses of greenish hosting rocks of the Santa Elena pit. D: Idem showing detail of subordinate en échelon veins that determine a thrust component to the left of the subhorizontal faulting.

subparallel to the primary anisotropies of the granitic bodies. However, the presence of crystalloblastic porphyritic textures resemble ultramylonitic rocks of the pseudotachylithic type (to be confirmed with petrographic studies): In this site, step-like sigmoidal veins of milky quartz appear discordant with others developed subparallel to each other with strong planar anisotropy approximately submeridianal (Fig. 3C).

In the Nechí District the main occurrences seem to be arranged with preferential NNW orientations and right-stepping (Fig. 2B). Veins are emplaced discordant with respect to the anisotropy of the granitic host rocks (Fig. 5). In some occasions it is possible to identify thrusting movements from kinematic indicators provided by subordinate *en échelon* arrangement of veins (Fig. 5D).

Age of mineralization

Leal-Mejía (2011) and Salgado-González et al. (2021) determined the age of the mineralization/hydrothermal alteration of the La Ye - El Carmen vein system. Based on the K-Ar analysis, a hydrothermal sericite sample collected at the La Ye mine (Sample BMY-5) yielded a Permian age (280 ± 6 Ma). The sericite age needs to be confirmed by further geochronological data from the area, as it is also possible that this age records the resetting of the post-K-Ar closure associated with the Permo-Triassic widespread tectonothermal history proposed by Vinasco et al. (2006).

A post-mineralization diorite porphyry dike sample (WR-135) acquired in a hole from the El Carmen project yielded an Upper Jurassic age of 167 ± 5 Ma (Leal-Mejía 2011). This Late Jurassic age compares well with several ages obtained for the Segovia Batholith and indicates that gold mineralization in the El Carmen Stock of the El Bagre sector clearly predates the intrusion of the Segovia Batholith and thus, in general, Late Jurassic magmatism.

On the other hand, the distribution and values obtained from radiometric dating on lithologies belonging to the Antioquia Batholith and in particular the close disposition (possibly underlain?) of the La Culebra Stock with respect to the Segovia-Remedios Mining District (Fig. 1) are reproduced.

The Segovia Batholith is composed of diorite and quartz diorite with a medium-grained hypidiomorphic texture that varies from massive to locally laminated (Álvarez 1983). Its outcrops are highly elongated (270 km long and 50 km maximum width) along to a submeridianal disposition, preserving in most of its flanks metamorphic enclaves attributed to Paleozoic and/or Pre-Cambrian host rocks. Its spatial and structural occurrence suggests a syngenetic tectonic environment. From a temporal point of view, based on exhumation ages of zircons and apatite (Echeverry 2006, Frantz et al. 2007, Leal-Mejía et al. 2008) the Segovia Batholith is older than the Antioquia Batholith. In fact, new dates would give the Segovia Batholith a much older age, which would be Permian (Table 1). From the cartographic point of view (González 2001), it can be seen that towards its northern sector is unconformably covered by Cretaceous sedimentary units. This field relationship limits its minimum age to the Jurassic and forces to consider the action of a rapid period of cooling, erosion and deepening to allow the overlying Cretaceous marine sedimentation. Therefore, it can be affirmed that the basement constituted by these igneous bodies suffered the action of at least two strain fields associated with the following tectonic events:

i) The oldest and most intense tectonic event occurred prior to Cretaceous deposition (González 1992) since it exposed on the surface a granitic magmatism emplaced many kilometres deep as well as its associated mineralization, and

ii) The younger one, after the Cretaceous deposition, affected the basement including the meso-cenozoic sedimentary sequences from the large regional transpressive faults associated with the Andean tectonics' convergence (Cobbold et al. 2007).

METHODOLOGY

To achieve the objectives of this study, previous structural, petrological, and field data conducted by E. Rossello in 2011, both from surface analysis and underground workings, were considered, along with information from recent literature, particularly the works of Arias and López (2019) and Salgado-González et al. (2021). A review of the tectostratigraphic information available on the different granitic bodies linked to the mineralizations was carried out. In this regard, special interest was placed on the recognition of isotopic data that show a temporal differentiation of the magmatites that hosted them with respect to the traditionally known Antioquia Batholith. Also, the spatial arrangements of the main mineralized bodies of both districts were compiled to relate them to the mechanisms responsible for the generation of the spaces that allowed their emplacement.

On the other hand, the spatial relationships between the stress field and the fractures generated (faults and joints), based in the Anderson Law (see details in Rossello and López-Isaza 2023) are taken into account in order to interpret the kinematics that the buckling-flexures, protrusions and/or terminations of the faults generate. Thus, vein thickening can be linked to favourable dilatancy situations, both in plan and in section, for the emplacement of vein-shaped mineralization (Rossello and López-Isaza 2023).

