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GEOLOGICAL NOTE

# Is the Central Cordillera of Colombia a potential source of graphite?: Implications for the energy transition in Colombia

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**ABSTRACT.** With the imperative to diversify energy matrices and reduce dependence on fossil fuels, nations are actively exploring alternative sources of energy. In that sense, graphite, due to its role in lithium batteries, emerges as a pivotal component in the global energy transition. Governments, recognizing the strategic significance of certain minerals, compile lists of critical minerals to achieve energy autonomy. However, in the recent update of Colombia's critical mineral list, noteworthy minerals such as lithium and graphite were overlooked.
Despite the widespread presence of graphite along the Central Cordillera of Colombia, potentially extending into the Real Cordillera in Ecuador, its importance has remained largely unnoticed for years. This manuscript underscores the critical need to comprehensively characterize graphite occurrences in the Andes of Colombia. The manifestations of graphite suggest its potential significance in the pursuit of cleaner energy sources. This study aims to draw attention to the overlooked role of graphite, urging a reevaluation of its inclusion in Colombia's critical minerals list to enhance the nation's strategic positioning in the global shift towards sustainable energy solutions.

*Keywords: Graphite, Pelitic schists, Cajamarca Complex, Central Cordillera, Energy transition, Critical minerals.*

**RESUMEN. ¿Es la Cordillera Central una fuente potencial de grafito?: Implicaciones para la transición energética en Colombia.** Con el imperativo de diversificar las matrices energéticas y reducir la dependencia de los combustibles fósiles, las naciones están explorando activamente fuentes alternativas de energía. En ese sentido, el grafito, debido a su papel en las baterías de litio, emerge como un componente importante en la transición energética global. Los gobiernos, reconociendo la importancia estratégica de ciertos minerales, elaboran listas de aquellos que son críticos para lograr la autonomía energética. Sin embargo, en la reciente actualización de la lista de minerales críticos de Colombia, se pasaron por alto algunos destacados como el litio y el grafito.
A pesar de la amplia presencia de grafito a lo largo de la cordillera Central de Colombia, potencialmente extendiéndose hasta la cordillera Real en Ecuador, su importancia ha pasado mayormente desapercibida durante años. Este manuscrito subraya la necesidad crítica de caracterizar de manera integral la existencia de grafito en los Andes de Colombia. Las manifestaciones de este elemento sugieren su importancia potencial en la búsqueda de fuentes de energía más limpias. Este estudio tiene como objetivo llamar la atención sobre el papel pasado por alto del grafito, e instar a una reevaluación de su inclusión en la lista de minerales críticos de Colombia para mejorar la posición estratégica del país en el cambio global hacia soluciones energéticas sostenibles.

*Palabras clave: Grafito, Esquistos pelíticos, Complejo Cajamarca, Cordillera Central, Transición energética, Minerales críticos.*

## 1. Introduction

Graphite, a soft and crystalline form of carbon (C), serves diverse purposes, including applications in high-temperature lubricants, brushes for electrical motors, refractories for steelworks, friction materials, and crucially, in batteries and fuel cells (Beyssac and Rumble, 2014). Given its integral role in energy generation, graphite stands as a key component in Li-ion batteries, positioning it as one of the 50 critical minerals identified by the International Energy Agency (International Energy Agency, 2022[1]) for its anticipated escalating global demand in the coming years (World Economic Forum, 2019[2]).

Graphite is a common mineral in many metamorphic supracrustal rocks. Hyuck (1990) suggested that rocks should contain a minimum of 0.5% TC (total carbon) to be classified as carbon-bearing (graphite). The presence of graphite not only endows rocks with excellent electrical conductivity but also facilitates their detection through geophysical methods (Gautneb *et al*., 2020).

