Boletín Geológico

Boletín Geológico, 50(1), 2023

https://doi.org/10.32685/0120-1425/bol.geol.50.1.2023.666



Received: July 19, 2022

Revision received: November 17, 2022

Accepted: December 5, 2022

Published online: June 23, 2023

Research article

# Geological mapping for phosphate in the central region of the Eastern Cordillera, Department of Boyacá, Colombia

## Cartografía geológica para fosfatos en la región central de la cordillera Oriental, departamento de Boyacá, Colombia

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## Abstract

Detailed geological mapping, stratigraphic surveys, fossil collection and rock sampling for geochemical analysis were the tools used to identify lithostratigraphic units and specify the most interesting phosphate layers in the axial region of the Eastern Cordillera in the areas surrounding Tunja (Boyacá).

Sedimentary rocks with stratigraphic range between the Cretaceous and the Paleogene represent this part of the Eastern mountain range, and in some sectors, they are unevenly covered by Neogene and Quaternary deposits. The lithostratigraphic units of interest for phosphate prospection correspond to the Arenisca Dura Formation and equivalent siliceous fine-grained facies, and the overlying Plaeners and Arenisca de Labor-Tierna formations, which belong to the Guadalupe Group.

The reverse faults follow a preferential NE–SW direction and have vergences both to the SE and to the NW, though some are strike-slip faults motion (faults of Chivatá, Cormenchoque, Puente Hamaca, Viracachá, Soapaga, Machetá, Río Icabuco and Hermitaño), and have regional folds (synclines of Tunja, Cómbita and Úmbita) and local folds, they are equally oriented to the NE–SW, and are the dominant structures in the study area.

The geostatistical analysis of the geochemical X-ray fluorescence data (XRF) performed on 299 rock samples collected from the units of interest to determine phosphate contents in the Guadalupe Group, allowed us to define four sectors with high to medium $P_2O_5$ mineral potential: 1) Turmequé, Nuevo Colón and Tibaná zone, with 10.8-27.5%; 2) Ciénega and Viracachá area, with 6.74-10.8%; 3) the Samacá and Cucaita area, with 6.74-17.3%, and 4) the Toca and Tuta area, with 6.74-17.3%.

**Keywords:** stratigraphy, structural geology, Guadalupe Group, phosphates, geostatistical analysis.

**Citation:** Martínez, G., Rojas, N., Terraza, R., Martín, C., & Rojas, S. (2023). Geological mapping for phosphate in the central region of the Eastern Cordillera, Department of Boyacá, Colombia. *Boletín Geológico, 50*(1). https://doi.org/10.32685/0120-1425/bol.geol.50.1.2023.666

**Resumen**

La cartografía geológica detallada, los levantamientos estratigráficos, la recolección de fósiles y el muestreo de roca para análisisgeoquímicos fueron las herramientas utilizadas para reconocer las unidades litoestratigráficas y precisar los niveles de mayor in- terés de fosfatos en la región axial de la cordillera Oriental, en los alrededores de Tunja (Boyacá).

Rocas sedimentarias con un rango estratigráfico situado entre el Cretácico y el Paleógeno representan esta parte de la cordillera Oriental, en algunos sectores cubiertas discordantemente por depósitos del Neógeno y el Cuaternario. Las unidades litoestratigráficas de interés en fosfatos corresponden a la Formación Arenisca Dura y facies fino-granulares silíceas equivalentes, y las suprayacentes formaciones Plaeners y Arenisca de Labor y Tierna pertenecientes al Grupo Guadalupe.

Las fallas inversas con dirección preferencial NE-SW y vergencia tanto al SE como al NW, algunas con salto transcurrente (fallas de Chivatá, Cormenchoque, Puente Hamaca, Viracachá, Soapaga, Machetá, Río Icabuco y Hermitaño) y pliegues de carácter regional (sinclinales de Tunja, Cómbita y Úmbita) y local, igualmente orientados al NE-SW, son las estructuras dominantes en el área de estudio.

El análisis geoestadístico de los datos geoquímicos de fluorescencia de rayos X (FRX) realizado a 299 muestras de roca de las unidades de interés para determinar fosfatos, del Grupo Guadalupe, permitió definir cuatro sectores con potencial mineral alto a medio de $P_2O_5$: 1) zona de Turmequé, Nuevo Colón y Tibaná, con 10,8-27,5 %; 2) zona de Ciénega y Viracachá, con 6,74-10,8 %; 3) zona de Samacá y Cucaita, con 6,74-17,3 %, y 4) zona de Toca y Tuta, con 6,74-17,3 %.


**Palabras clave:** estratigrafía, geología estructural, Grupo Guadalupe, fosfatos, análisis geoestadístico.

## 1. Introduction

One of the fundamental objectives of the Servicio Geológico Colombiano (SGC) in the Directorate of Mineral Resources is to carry out prospecting to determine phosphorus minerals, following the guidelines presented in Conpes 3577 of 2009 (National Policy for the rationalization of the cost component of production associated with fertilizers in the agricultural sector), in order to identify and geologically evaluate areas of interest that contain phosphates in Colombia. Boyacá is one of four departments that potential contains this mineral resource.

Between 2013 and 2015, the SGC carried out detailed geological mapping work focused on prospecting for phosphates in the central region of the Eastern Cordillera in the surroundings of Tunja, which includes the municipalities of Samacá, Ventaquemada, Turmequé, Nuevo Colón, Tibaná, Jenesano, Ramiriquí, Ciénega, Viracachá, Boyacá, Soracá, Siachoque, Toca, Oicatá, Tuta, Cómbita and Motavita in the Department of Boyacá (Figure 1). The prospective units for phosphates are found in Upper Cretaceous rocks present in the Guadalupe Group, formed from base to top by the Arenisca Dura Formation or equivalent fine-granular siliceous facies, and the Plaeners and Arenisca de Labor-Tierna formations.