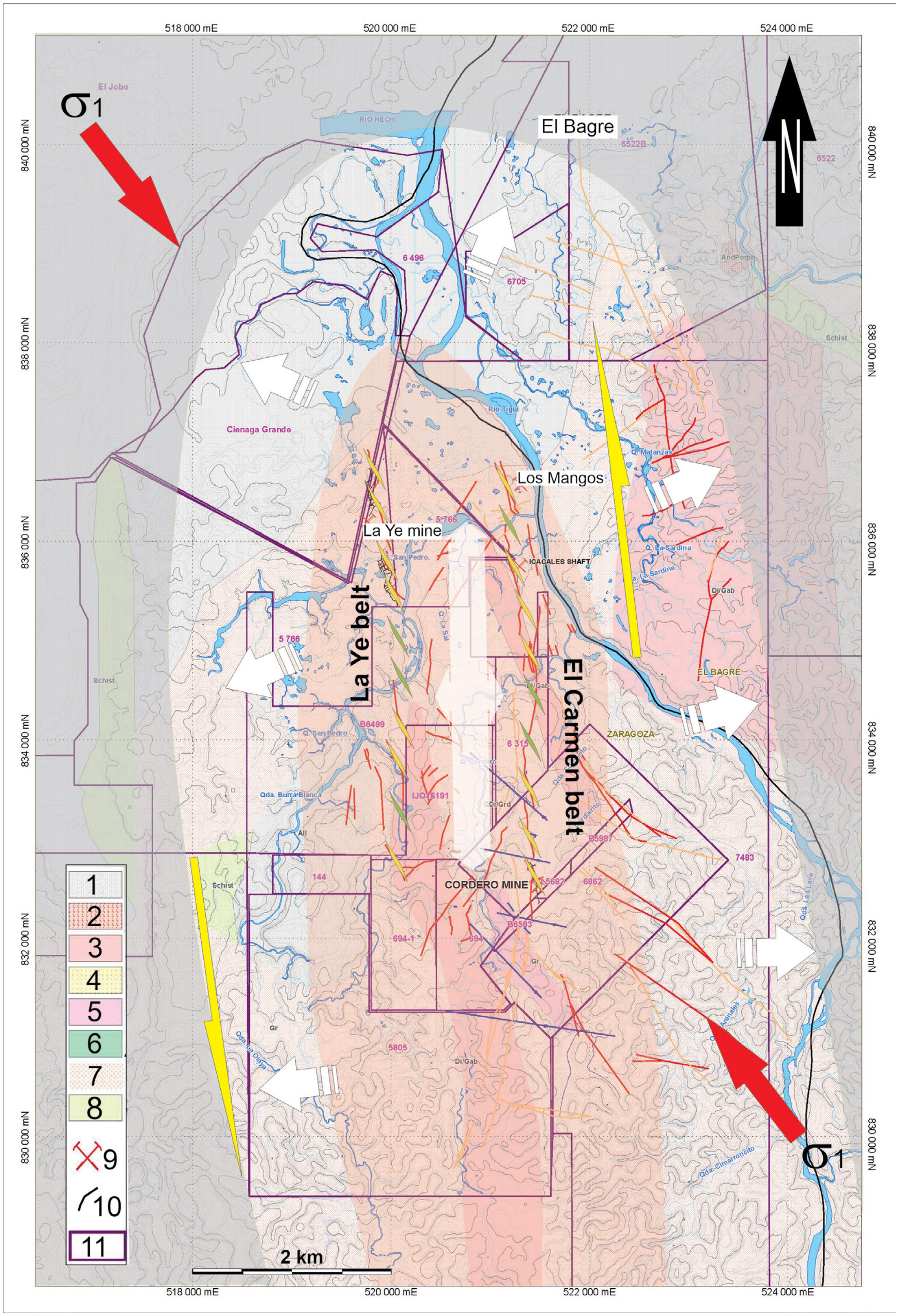

Figure 6. A: Idealized scheme of the preferential position of the gold mineralization at El Bagre. Its haloes in the western (La Ye belt) and eastern corridors (El Carmen belt, with Los Mangos, Cordero mines, etc.) are apparently symmetrically arranged with respect to a central lithosome that appears to constitute a dome. 1: Alluvial deposits. 2: Andesitic porphyry. 3: Diorite-gabbro. 4: Gneiss/Biotite schist. 5: El Carmen granite. 6: Amphibolite. 7: Quartzdiorite/granodiorite. 8: Schist. 9: Underground and mining labours. 10: Municipal boundary. 11: Mining tenements. (based in Mineros S.A. and modified from Rossello 2011). Red arrows: principal maximum horizontal strain. Yellow arrows: sinistral wrenching along the N-S trending corridor.

Finally, with the aim of facilitating the observation of the spatial relationships between the mineralizations and the structural context, simple diagrams and graphs were created.

PETRO-TECTONIC CONTROLS

The petro-tectonic characterization of the gold mineralization of the El Bagre and Nechí districts is carried out below according to the different scales of observation.

Hectometric to kilometric characterization

Based on the geological surveys, it is believed that the current topographic surface is likely close to the contact zone between the intrusive bodies and their host rocks, remnants of which have been mapped a short distance to the east and west. Additionally, some residual materials from the colluvial-alluvial Quaternary succession and thicker saprolites directly overlie this surface, as they share similar lithologies.

The studied gold mineralizations, particularly in the case of the El Bagre mineralization, are found in areas associated with the El Carmen Stock dome or in close proximity to its intrusive contacts (Fig. 6). The vetiform bodies are distributed along a submeridianal corridor (the La Ye and El Carmen belts), situated along the western and eastern contacts of the intrusion, exhibiting preferential inclinations and a western vergence.