The pricing of graphite is intricately tied to factors like purity and flake size (Simandl *et al*., 2015; Gautneb *et al*., 2020). Among the globally recognized types of natural graphite deposits, such as microcrystalline or amorphous, vein-related, and crystalline flake, the latter is the most extensively extracted due to its widespread occurrence; vein-related deposits contain higher concentrations of this mineral but are less common (Krauss *et al*., 1988; Simandl *et al*., 2015; Cui *et al*., 2017).

The Colombian Andes, particularly the Central Cordillera, boast continuous belts of pre-Jurassic medium- to high-grade metasedimentary rocks containing variable amounts of graphite that were affected by successive pulses of arc-related magmatism during the Meso-Cenozoic (Bustamante *et al*., 2017a). Despite the prevalent occurrence of graphite in these rocks (Orrego, 1987), comprehensive studies aimed at characterizing this mineral are lacking in Colombia. Until now, the potential of graphite as a strategic mineral in Colombia remains uncertain, particularly since it was not included among the 17 strategic minerals for the energy transition in the country (Agencia Nacional de Minería, 2023[3]).

This manuscript aims to underscore the critical need for a more in-depth study of graphite occurrences in the Central Cordillera of Colombia, demonstrating their potential economic significance for the country despite their omission from the published list of strategic minerals.

## 2. Geologic background

In general, Colombian geology can be understood in terms of three major mountain ranges, the Eastern, Central, and Western Cordilleras (Fig. 1). The Eastern Cordillera contains a Precambrian basement overlain by metasedimentary rocks of oceanic affinity deposited in the Early Paleozoic. The Central Cordillera is constituted by a crystalline basement including high-grade Proterozoic metamorphic rocks to the north (Cuadros *et al*., 2014), and a ~N-S distribution of plutonic rocks with zircon U-Pb crystallization ages ranging from the Paleozoic (Leal-Mejía *et al*., 2019; Rodríguez-García *et al*., 2019; Restrepo *et al*., 2023) to the Cenozoic, forming different continental magmatic arcs (Bustamante *et al*., 2016, 2017b; Leal-Mejía *et al*., 2019; Rodríguez-García *et al*., 2019) (Fig. 1). Both flanks of the Central Cordillera include Paleozoic to Mesozoic medium- to high-grade metamorphic rocks such as metapelites and metabasites (Fig. 1). The Western Cordillera comprises Cretaceous, allochthonous ultramafic and mafic rocks, and marine sediments formed in an intra-oceanic plateau and arc-related setting (Kerr *et al*., 1997; Villagómez *et al*., 2011; Hincapié-Gómez *et al*., 2018). The Central Cordillera is bounded to the west by Cretaceous mafic volcanic rocks of oceanic to continental affinity gathered in the Quebradagrande Complex (Nivia *et al*., 2006) and the medium- to high-pressure metamorphic sequences of the Cretaceous Arquía Complex (Bustamante and Bustamante, 2019). The contact between the allochthonous rocks of the Western and the more continental-related Central cordilleras is the Cauca-Almaguer fault (Fig. 1).

## 3. What makes a graphite commercially interesting?

When evaluating the economic potential of diverse graphite projects or occurrences, it is essential to consider several key factors, as highlighted in reviews by Krauss *et al*. (1988), Beyssac and Rumble (2014), Scogings *et al.* (2015), and Simandl *et al*. (2015).

[1] International Energy Agency. 2022. Final List of Critical Minerals. https://www.iea.org/policies/15271-final-list-of-critical-minerals-2022

[2] World Economic Forum. 2019. A Vision for a Sustainable Battery Value Chain in 2030. World Economic Forum: Cologny 2019: 52 p. Geneva, Switzerland.