This article synthesizes the geological cartography and stratigraphy of the Upper Cretaceous in the region to identify the intervals and stratigraphic layers of interest for phosphate prospection and to determine the lithostratigraphic changes and the lateral and vertical continuity of the geological units that potentially contain phosphorus. Additionally, the other geological units and the structural features of the study area were delimited. The importance of studying phosphate deposits in sedimentary rocks lies in the fact that phosphorus is an essential nutrient for plants, and its deficiency greatly reduces crop yields. In addition, the appropriate and rational use of phosphate rocks as a source of phosphorus contributes to the sustainable agricultural growth of developing countries, particularly those endowed with phosphate deposits (FAO, 2007).

## 2. Methods

Geological cartography began with the analysis of the regional geology and the stratigraphy of the central portion of the Eastern Cordillera to define the main geological structures and the stratigraphic nomenclature that would be used, this involved compiling all the geological information previously collected (geological maps, technical reports, scientific articles, etc.).

During fieldwork, transects were made perpendicular to the geological structures, with a distance of between 0.5 and 2 km, establishing at least four control stations. This ensured the systematic mapping of lithostratigraphic units and geological structures (folds, faults and geological contacts) at a 1:25 000 scale, for which Google Earth images and conventional aerial photographs were used. Biostratigraphic ammonite studies (Etayo Serna, 2015) were fundamental to infer changes between specific stratigraphic intervals, allowed for comparison between contemporary lithological bodies and for the corroboration of the stratigraphic ranges of the existing units, as well as to determine the displacement of the geological faults.

For the description of outcrops and macroscopic samples, the following techniques were used: the thickness of laminae and beds (Campbell, 1967); the geometric description of laminae and beds (Reineck and Singh, 1980); the degree of stratigraphic disturbance by bioturbation (Moore and Scrutton, 1957); the rock color (Munsell chart from the Geological Society of America, 1995); the degree of weathering (terminology followed the Geological Society of London, 1990); grain shape and particle size (diagrams from Krumbein and Sloss, 1969); particle selection (Pettijohn and Siever, 1973); types of contacts between grains (Taylor, 1950); state of textural maturity of siliciclastic rocks (Folk, 1954); calculation of percentage of fossils, terrigenous and allochemical grains (diagrams from Baccelle and Bosellini, 1965); textural classification of siliciclastic sedimentary rocks (Folk, 1954); compositional classification of sedimentary rocks (Folk, 1974); and textural classification of calcareous rocks (Dunham, 1962, Folk, 1962).

The classification of siliceous rocks was based on Williams et al. (1954) which takes into account the percentage of microcrystalline quartz present in the rock. The procedure is as follows: in cases of values between 80 and 100%, the rock was classified as chert; between 50 and 80%, the rock corresponds to porcellanite, and in values between 25 and 50%, to siliceous claystone or mudstone.

Systematic sampling was carried out in the stratigraphic sections to carry out geochemical and paleontological analyses. The samples were sent to the Chemical Laboratory of the Servicio Geológico Colombiano for X-ray diffraction (XRD) and X-ray fluorescence (XRF) analyses to establish the mineralogy and chemical composition of the phosphates and associated rocks. A lithological correlation of the stratigraphic sections was performed based on the ammonite biostratigraphy and the stratigraphic position of the phosphates, calcareous layers and siliceous beds.

During the geological mapping and while measuring the stratigraphic sections, 299 samples were taken from the phosphorite layers and phosphate rocks of the Guadalupe Group, which is the unit with the highest potential for phosphates, to perform X-ray fluorescence analysis (XRF). With these data, a geostatistical analysis of the concentrations of $P_2O_5$ was performed to define the mineral potentiality (high, medium or low) of phosphates in the study area (appendix 1). The type of sampling corresponds to "non-probabilistic for convenience", because the samples were taken according to the experience and criteria of the field geologist.

The geostatistical analysis was carried out in three stages: 1) revision and adjustment of the data, which consisted of the verification of the coordinates (georeferencing, origin of coordinates, etc.); 2) exploratory analysis of the data by means of the geostatistical analyst tool in the ArcGIS software; and 3) developing the interpolation models and performing error analysis to determine the most suitable interpolation method.

## 3. Geological and stratigraphic framework

The study area is located in the axial zone of the Eastern mountain range between the municipalities of Tunja and Sogamoso. There are rocks of sedimentary origin with ages ranging from Cretaceous to Quaternary, belonging to the Eastern Cordillera basin (*sensu* Cediel, 2010).

The following stratigraphic nomenclature is used in this area (Figure 2): between the SE flank of the Arcabuco anticline and the Viracachá and Machetá faults, the Villa de Leiva stratigraphic nomenclature was used with the Arcabuco, La Paja, Tablazo formations (equivalent to San Gil Inferior), Simití (equivalent to San Gil Superior), Churuvita, Simijaca, San Rafael and Conejo (Etayo Serna, 1968 a and b; 2015). For the Paleogene, the nomenclature of the Bogotá savanna and surroundings (Cacho and Bogotá formations) was used.

For the NW sector of the Soapaga fault, the nomenclature of the Bogotá savanna and its surroundings (Une, Chipaque, Guadalupe Group and Guaduas, Cacho, Bogotá and Tilatá formations) was used. The Guadalupe Group is composed of the Arenisca Dura Formation or equivalent siliceous facies and the Plaeners and Arenisca de Labor-Tierna formations.

Toward the S and SE of the Soapaga fault, in the Úmbita syncline, the nomenclature of the Bogotá savanna is used for the Cretaceous units, and for the units that vary from Paleogene to Neogene, the nomenclature of the area of Paz del Río is used (Socha Inferior, Socha Superior, Picacho and Concentración formations) because this nomenclature is quite common and used by the geological community.

The geological units mapped in ascending stratigraphic order are briefly described below (Figures 1 and 2).