On the contrary, the veins of the eastern corridor (Cordero, Los Mangos mines, etc.) are distributed along a corridor located on the eastern contact (El Carmen belt) with

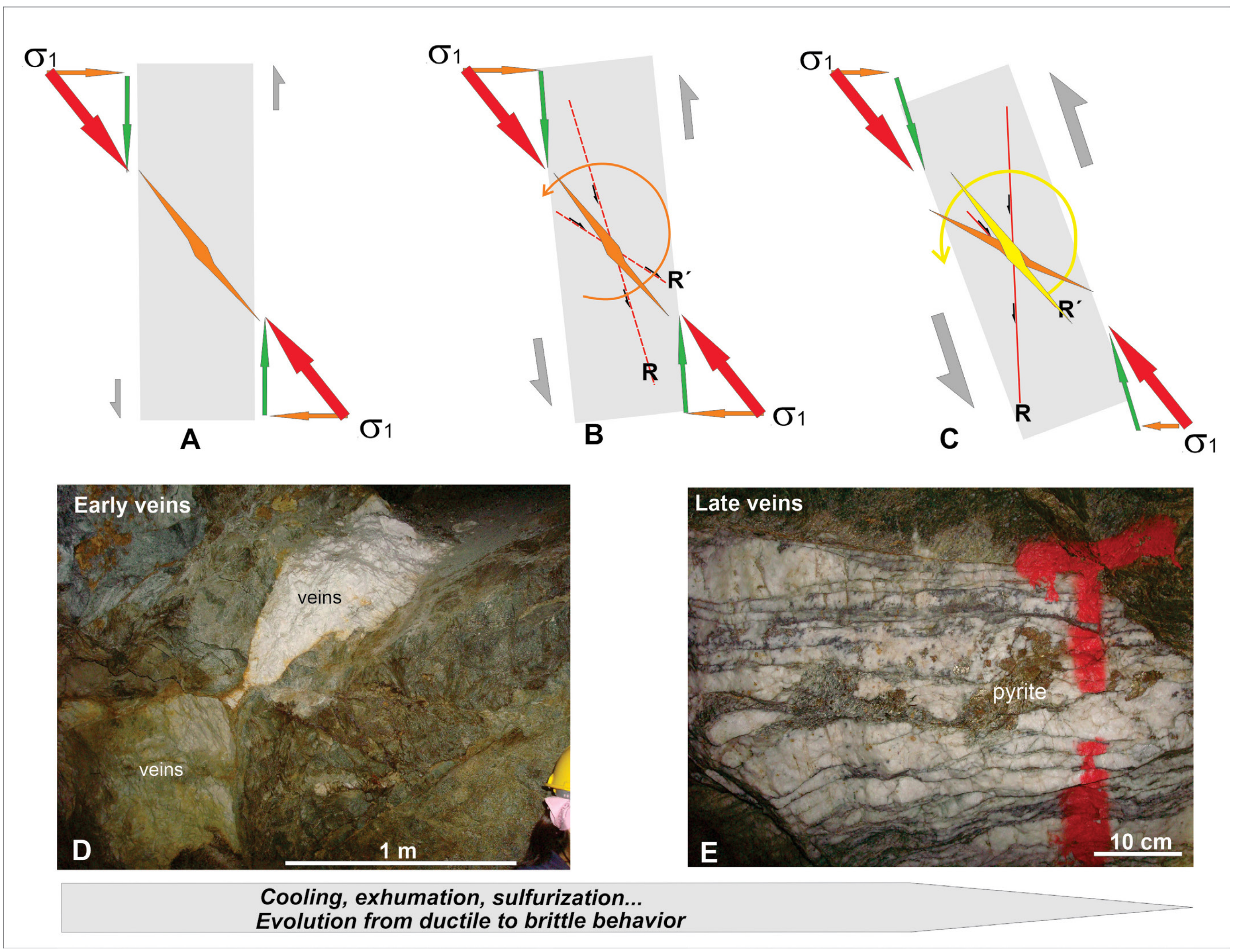

Figure 7. Evolution diagram from an early ductile to a late brittle environment. A: Early stage of sinistral shear system produced by principal horizontal stress (σ_1) in red arrows. Green arrow: transcurrent compound. Orange arrow: compressive compound. B: Clockwise evolution with Riedel (R) and AntiRiedel (R') subordinate fractures associated with early orange-coloured veins. C: Late stage. Early emplaced veins (orange) have been subjected to cumulative deformation rates to the point where they exhibit counterclockwise rotation and sigmoidal evolution of late veins (yellow). D: Irregular and concordant quartz vein. E: Tabular and discordant ribbon banded quartz veins.

inclinations preferentially to the east. It is considered that both corridors were emplaced in cuspidal and/or flank sectors in pulses of mineralizing fluids generated in the late stages of the El Carmen Stock emplacement taking advantage of the dilatancy produced contemporaneously as it cooled.

Decametric characterization

In the El Bagre District, two main submeridianal trends (the La Ye and El Carmen belts) can be identified, containing the most continuous decametric vetiform developments currently known (Fig. 7):

i) The La Ye belt, whose vein-shaped bodies exhibit right-stepping in plant arrangements that dip to the west, and ii) The El Carmen belt, whose vetiform bodies dip to the east. Although it is also possible to recognize sectors with en échelon arrangement distribution following a right-stepping pattern of the vetiform segments contained in NNW-SSE corridors.