[3] Agencia Nacional de Minería. 2023. Resolución número 1006 del 30 de noviembre de 2023, República de Colombia. URL: https://www.anm.gov.co/sites/default/files/Resoluci%C3%B3n_ANM_1006_de_30_noviembre_de_2023.pdf

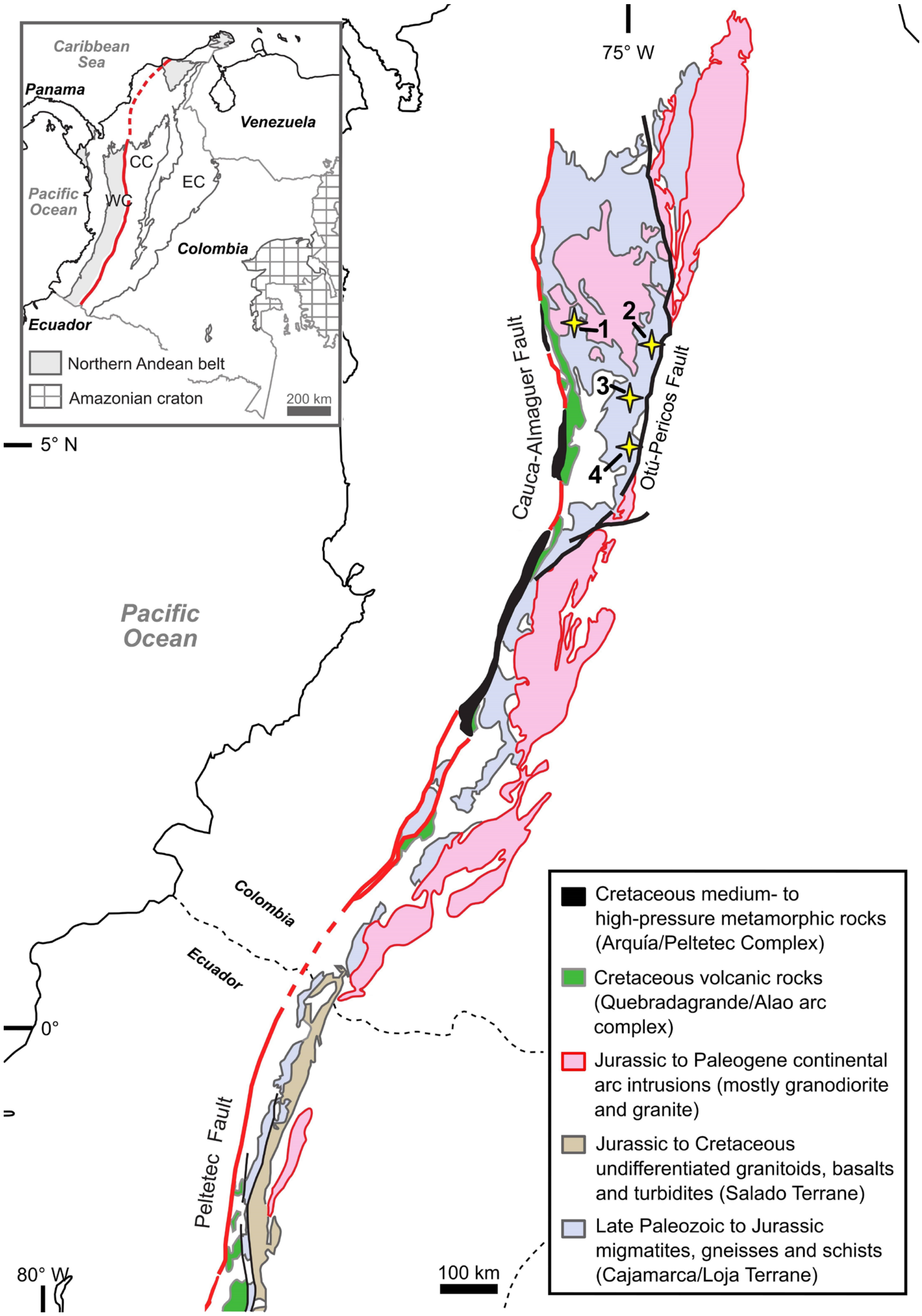


FIG. 1. Geology of the Central Cordillera of Colombia, showing the distribution of metamorphic belts and their relationship with the Meso-Cenozoic continental arc-related intrusions. Yellow stars represent the sites with graphite bearing-schists mentioned in this manuscript. **1**: Palmitas, **2**: Río Claro, **3**: La Victoria-Samaná, **4**: Fresno. Inset: main geological domains of Colombia showing the Western (WC), Central (CC), and Eastern (EC) Cordilleras. Red continuous/segmented line: Cauca-Almaguer Fault. Map after Bustamante *et al*. (2023).