**Arcabuco Formation (Schiebe, 1938; Hubach, 1957b).** This formation crops out to the northwest of Tunja on the eastern flank of the Arcabuco anticline. It is primarily composed of quartzarenites of variable grain size and is strongly cemented by silica with some thin layers of intercalated red mudstones. It shows large, inclined laminations and the sandstones are white or yellowish. Underneath the sandstones and toward the central part of the core of the Arcabuco anticline, very dense red claystones outcrop. Only the upper part of the Arcabuco Formation unit outcrops; therefore, the lower contact with the La Russia Formation is not observable. The upper contact with the Ritoque Formation is paraconformable and is not observed because it is covered with quaternary deposits (alluvial fans). The thickness calculated on the eastern flank of the Arcabuco anticline is 200 m (Etayo Serna, 1968b), and the stratigraphic range corresponds to the Berriasian (Etayo Serna and Rodríguez, 1985).

**Rosa Blanca Formation (Wheeler, 1929; Morales et al., 1958; Etayo Serna and Guzmán Ospitia, 2019).** The Rosa Blanca Formation is wedged against the Arcabuco Formation in the Arcabuco anticline (Etayo Serna, 1968 a and b; Etayo Serna et al., 2015); therefore, it does not outcrop in the study area, so there is a stratigraphic gap in part of the Berriasino and the Valanginian. For this reason, the Ritoque Formation is resting directly on the Arcabuco Formation.

**Ritoque Formation (Etayo Serna, 1968 a and b).** This formation crops out on the eastern flank of the Arcabuco anticline and is covered by alluvial fans deposits. According to Etayo Serna et al. (2015), in this sector is composed of an alternation between lenticular siltstones and lumachelic limestones in layers 30 to 50 cm thick that are solid or laminated and have parallel-plane stratifications and are gray in color where the rock is fresh or pink where the rock is weathered. The lower contact with the Arcabuco Formation and the upper contact with the La Paja Formation are net and paraconformable. The stratigraphic range dates to the lower to middle Valanginian, and its thickness is 70 m (Etayo Serna, 1968b).

**La Paja Formation (Wheeler, 1929; Morales et al., 1958; Etayo Serna, 1968 a and b; Montoya, 2019).** This formation crops out in the northwestern part of the study area on the eastern flank of the Arcabuco anticline. This unit is recognized for presenting a typical geomorphological expression of valleys and hills. At the base, it is composed mainly of pale red and light brown-gray claystones sets, with lenses and beds of very fine-textured quartzarenites interspersed with very fine-grained micaceous quartzarenites. Locally, there are nodular layers and fossiliferous concretions of the ferruginous type with hollows filled with gypsum in some sandy layers. Toward the middle and upper parts, it is composed of layers of fossiliferous siltstones and claystones with bivalves. The occurrences of robust oysters up to 10 cm, bivalves, gastropods and echinoderms are frequent. The lower contact with the Ritoque Formation is a paraconformity and is not observable because it is covered. The upper contact is concordant and net from the Tablazo Formation. The estimated thickness is 850 m, and the stratigraphic range is within the Hauterivian to the Aptian (Etayo Serna, 1968 a and b; Patarroyo, 2020).

**Tablazo Formation (Wheeler, 1929; Morales et al., 1958; Etayo Serna, 1968 a and b; Montoya, 2019).** This formation crops out in the northwestern part of the study area in an elongated strip parallel to the eastern flank of the Arcabuco anticline. This unit is recognized by its abrupt morphology of pronounced ridges and escarpments. Toward the base, it is made up of packages of dark gray, micaceous claystone that contain visible inclusions of fine-grained, pale red quartzarenites; slightly calcareous and contains muscovite. Toward the top, there are pale yellowish-brown claystones, that are locally micaceous, with impressions of bivalves (lamellibranchs), and is interspersed with thick layers of very fine and fine-grained quartzarenites. The lower contact, with the La Paja Formation, is concordant and net, and the upper contact is concordant and gradual, with the Simití Formation. The stratigraphic range corresponds to the Upper Aptian-Lower Albian (Etayo Serna, 1968 a and b; Etayo Serna et al., 2015; Montoya, 2019). The thickness measured by Etayo Serna (1968 a and b) in the Villa de Leyva area is 480 m. Moreno and Sarmiento (2002) consider the "Lower San Gil Formation" (Etayo Serna, 1968 a and b) of the Villa de Leyva area synonymous with the Tablazo Formation.

**Simití Formation (Wheeler, 1929; Morales et al., 1958; Hubach, 1957b; Etayo Serna, 1968 a and b; Etayo Serna, 2019).** This formation crops out on the eastern flank of the Arcabuco anticline. Due to its fine-grain lithology, it morphologically forms a valley. It is made up of intercalations of pale yellowish-brown mudstones, light gray-brown claystones, gray-greenish fissile and siltstones, with intercalations of very fine-grained quartzarenites; is locally silty, and toward the top, it is micaceous and glauconitic. The lower contact, with the Tablazo Formation, is concordant and gradual, and the upper contact, with the Churuvita Formation, is net and paraconformable. The thickness reported by Etayo Serna (1968) is 620 m in the Villa de Leyva area. Moreno and Sarmiento (2002) consider the "Superior San Gil Formation" (Etayo Serna, 1968) of the Villa de Leyva area synonymous with the Simití Formation. The stratigraphic range varies from the middle Albian to upper Albian (Etayo Serna, 1968 a and b; Etayo Serna, 2019).

**Une Formation (Hubach, 1931; Renzoni, 1962).** This formation crops out to the east of the Soapaga fault in the municipalities of Toca, Siachoque and around Ramiriquí. In general, the unit is composed of light gray and yellowish quartzarenites, is very fine-grained (with the presence of micas and iron oxides) and contains gray siltstones with intercalations of dark gray mudstones. Additionally, the formation contains sporadic layers of thin and very thin anthracite and very thick layers of fine- to medium-grained quartzarenites appear at the top of the sequence along with organic matter, muscovite, and cross-laminations. The lower contact, with the Fomeque Formation, is not observed, and the upper contact, with the Chipaque Formation, is concordant and net. The thickness calculated in the geological section in the Úmbita syncline is 1300 m (Terraza et al., 2010). The stratigraphic range is from the Albian and is partly Cenomanian (Montoya and Reyes, 2003b).