Taken in account the Anderson Law that relates univocally the stress field with the position of the generated fractures (both faults and joints) this arrangement suggests a sinistral transcurrent component (see more details in Rossello and López-Isaza 2011). In particular, because the position of the controlling joints of the mineralization are those parallel to the maximum principal stress (σ_1), an NNW-SSE orientation of this stress can be estimated (Fig.7). As a consequence of this spatial relationship, a NS sinistral transcurrent component can be interpreted for these corridors of ore bodies. Previous model based only on the kinematics related to the stress field responsible for the Otu Fault indicates a dextral transcurrent component (Naranjo Sierra et al. 2018). In addition, this spatial distribution allows the identification of subordinate Riedel

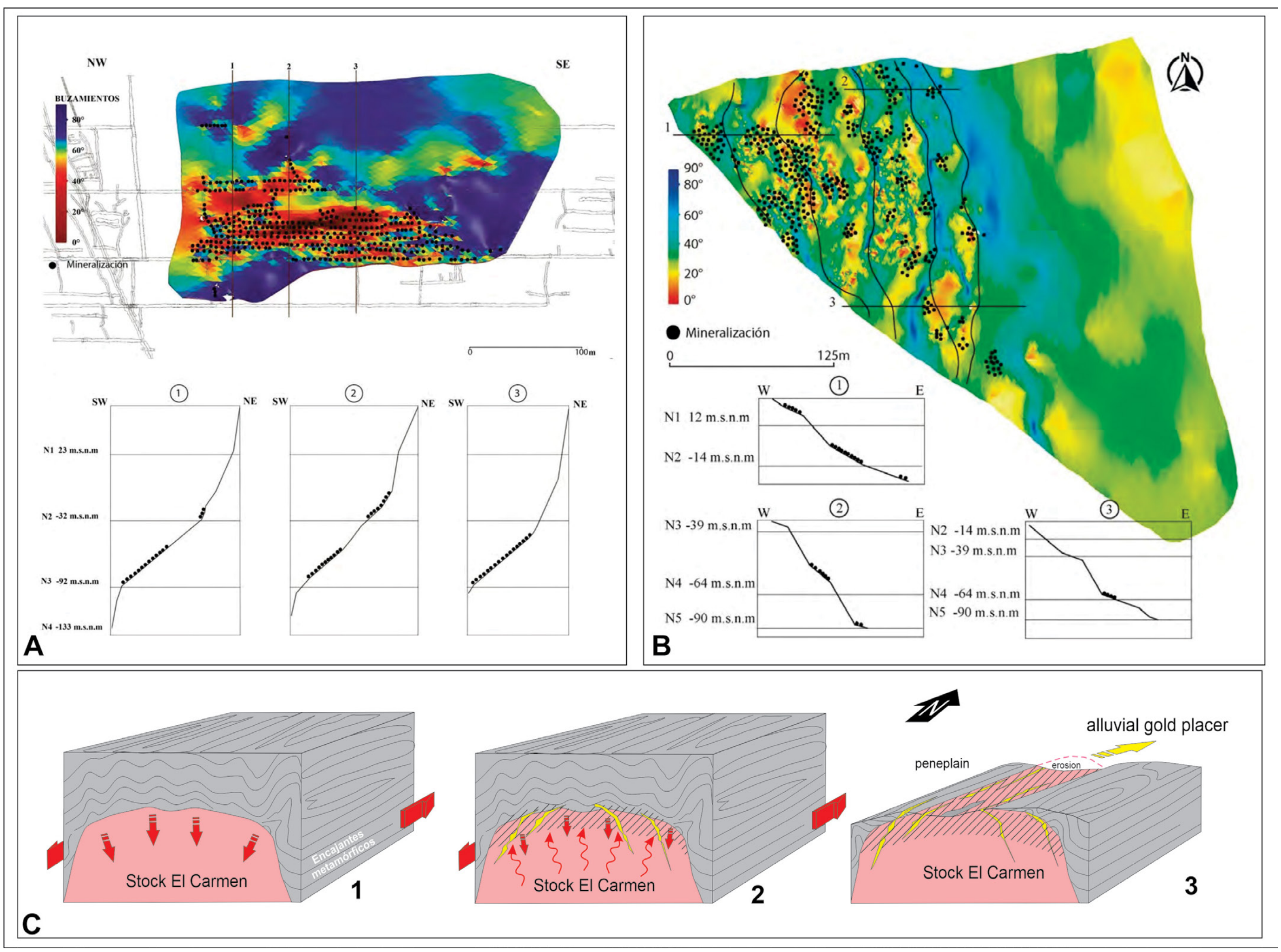

Figure 8. A. Frontal projection of block C, La Ye mine with vertical profiles showing the existence of high ore grades related to the dip inflection of the structure. B: Plan projection for block E of the Los Mangos mine. In both cases the highest concentration of gold (black dots) associated with dilatant flexures is observed (taken from Salgado-González et al. 2021). C: Evolutionary cartoon of the mineralization from late stock contraction by cooling (1), fluid generation and vein emplacement on the stock dome (2), and present stage showing an eroded peneplain close to the stock top with erosion and gold placer generation (3).

fractures (R and R') capable of controlling mineralization along the fracture development.

Based on the vein morphologies, the emplacement shows an evolutionary behaviour from a more ductile early stage to a more brittle one, favoured by cooling associated to exhumation with increasing sulphidation (Fig. 7). As a consequence of this process, the early veins are more irregular with pinch and swell morphologies, massive, mostly concordant with the host rocks anisotropies and with evidence of little sulphidation. In contrast, the late veins are more tabular, multibanded with sulphidation and discordant in relation to the anisotropy of the host rocks.

In addition, the earliest veins (orange colour in Fig. 7A) show a change of counterclockwise rotational disposition due to left-handed transcurrence that places them on more NW-SE courses (Fig. 7B). In contrast, the later veins (yellow in Fig. 6C) are arranged subparallel to the position of the maximum principal stress NNW-SSE.

Salgado-González et al. (2021) describe in the Block E of the Los Mangos mine (Fig. 8), vein inflections both in plan-view and in profile section, where the highest grades of Au mineralization stand out. These segments of enriched veins are located where they acquire general values of inclination of the order of 20°- 35° and buckling in plan that reach 15° with respect to the regional dip (Fig. 8A and 8B). These changes in the three-dimensional deformation of the faults controlling the mineralization created differential dilatational environments that were highly favourable for the transport and deposition of fluids (Rossello and López-Isaza 2022).