These factors include the grade of total carbon (% TC), deposit size, and the amount of contained graphite, which is calculated as the product of grade and tonnage, with grade taking precedence over tonnage in ranking. Additionally, the geographical location of the deposit plays a crucial role in determining its economic viability. Furthermore, if available, metallurgical test data should be taken into consideration, focusing on factors such as flake size distribution and product purity. These considerations are summarized in table 1.

Maintaining low levels of impurities is crucial, especially of minerals that could adversely impact the properties of the extracted graphite (Krauss *et al*., 1988; Simandl *et al*., 2015). For applications in electronics and high-temperature environments, high-purity graphite is indispensable (Table 1). Careful consideration of other minerals within the rock is necessary as well; some may serve as valuable co-products (*e.g*., micas), while others may complicate the extraction process or diminish the quality of the extracted graphite (*e.g*., clays and sulfurs).

The degree of crystallinity plays an important role in influencing the performance of graphite in specific applications (Simandl *et al*., 2015). Higher crystallinity is often preferred for applications requiring superior electrical conductivity and thermal stability. Additionally, the degree of weathering and alteration of the rock can influence graphite extraction and processing; in the case of schists, fresh, unaltered rocks are generally preferred for graphite mining.

Deposit location and accessibility are important considerations for the economic viability of exploitation. Transportation costs and logistical challenges can significantly impact overall production costs. For graphite-bearing schists, the size and geometry of the deposit are key in determining the feasibility of commercial exploitation, with larger, well-defined deposits generally proving more economically attractive (Krauss *et al*., 1988).

Geological classification of graphite deposits includes those associated with regional and contact metamorphism, and hydrothermal ones, associated with magmatic intrusions (Cui *et al*., 2017; Sun *et al*., 2018). In all these cases, protolith type plays a major role being more important those in which more organic matter is available, because it that can be transformed into graphite due to the thermal effects on coal or carbonaceous mudstones (Cui *et al*., 2017; Sun *et al*., 2018).

## 4. Characteristics of the graphite-bearing schists of the Central Cordillera of Colombia

The Central Cordillera hosts a ~N-S-oriented belt comprising medium- to high-grade (Paleozoic to Mesozoic) metamorphic rocks, extending the entire length of the Cordillera (Fig. 1). These rocks constitute the Cajamarca Complex in the sense of Maya and González (1995), and includes pelitic schists and gneisses, quartzites, marbles, and minor amphibolites and migmatites. Zircon U-Pb and amphibole-mica $^{40}Ar/^{39}Ar$ metamorphic ages within the northern part of the Complex range from *ca*. 240 to 230 Ma (Vinasco *et al*., 2006; Restrepo *et al*., 2011; Martens *et al*., 2014; Cochrane *et al*., 2014), whereas the southern part exhibits ages from *ca*. 158 to 146 Ma (Blanco-Quintero *et al*., 2014).

To illustrate the prevalence of graphite in the metamorphic rocks of the Central Cordillera, our investigation focused on four distinct areas: Palmitas and Río Claro, in Antioquia, La Victoria-Samaná, in Caldas, and Fresno, in Tolima (Fig. 1).