**Churuvita Formation (Etayo Serna, 1968 a and b).** This formation crops out on the eastern flank of the Arcabuco anticline and forms part of anticline structures at the vicinity of the Ventaquemada municipality and lies along the road that leads from Tunja to Toca. It is made up of very fine- to fine-grained quartzarenites, with siliceous cement, glauconite and micas. The formation consists of slightly silty claystones and claystones with bivalve fossils are interspersed. Toward the top of the succession, there are fine-grained quartzarenites that are micaceous with impressions of bivalves and intercalations of sandy claystones and layers of bivalve *wackestone* with glauconite. Additionally, there are horizontal burrows toward the base of the layers and decimetric calcareous concretions. The lower and upper contacts, with the Simití and Simijaca formations, are nets and paraconformable (Etayo Serna et al., 2015). The thickness reported by Etayo Serna (1968 a and b) is 323 m. The stratigraphic range corresponds to the Cenomanian, as inferred by the presence of *Rhynchostreon* sp. and *Ostrea* sp. (Gaona, 2003).

**Simijaca Formation (Ulloa and Rodríguez, 1979, 1991).** This formation crops out on the eastern flank of the Arcabuco anticline and along the road that leads from Tunja to Toca in the core of the San Francisco anticline. Morphologically, it forms a narrow valley. It is made up of light olive-gray claystones, where noncalcareous centimetric concretions are observed. Locally, layers of fine-grained, mature quartzarenites with siliceous cement are observed. The Simijaca Formation, established by Ulloa and Rodríguez (1979, 1991), corresponds to "segment A" or the lower part of the San Rafael Formation originally proposed by Etayo Serna (1968b, 2015). The lower contact, with the Churuvita Formation, is net and paraconformable, and the upper contact, with the San Rafael Formation, is concordant and net (Etayo Serna, 2015). The stratigraphic range corresponds to the lower Turonian (Etayo Serna, 2015). The thickness reported by Etayo Serna (1968 a and b) is approximately 60 m.

**San Rafael Formation (Etayo Serna, 1968 a and b; Etayo Serna, 2015).** This formation crops out on the eastern flank of the Arcabuco anticline and along the road that leads from Tunja to Toca in the core of the San Francisco anticline. The morphological expression is of small and elongated mounds. It is composed of a sequence of porcellanites, cherts, claystones, siliceous siltstones and occasionally very fine-grained quartzarenites. Locally centimetric siliceous concretions are found. The lower contact, with the Simijaca Formation, is concordant and net, and the upper contact, with the Conejo Formation, is concordant and gradual. The ammonites (*Hoplitoides lacabagnae*; Etayo Serna, 1979, 2015) collected in the study area were from the stratigraphic range that corresponds to the middle Turonian. The thickness measured by Etayo Serna (1968 a and b) is 14 m. Etayo Serna (2015) redefines the San Rafael Formation, restricting it to "segment B", siltstone-siliceous or higher, of the original San Rafael Formation proposed by Etayo Serna (1968 a and b).

**Chipaque Formation (Hubach, 1931; Renzoni, 1962).** This formation crops out to the east of the Soapaga fault along the road that leads from Ramiriquí to Ciénega and Zetaquira. It also appears at the southeastern end of the study area and on the southeastern flank of the Úmbita syncline. It is made up from base to the top of very fine and medium-grained quartzarenites of a brownish-gray color and contains glauconite and organic matter, interspersed with medium-dark gray claystones. Stratigraphically ascending are layers of siliceous mudstones of brownish-gray color with impressions of the ammonites *Hoplitoides* cf. *lacabagnae* (Etayo Serna, 1979) and crabs such as *Opthalmoplax spinosus* (Feldman, Villamil and Kauffman, 1999) from the middle Turonian (Etayo Serna, 2015). The lower contact, with the Une Formation, is concordant and net, and the upper contact, with the Arenisca Dura Formation, is rapid transitional and concordant. By geological section, a thickness of 320 m was calculated (Terraza et al., 2016). The stratigraphic range corresponds to the upper Cenomanian to Santoniano (Montoya and Reyes, 2003b).

**Conejo Formation (Renzoni, 1981; Etayo Serna, 1968 a and b).** This formation crops out widely on the western side of the study area in elongated strips oriented NE–SW. It is observable in the core of the Las Pavas anticline and in the core of the San Francisco syncline and anticline. It consists mainly of verythick layers of dark yellowish-brown claystones and mudstonesthat form topographic valleys, alternating with thick layers of quartzarenites with some siliceous siltstones beds of yellowish-brown color that generate scarps morphologically. The Cucaita Member (Etayo Serna, 1968 a and b) is observable along the road that leads from Tunja to Arcabuco and consists of layers of siliceous siltstones of a very pale orange color where it is common to observe impressions of ammonites, inoceramids and crabs, which are interspersed with medium and thick layers of very fine-grained quartzarenites, pale yellowish-orange, siliceous cement and micaceous. Toward the top of the succession, there is a progressive increase in yellowish-brown mudstones. The lower contact, with the San Rafael Formation, and the upper contact, with siliceous facies, at the base of the Guadalupe Group (Martínez et al., 2020) is rapidly transitional. These siliceous facies represent a facial change in the Arenisca Dura Formation that outcrops to the east of the Bogotá savanna and its surroundings, as will be discussed later. The thickness established by geological section is 340 m in the San Francisco anticline. The stratigraphic range varies between upper Turonian and Santonian, based on the ammonites *Subprionocyclus* sp. cf. S. *neptuni* (Geinitz, 1850); *Subprionocyclus hitchinensis* (Billinghurst, 1927)*; Peroniceras guerrai* (Etayo Serna, 1979); *pseudoschloenbachia* sp. ind; *Texanites (Texanites*) sp. cf. T. (T) *gallicus* (Collignon, 1948), collected in the study area and determined by Etayo Serna (2015).