Although a detailed analysis of the La Ye Mine is not available, the presence of numerous workings in adjacent areas where the thicker veins assume a mantiform arrangement suggests an equivalent relationship. Salgado-González et al. (2021) observed little or no high tenors in the high dip angle zones and, on the contrary, the existence of high tenors in the lower dip zones. These increases in vein thickness and mineralization can also be linked to their cuspidal position within the migmatitic host rock, near its contacts (Fig. 8C). In

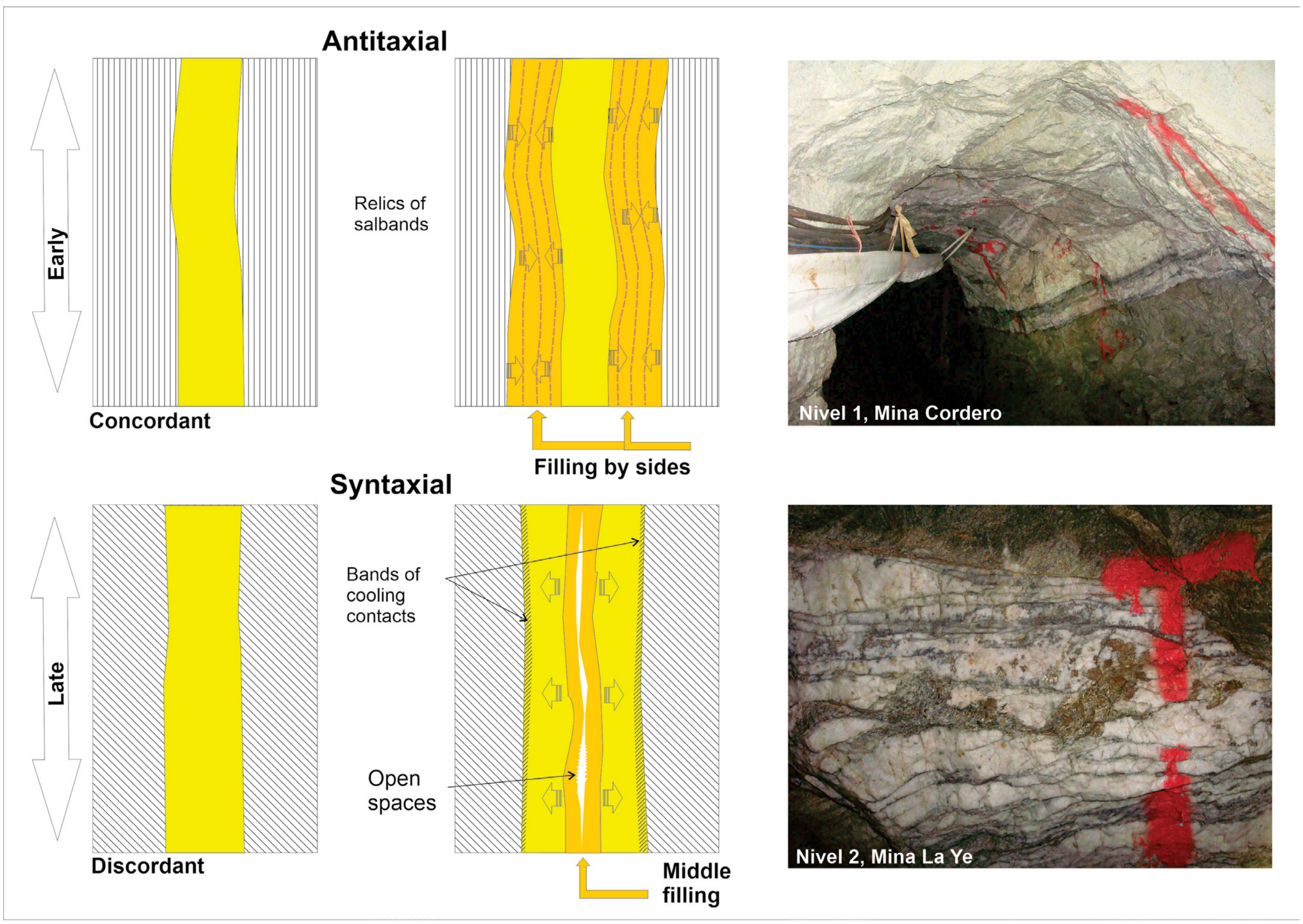

Figure 9. Idealized scheme of the two extreme types of infill mechanisms of auriferous mineralization: from the quartz bands (Antitaxial) or from the central zone (Syntaxial).

this context, the reduction in the volume of the intrusive due to cooling, which facilitates the emplacement of mineralizing fluids, would be evident.

Metric characterization

An analysis of the mineralization in several vein outcrops within the underground workings of the La Ye mine reveals an evolution associated with a ductile-to-brittle deformation system. The veins exhibit a variety of textures, ranging from typical ribbon quartz, sometimes with misty edges and mineralized banding (antitaxial and syntaxial bands following Ramsay 1980), to more tabular forms (Fig. 9). They are also affected by fracturing and brecciation linked to very late-stage processes, resulting in natural crushing.

The textural characteristics of the quartz veins allow identifying early mechanical behaviours preferentially more ductile (Fig. 9A). Thus, we can recognize bands with pinch and swell to boudinage-type development, frequently concordant with the anisotropy of the bedding. These features are superimposed by later events that determine more brittle behaviours expressed by conspicuous brecciation and fracturing (Fig. 9B).