The Palmitas schists outcrop on the western flank of the Central Cordillera. These rocks correspond to dark-grey schists with quartz lenses and noticeable

**TABLE 1. MAIN USES OF GRAPHITE ACCORDING TO ITS TOTAL CARBON CONTENT AND FLAKE SIZE.**

| Property | Traditional uses (*e.g.*, lubricants, foundry applications) | Refractories and crucibles | Expandable graphite production | High-tech applications (*e.g.*, lithium-ion batteries, graphene production) |
|---|---|---|---|---|
| Graphite content | 10-20% | 20-30% | ≥80% | ≥99% (high-purity graphite) |
| Flake size | Small to medium | Medium to large | Generally, larger flakes are preferred | Large and well-defined flakes |

See Krauss *et al*., 1988; Beyssac and Rumble, 2014; Scogings *et al*., 2015; and Simandl *et al*., 2015 for a complete review of graphite uses.

andalusite crystals (Fig. 2A and B). Biotite and graphite define the main foliation and the crenulation cleavage. The andalusite crystals are prevalent near the contact area with the diorites of the Altavista stock. This intrusive contact also led to the formation of a hornfels zone.

The Río Claro quartz-sericitic schists (Fig. 2C and D) outcrop on the eastern flank of the Central Cordillera (Feinniger *et al*., 1972). These schists are intruded by the Antioqueño Batholith with zircon U-Pb crystallization ages between 97 and 58 Ma (Duque-Trujillo *et al*., 2019). Associated lithologies include quartzites, amphibolites, and feldspathic gneisses near the Palestine Fault, along with marbles interleaved with the schists (Feininger *et al*., 1972; González, 1980). The marbles predominantly comprise carbonates and accessory quartz, graphite, micas, and pyrite (Feininger *et al*., 1972; González, 1980).

The La Victoria-Samaná schists are commonly found as intercalations in which graphitic beds alternate with either more quartzose or micaceous beds. The intrusion of post-Triassic granitoids commonly formed hornfelses in the schists, developing a granoblastic texture.

Lastly, the Cajamarca schists in the Fresno area form a folded sequence of metapelites, occasionally interleaved with metabasites (Blanco-Quintero *et al*., 2014; Bustamante *et al*., 2017a). Biotite, quartz, and graphite are the major minerals defining the schistosity of the rock (Fig. 2E and F). These rocks are in intrusive contact with the Paleogene tonalites of the Hatillo Stock (Bustamante *et al*., 2017b), resulting in a hornfels zone with fine decussate biotite crystals.

Compositional analyses of the schists reveal a consistent mineralogy across all four areas. Under the microscope, the rocks predominantly consist of muscovite (30-50%), quartz (20-50%), graphite (10-15%), biotite (10-40%), and plagioclase (<5%) (percentages determined by point counting). Such an amount of graphite would make these rocks as an average international deposit (see Gautneb *et al*., 2020). However, detailed geological mapping of these areas is required. Andalusite may also be present (<3%), so may other accessory minerals such as apatite, zircon, and opaques. The grano-lepidoblastic texture, which defines the schistosity, is characterized by alternating bands of oriented micas and graphite, along with recrystallized quartz (Fig. 2).