**Grupo Guadalupe (Hettner, 1966; Hubach, 1931; 1957 a and b; Pratt et al., 1961; Pérez and Salazar, 1978).** The Guadalupe Group appears distributed throughout various sectors of the study area. To the north and central sides of the area, it forms strips oriented in the NE–SW direction and is part of the flanks of the Tunja syncline, San Francisco anticline, San Francisco syncline, Cómbita syncline and other second-order folds. The Guadalupe Group, in these structures, shows in the base siliceous and lodolytic fine-granular rocks, described by Martínez et al. (2020) in the Tunja area and surroundings. It is superseded by the Plaeners Formation, and its top culminates with the Arenisca de Labor-Tierna Formation.

The biostratigraphic study carried out by Etayo Serna (2015) in the study area concludes the following regarding the rocks present at the base of the Guadalupe Group: 1) The siliceous siltstones that constitute the eastern limit of the Samacá plain (Loma del Azulejo) stand out as the most abrupt and prominent eastern cornice of the region, which were called the Plaeners Formation (Etayo Serna, 1968b, p. 47), though these do not correspond to this unit, but to the "Lidita Superior Formation" described by Montoya and Reyes (2003b, p. 98). 2) Interdigitation is confirmed at some sites between segments of the Arenisca Dura Formation and segments of the "Lidita Superior Formation" (*sensu* Montoya and Reyes, 2003b, p. 98) at the base of Grupo Guadalupe. 3) The predominant fine-textured lithological succession that overlaps the "Lidita Superior" corresponds to the Plaeners Formation, which stands out very well for its smooth morphology located between two hard rock formations that form escarpments and thus highlight its soft nature. 4) The paleontological documentation allows us to recognize the Santonian stage in the upper part of the Conejo Formation, although it is not yet possible to establish divisions or unequivocally trace the limit with the Santonian stage. However, in a preliminary way, the base of the stratigraphic interval that presents an abundance of ammonites of the genus *Submortoniceras* is adopted as the base of the Campanian stage. As already indicated, the siliceous fine-grain facies at the base of the Guadalupe Group ("Lidita Superior Formation", for Montoya and Reyes, 2003b) represent a facial change in the Arenisca Dura Formation to the east of the Bogotá savanna and surroundings. Toward the extreme south and east, the base of the Guadalupe Group presents characteristics more similar to the Arenisca Dura Formation in its the type locality in the eastern hills of Bogotá.

Toward the Úmbita syncline sector, the upper unit of the Guadalupe Group is represented by the Arenisca de Labor y Arenisca Tierna formations, grouped in this study as the Arenisca de Labor-Tierna Formation, according to the proposal of Renzoni (1962). The lower contact (with the Conejo Formation or with the Chipaque Formation) is concordant and rapidly transitional; the upper contact, with the overlying Guaduas Formation, is continuous and net. The thickness fluctuates between 109 m SE of Cucaita (Etayo Serna et al., 2015), up to 300 m in Alto del Volador, NW of the municipality of Garagoa (Terraza et al., 2010). The stratigraphic range is between the upper Santonian and the lower Maastrichtian (Etayo Serna, 2015; Etayo Serna et al., 2015; Martínez et al., 2020).

**Guaduas Formation (Hettner, 1966; Hubach, 1931, 1957a; Sarmiento, 1992).** This formation crops out in elongated strips with a NE–SW orientation along the flanks or core of the Tunja syncline, the San Francisco anticline and syncline, the Cómbita syncline, the Úmbita syncline and other folds. It is recognized for presenting a smooth morphology, which generates valleys and hills with a low slope, due to its predominantly clayey lithology. It is made up of gray claystone and carbonaceous mudstones at the base. In the middle part, there is a sandstone layer ("arenisca la guia") that is composed of layers of fine- and medium-grained quartzarenites of pale greenish yellow and pale yellowish-orange, with sporadic intercalations of siltstones and mudstones. In the upper part, olive-gray carbonaceous mudstones are recognized that alternate with light orange-yellow siltstones and coalbeds of up to 1.5 m in thickness. Occasionally, remains of leaves and fossil stems appear in the layers. The lower contact with the Guadalupe Group and the upper contact with the Cacho Formation are concordant and net. The calculated thickness in the San Francisco anticline is 550 m, and in the Tunja syncline, it is 240 m. Its stratigraphic range from the upper Maastrichtian to the lower Paleocene (Sarmiento, 1994).

**Cacho Formation (Schiebe, 1934a; Hubach, 1931, 1945; Pratt et al., 1961).** This formation It crops out in the Tunja and Cómbita synclines, the Puente Hamaca anticline, and to the west of the Icabuco River fault. In the lower part, it is composed of layers of quartzarenites that go from fine to medium grain at the base, and from coarse to very coarse grain toward the top. These are of grayish-orange, pinkish gray and grayish purplish red colors. The upper part consists of layers of medium to coarse-grained quartzarenites with a very pale orange or dark yellowish-orange color, that are somewhat lithic and feldspathic, separated by thin and lenticular layers of very pale orange and grayish yellow claystones. Quartzarenites occur in banks of up to 2.5 m. The contacts, both lower and upper, with the Guaduas and Bogotá formations are concordant and net. The calculated thickness of the Tunja anticline is 205 m. The stratigraphic range covers from the Paleocene (McLaughlin and Arce, 1972) to the lower Paleocene (Sarmiento, 1992).