DISCUSSION

Mineralizing episodes

Analysis of radiometric data from the magmatic units of the Segovia Batholith and El Carmen Stock, along with some spatially associated mineralization (Leal-Mejía et al. 2008), reveals two magmatic-mineralizing events, approximately corresponding to: i) the Carboniferous (possibly Permian) in the El Bagre-Nechí districts, and ii) the Jurassic-Cretaceous in the Segovia-Remedios district.

The emplacement of quartz veins took place during the post-emplacement phases of the plutonic bodies, in cuspidal positions near their contacts with the surrounding rocks. As a result, concordant veins can be identified, which are later intersected by discordant veins that cut through them (Fig. 10).

Understanding the structural processes that lead to dilatancy is crucial, not only for defining the geometry, size, and spatial distribution, but also for controlling the crystallization of mineralization. Dilatancy resulting from thermal contraction in brittle rock masses may be the outcome of dynamic fracture growth induced by localized stresses or mismatches in elastic properties (such as mode I joints), which propagate during the contraction caused by cooling (Li et al., 2017, Rossello and López-Isaza 2023) is unconformably covered by Cretaceous sedimentary units

Although the spatial distribution of the mineralized veins is arranged in submeridional corridors, the low dip angles they exhibit are inconsistent with a genesis solely linked to transcurrent phenomena. In such cases, the faults responsible for dilatancy should be preferentially oriented subvertically. The most common vein patterns, observed as steps in plan, show a right-lateral disposition, which is consistent with sinistral kinematics along the submeridional corridors.

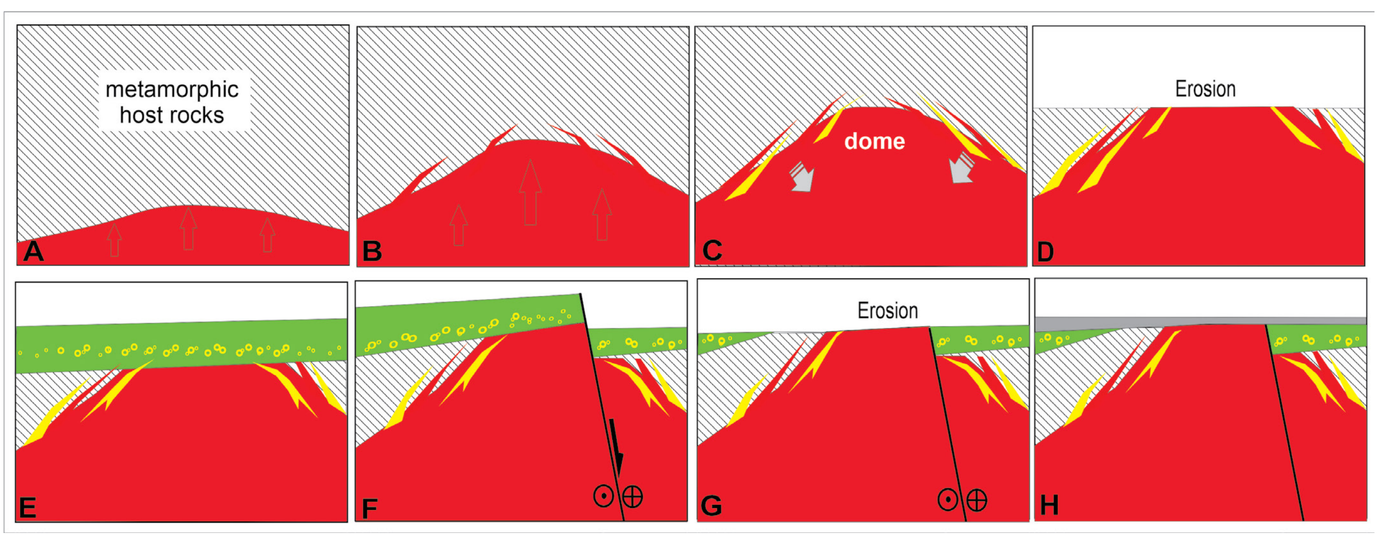

Figure 10. Idealized evolutionary scheme of the emplacement of gold mineralization in domes of the present-day intrusive bedding after having undergone two major periods of exhumation. A: Beginning of the diapiric ascent of the El Carmen Stock. B: Intrusion of early veins into the metamorphic basement (Carboniferous). C: Cooling contraction with development of dilatancy in the dome occupied by synchronous late veins. D: Exhumation and erosion (Mesozoic). E: Deposition of Cretaceous sequences on the peneplains carved i the basement with development of fossil alluvial placers. F: Deformation by the Andean Inca tectonic phase. G: Exhumation and erosion and final emplacement. H: Development of saprolites and discordant deposition of Quaternary successions with active gold-bearing placers.

Additionally, veins with a left-stepping arrangement also occur, and, applying the same criteria, they clearly indicate opposite kinematics (Rossello and López-Isaza 2023). This ambiguity allows for the interpretation of superimposed episodes, as proposed by Naranjo-Sierra (2021), although without strong temporospatial evidence. This analysis is further supported by the recognition of an evolutionary sequence in vein-shaped textures, from a primary character with boudinages and banding to the filling of open spaces, followed by brittle deformation resulting in brecciation.

a) In the first stage, a volumetric contraction of the granitic body of the El Carmen Stock occurs, creating spaces that are synchronous with its cooling during the Carboniferous (and possibly continuing into the Permian?). This process favours the emplacement of predominantly quartz mineralization, followed by sulphides, which are positioned sub-parallel to the contacts with the metamorphic host rocks. The presence of elongated basement blocks within the veins (Fig. 4F and I) supports the generation of dilatancy.

b) Subsequently, the earliest deformation, driven by the strain field associated with the Inca phase of Andean tectonics, affects the veins under conditions of shallow burial depth and lower temperatures, imparting a brittle character to them.