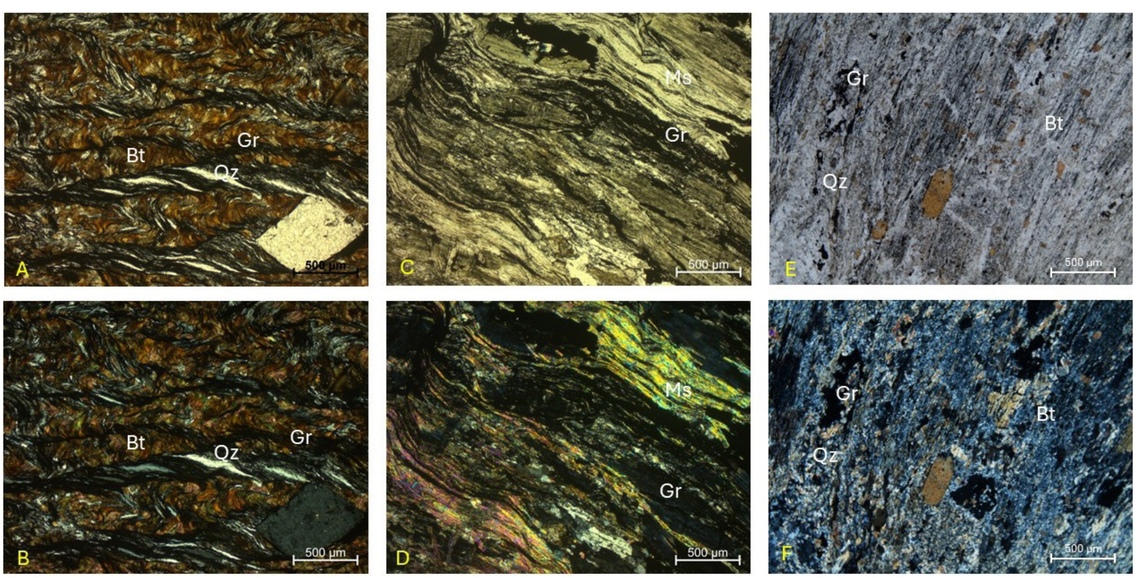


FIG. 2. Photomicrographs of representative samples of the metasedimentary rocks of the Central Cordillera showing the graphite crystals as one of the minerals that defines the foliation. **A-B.** Palmitas biotite-schists with square andalusite porphyroblasts. **C-D.** Río Claro quartz-sericitic schists with a large graphite crystal defining the main foliation. **E-F.** Quartz-biotite schists of the Fresno area with a square andalusite porphyroblast. Gr: Graphite; Qz: Quartz; And: Andalusite; Bt: Biotite; Ms: Muscovite. Photomicrographs A, C, and E were obtained with plane polarized light; B, D, and F were obtained with cross polarized light.

The distinctive decussate texture, defined by biotite and andalusite porphyroblasts crosscutting the schistosity planes (Fig. 2A and B), suggests a potential superimposed contact metamorphism event. This feature may be consequence of the intrusion of granitoid bodies present in all of the areas.

The mineral assemblage of these rocks allows us to suggest that they reached the greenschist facies of metamorphism, originating from a pelitic to semi-pelitic protolith. Blanco-Quintero *et al*. (2014), however, suggested the possibility that the schists of the Cajamarca complex may have reached the amphibolite facies. Intriguingly, the superimposed contact metamorphism may have elevated temperatures to the hornblende-hornfels metamorphic facies or even higher. Thermobarometric calculations for this thermal metamorphic event are, however, currently unavailable.

## 5. Concluding remarks

The Central Cordillera of Colombia hosts a suite of metamorphic rocks derived from pelitic to semi-pelitic protoliths, undergoing metamorphism within the greenschist to amphibolite facies conditions, as extensively proposed in previous studies. These conditions facilitated the conversion of organic matter into graphite. An additional thermal event, likely triggered by the late intrusion of granitoids ranging from stock to batholite sizes, may have allowed the further crystalline growth of graphite.

A petrographic comparison between the graphite-bearing schists described in this study and classical exposures in countries like Norway or Canada, where commercial extraction of this mineral is prevalent, reveals noteworthy similarities. The shared features encompass the nature of protoliths, the type of metamorphism, and the modal abundance of graphite. The graphite-bearing schists in the Central Cordillera therefore emerge as a compelling subject for future exploration and evaluation.

To assess the potential commercial viability of these rocks, a comprehensive approach is essential. This involves meticulous cartography of the schist belt, an examination of the metamorphic conditions governing their formation, with a specific emphasis on thermal metamorphism, and a detailed characterization of the physical properties of the graphite within these rocks. In addition, because graphite-bearing rocks are usually the most weathered and least exposed rock units where they occur, geophysics is usually required to outline promising occurrences. Such an evaluation will contribute to a thorough understanding of the economic prospects associated with the graphite-bearing schists in the Central Cordillera of Colombia.

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