**Socha Inferior Formation (Alvarado and Sarmiento, 1944).** This formation crops out in the Úmbita syncline. Due to its predominantly sandy lithological constitution and its stratigraphic position between clayey units, it generates scarps or topographic ridge in the relief. In general, it is made up of pale reddish-brown and dark yellowish-orange quartzarenites, with a very fine to conglomerate texture, in sets of very thick layers (up to 4 m thick). Toward the contact with the Guaduas Formation and the Socha Superior Formation, the layers are medium and thick with interpositions of gray claystones with reddish mottling (Terraza et al*.,* 2010). The lower and upper contacts with the Guaduas and Socha Superior formations are concordants and nets. The thickness calculated in the Úmbita syncline is 200 m (Terraza et al*.,* 2010). The stratigraphic range corresponds to the lower Paleocene (Hubach, 1957b; Pardo Trujillo and Jaramillo, 2014).

**Bogotá Formation (Hubach, 1931, 1957a; Julivert, 1963)**. This formation crops out in the northern sector of the area in the Tunja and Cómbita synclines, the Puente Hamaca anticline and on the western flank of the San Francisco anticline. Due to its mainly clayey lithology, this unit forms a smooth relief of rounded hills. It is made up of layers of fine- to medium-grained quartzarenites with a medium pinkish orange or light brownish color, alternating with layers of various colored mudstones (pale reddish-brown, grayish blue and grayish violet red). Toward the upper part, there are banks of variegated mudstones interspersed with thick layers of reddish and violet quartzarenites. The lower contact with the Cacho Formation is concordant and rapidly transitional, and the upper contact is not observed. The calculated thickness in the Tunja syncline is 350 m. The inferred stratigraphic range is the lower Eocene (De Porta, 1974).

**Socha Superior Formation (Alvarado and Sarmiento, 1944).** This formation crops out in the Úmbita syncline, and due to its predominantly clayey lithology, it formed a soft topographyon the ground. It mainly consists of a succession of claystoneswith minor intercalations of mudstones, quartz siltstones and sandstones. Fine-grain rocks (claystones and mudstones) are gray, variegated (different colors of gray, red, and purple) or gray with reddish or violet mottling, and sandstones are pale brown, very pale orange, or dark yellowish green in layers or sets of layers that vary from thick to very thick (Terraza et al., 2010). The lower contact, with the Socha Inferior Formation, and the upper contact, with the Picacho Formation, is concordant and net. In the Úmbita syncline, a thickness of 260 m was measured (Terraza et al., 2010). The stratigraphic range corresponds to the upper Paleocene (Pardo Trujillo and Jaramillo, 2014).

**Picacho Formation (Alvarado and Sarmiento, 1944).** This formation out crops in the core of the Úmbita syncline, where it forms an almost continuous escarpment due to its erosion-resistant sandy rocks. It is made up of very thick layers of white or light gray quartzarenites, with a texture that ranges from medium to conglomerate, somewhat lithic and feldspathic. Rounded pebble beds of milky quartz and intercalations of micaceous variegated mudstones are common. The lower and upper contacts, with the Socha Superior and Concentration formations, respectively, are concordant and net. The thickness measured on the SE flank of the Úmbita syncline is 230 m and 180 m on the NW flank (Terraza et al., 2010). The stratigraphic range falls within the lower and middle Eocene (Van Der Hammen, 1958; Parra et al., 2009; Pardo Trujillo and Jaramillo, 2014).

**Concentration Formation (Alvarado and Sarmiento, 1944).** This formation crops out in the extreme south of the area and occupies the core of the Úmbita syncline, where due to its essentially muddy lithological composition, it forms relatively smooth relief. In the study area, only the lower part of the unit appears and is made up of a succession of variegated claystone and mudstones (red, gray and purple), micaceous, with intercalations of very thick layers of sandy conglomerate or sublitharenites conglomeratics. The lower contact, with the Picacho Formation, is concordant and net and the upper contact is not observed. The partial thickness calculated in the Úmbita syncline is 400 m (Terraza et al., 2010). The deduced stratigraphic range is between the middle Eocene and middle Oligocene (De Porta, 1974; Pardo Trujillo and Jaramillo, 2014).

**Tilatá Formation (Scheibe, 1934b; Hubach, 1957a; Julivert, 1961, Renzoni, 1981).** This formation crops out in the depression of the Chulo River, between Tunja and Tuta, in the core of the Tunja syncline and from the municipality of Siachoque to the northeastern area of the La Copa dam. It rests discordantly on the Cretaceous units (Conejo Formation, Guadalupe Group, part of the Guaduas Formation) and Paleogene (part of the Guaduas, Cacho and Bogotá Formations). Morphologically, it forms flat areas with smooth and rounded hills (by folding inherited from the Cretaceous and Paleogene). It is made up of a sequence of gravels and sands on which an interval rests made up of porcelllanites and quartzarenites gravels with a conglomerate sandy matrix. Paleochannels and diatomite levels were observed in the Tunja-Oicatá road. The thickness measured in deep gullies and quarries is at least 30 m, and according to Renzoni (1981), the formation has a thickness of 150 m. The stratigraphic range is upper Pliocene-lower Pleistocene (Helmens and Van der Hammen, 1995; Renzoni, 1981).