The presence of structural patterns indicative of contrasting kinematics suggests the involvement of early contractional mechanisms related to a volumetric decrease in the granitic body, occurring long before the stress fields associated with the formation of the Otú fault system, which is interpreted as dextral transcurrent (Naranjo-Sierra 2021). Given the temporal nature of the pre-Mesozoic mineralization, the deformational events linked to the Peruvian phase of Andean tectonics are unrelated to its spatial control.

Simplified relationships of discrete displacements and dip angles suggest a significant dilatancy potential, which facilitates the emplacement of syntectonic mineralization. The subvertical spatial arrangement of the transcurrent faults is likely to enable a direct connection between deep sectors associated with the generation of magmatogenic fluids and shallower environments typical of porphyritic deposits, particularly their epithermal and geothermal crusts. Thus, it would not be exclusive to consider a direct relationship between the emplacement of the veins and a stress field that generated transcurrent deformation, as interpreted by Naranjo-Sierra et al. (2016). Additionally, the presence of doleritic-type basic dykes observed in the underground workings, which cut through the veins attributed to the Jurassic (Fig. 2D), further supports their early temporality in relation to Andean faulting.

Ages of mineralization

The youngest ages of the Antioquia Batholith (around 60 Ma) are found in its central portion, in contrast to the older ages (around 80 Ma) at its periphery. This distribution suggests a less viscous flow of the batholith in the central area and indicates significant crystallization times, with the batholith currently at an erosional level (Restrepo-Moreno et al., 2009).Although widely accepted by many colleagues, preliminary analysis of available regional mapping (Feininger et al. 1972; Gómez and Montes 2020) and specific studies (Echeverry-Castañeda et al. 2009; Londoño-Herrera et al., 2009) suggests that the Otú Fault does not exhibit significant surface expression or proven displacement in the Remedios-Segovia area (Fig. 1). According to Feininger et al. (1972), the contacts of the units bounded by this fault could be normal, as no conclusive structural evidence supporting such an interpretation is visible in the available maps and studies. Therefore, it cannot be definitively stated that the inflection towards the NW quadrant, north of the latitude of Remedios, represents an extensional environment (releasing bend), if its function is considered to be sinistral transcurrent, as proposed by Echeverry-Castañeda et al. (2009), to explain the emplacement of the mineralization in the Segovia-Remedios district.

The El Carmen Stock, with Carboniferous-aged magmatism (ca. 330-310 Ma), hosts an important auriferous vein system in the El Bagre District (El Carmen - La Ye belts, Fig. 6). Although the precise age of the auriferous mineralization in these occurrences has not been established, the associated alteration suggests a minimum age of approximately 280 ± 6 Ma (K/Ar, sericite). However, this age could reflect the resetting of the isotopic system due to a regional Permian-Triassic tectono-thermal event (Vinasco et al. 2006). The Early Permian K-Ar sericite age of hydrothermal alteration obtained at La Ye (Naranjo-Sierra and Alvarán-Echeverri 2018) can be considered the minimum age for mineralization. However, given the widespread nature of Permo-Triassic magmatism, the possibility that this tectono-magmatic event re-set the age of an earlier mineralization must also be considered.

The age of the mineralization could extend back to the Carboniferous, corresponding to the magmatic assemblage of the El Carmen Stock, suggesting a direct relationship between magmatism and mineralization at La Ye - El Carmen. The Late Jurassic dioritic porphyry dike, which cuts through the leucotonalite of the El Carmen Stock (Fig. 2D), postdates the gold mineralization.

Although further geochronological analyses are needed to definitively determine the age of the mineralization in this district, lead isotope results for sulfide samples from both districts show distinct matrices: i) the El Bagre samples are less radiogenic ($^{206}Pb/^{204}Pb$ = 18.324-18.450), compared to ii) the sulfide samples from the El Silencio mine ($^{206}Pb/^{204}Pb$ = 18.687-18.710). Additionally, the lead isotope ratios are similar to those of sulfide samples from gold occurrences within or near the Late Cretaceous to Paleocene Antioquia Batholith (Álvarez 1983, Vinasco et al. 2006, Ibáñez-Mejía et al. 2007). Thus, El Bagre vein-type gold mineralization represents the only confirmed pre-Jurassic gold mineralization in the Colombian Andes.

Outcrop characteristics of the Nechí District

It is important to consider that the thick saprolithic cover significantly alters the original orientation of the veins, causing them to become more subhorizontal and displaced downhill from their original positions, potentially dispersing the 'weathered' material (colluvial displacement) far from its source (Fig. 11). Caution is necessary when analysing lineaments in the existing topography, as there is a risk of misinterpreting geomorphological features related to the basement structure as those formed by the influence of current runoff.