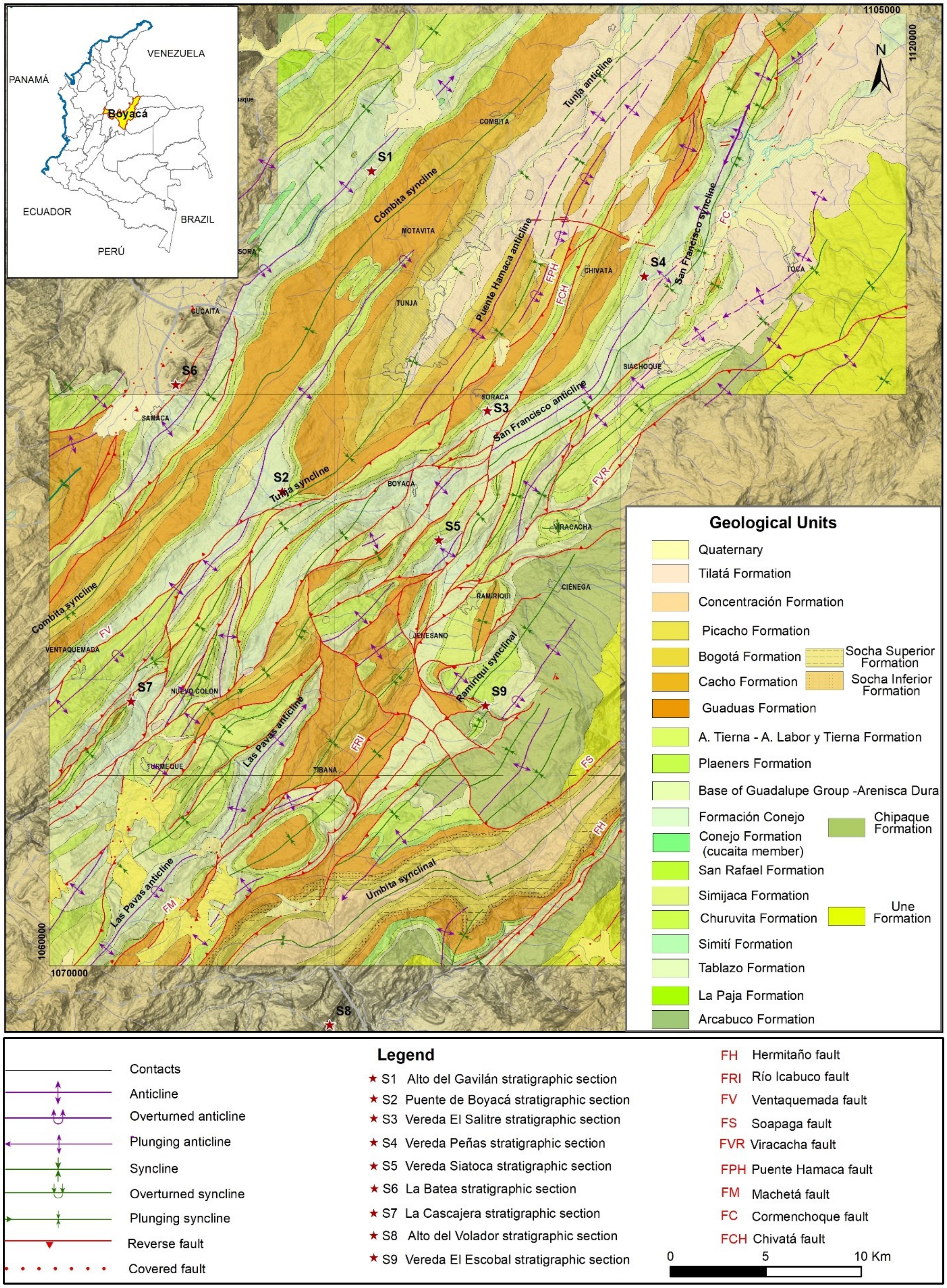



**Figure 1.** Geology and geographic location of the study area
The red stars show the locations of the measured stratigraphic sections.
Source: Terraza et al. (2016); digital terrain model taken from https://vertex.daac.asf.alaska.edu/