CONCLUSIONS

The new interpretations, based on available tectonostratigraphic data, allow us to conclude that in the El Bagre and Nechí districts, hypogene gold mineralization is associated with granitic rocks older than the Mesozoic. In the El Bagre district, mineralization is hosted within the Carboniferous-aged El Carmen Stock, while in the Nechí area, based on regional surveys, it is linked to Permian-aged rocks. Most of the mineralized veins in both districts are arranged along a north-south *en échelon* corridor with gentle to nearly subhorizontal dips, creating a spatial pattern that is difficult to reconcile with an exclusively subvertical transcurrent tectonic

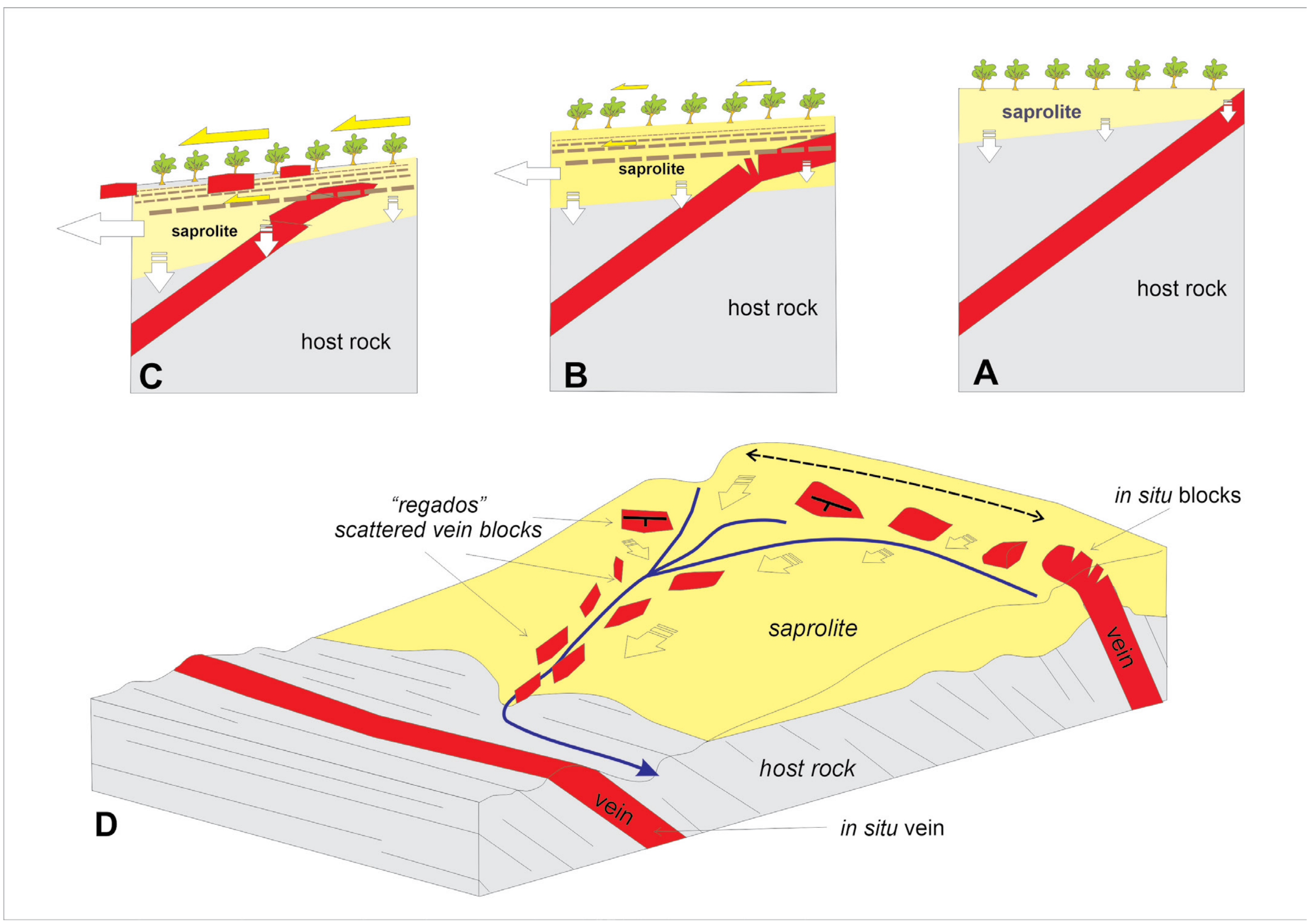

Figure 11. Idealized scheme of the development of the saprolite and the arrangement and migration of the scattered quartz vein relicts ("*regados*" in Spanish mean scattered). A: Initial stage where lithologies begin to disintegrate. B: Development of a saprolite cover where the edges may be showing the original position of the vetiform bodies. C: Blocks begin to creep according to the slope developing exotic (scattered) outcrops. D: Distribution of proximal detached blocks are usually arranged subparallel to contour lines, whereas distal blocks are usually aligned according to drainage design.

environment. This arrangement of gently dipping veins within granitic rocks, near their metamorphic host rocks, suggests a relationship with late magmatic emplacement as a key petrological control on the mineralization. Consequently, the traditional spatial association of mineralization with the Otú fault corridor, linked to Andean deformation, should be reconsidered, as it would create temporal inconsistencies. This apparent discrepancy in spatial configurations supports the need to consider tectonic episodes that may not be contemporaneous.

A new petro-tectonic structural control, combined with differential volumetric changes in the granitic host rocks, is proposed to explain the emplacement of the vetiform bodies associated with brittle-ductile fracturing in a sinistral transcurrent context. This new model is regarded as more suitable for the gold mineralization in the El Bagre District and shares similar characteristics with the less developed Nechí District. Despite the limited surface expression of geological outcrops and the thick soil cover, this alternative 4D petro-tectonic model supports the identification of unexplored areas with high potential for defining remaining primary gold targets. The most prospective resources are likely to be found near the contacts between the granitic stocks and their metamorphic host rocks.

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