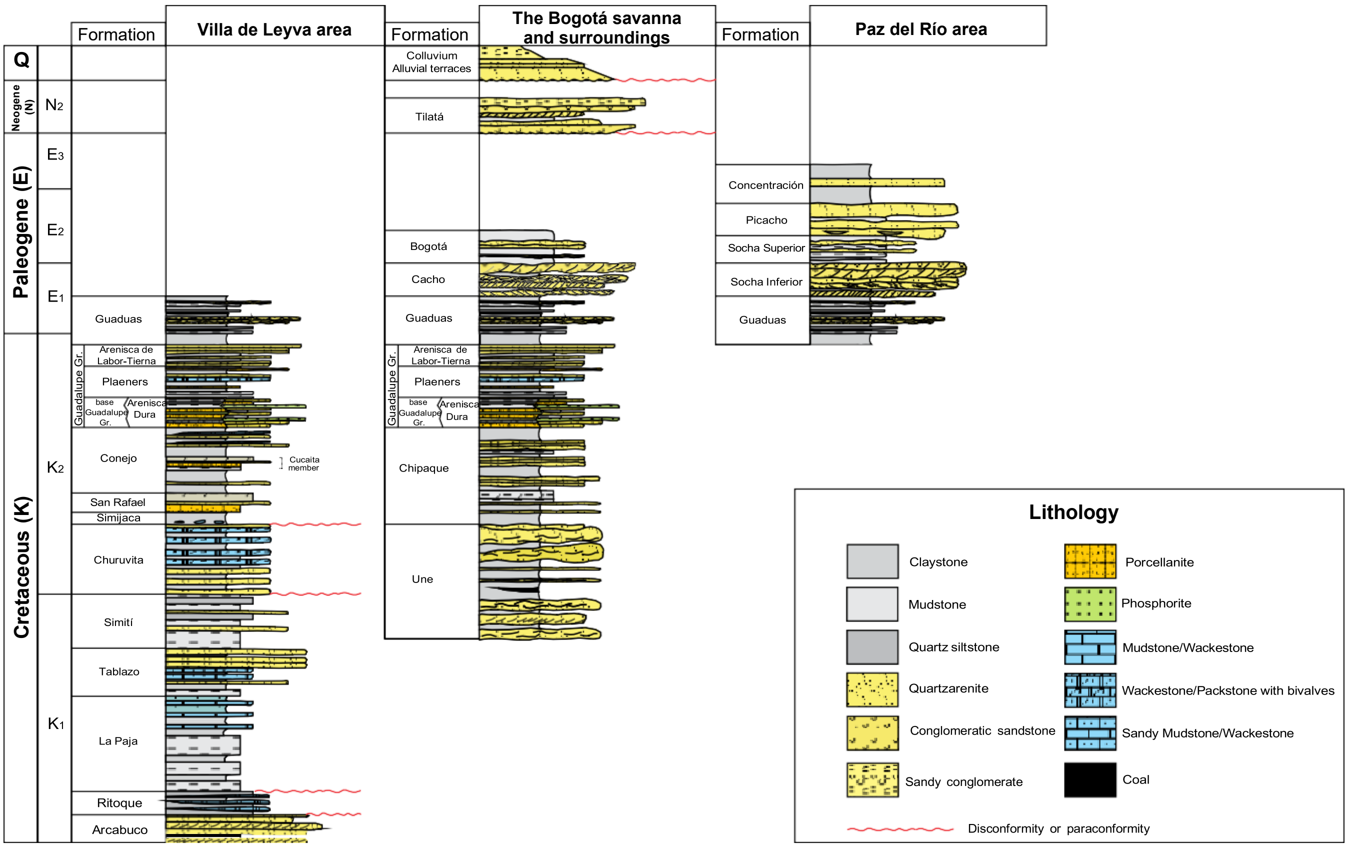



**Figure 2.** Nomenclature and generalized stratigraphic column of the study area

## 4. Structural geology

In the study area, there are regional or first-order geological structures (Twiss and Moore, 2007) important for their breadth and geographic extension, such as the Tunja syncline, which is a soft open, subvertical fold that dips to the SW and is oriented N 30° to 42° E with a length of 35 km that runs from the south of Tunja to the NE of the municipality of Oicatá. The core of the structure is covered by the Tilatá Formation and it is flanked by the Bogotá, Cacho and Guaduas formations. The Úmbita syncline is a smooth, subvertical fold that plunging weakly to the NW and is oriented N 40° to 45° E with a sinuous axis that extends more than 30 km from the W and south of Tibaná. Additionally, the Concentration Formation appears in the core. The Cómbita syncline is a tight fold that steeply inclined and moderately plunging to the NW; in the southern part of the fold, its western flank is inverted and it has a length greater than 40 km and an amplitude greater than 5 km. The line of the axis is sinuous and has a general orientation of N 35° to 40° E, and it extends from the north of the municipality of Ventaquemada to the northeast of Cómbita. The outcrop at its core consists of rocks from the Bogotá Formation.

Other minor folds related to the Tunja syncline are the Puente Hamaca anticline, the San Francisco syncline, and the San Francisco anticline. The Las Pavas anticline is related to the Úmbita syncline. These structures have a preferential NE–SW orientation and are narrower and less continuous. There are also numerous second-order folds (1 to 15 km long and less than 1 km wide), especially developed within the Churuvita, Conejo, Une and Chipaque formations. These folds are characterized by being tight and in some cases have an inverted flank.

The faults that affect the rocks have a reverse character that extend for several kilometers and some of these structures show a strike-slip fault motion. The densest geological faulting is located in the central part of the work zone and corresponds to short-length reverse faults related with imbricate thrust fault of the main faults. The most important faults in the central region of the Eastern Cordillera are those of Chivatá, Cormenchoque and Puente Hamaca on the north side and the Ventaquemada, Soapaga, Machetá, Icabuco River, Hermitaño and Viracachá faults on the south side, as described in Table 1.

## 5. Results

### 5.1. Stratigraphy of the units of interest for phosphates

The upper Cretaceous units of interest for phosphates are the Guadalupe Group: Arenisca Dura Formation, the Siliceous fine-grain facies at the base of the Guadalupe Group, and the overlying Arenisca Labor-Tierna and Plaeners formations, which are briefly described below.

#### *5.1.1. Siliceous fine-grained facies at the base of the Guadalupe Group (Martínez et al., 2020)*

This formation crops out in the northern and central sector of the area, in NE–SW oriented stripes located on the flanks of the Tunja syncline, the eastern flank of the Arcabuco anticline, on the flanks of the San Francisco anticline and on the flanks of the Cómbita syncline, as well as in other second-order folds. These facies overlie the Conejo Formation and underlie the Plaeners Formation, generating a morphology of escarpments or edges between these two units. Martínez et al. (2020) provided a detailed description of these facies in the municipality of Tunja and its surroundings.

At the base of the Guadalupe Group, two intervals are recognized: a lower interval, composed of intercalations of siliceous claystones, claystones, siliceous siltstones and porcellanites, of a yellowish-gray color, arranged in thin layers. Occasionally, there are medium and thick layers of *wackestone*-textured phosphorites and phosphorites with *a packstone* texture of phosphatic peloids with fish remains. The upper interval is made up of an alternation of chert, porcellanites and very fine-grained quartzarenites, arranged in thin and medium layers, with continuous and discontinuous plane-parallel stratification. The porcellanites and cherts are yellowish-gray and pinkish orange and appear in thin layers. The sandstones are muddy and siliceous, arranged in medium layers with very fine lenticular laminations. It is common to observe phosphatic

**Table 1.** Description of the main faults in the study area

| Nomenclature | Fault type | Location | Orientation | Vergence | Length (km) | Remarks |
|---|---|---|---|---|---|---|
| Chivatá (FCH) | Reverse | Extends from the north of the La Copa dam to the vicinity of the municipality of Jenesano | N 32° E (to the south) N 22° E (to the north) | SE | 34 | To the south of Chivatá puts in contact the Guaduas and Conejo formations, and to the north, the observed contact was between the Cacho Formation with the base of the Guadalupe Group and the Plaeners Formation. Through the Toca-Oicatá route, contact between the Bogotá and Plaeners formations was observed. The fault line to the south of Oicatá is displaced by a dextral strike slip fault |
| Cormenchoque (FC) | Reverse | Mapped to the W of the municipality of Siachoque | N 37° E | SE | 32 | Puts in contact the Conejo and Arenisca Tierna formations, and aligns the course of the Cormenchoque river; its fault trace to the south is intercepted by the Chivatá fault |
| Puente Hamaca (FPH) | Reverse | Mapped from the north of the municipality of Chivatá to the NW of the municipality of Ventaquemada | N 40° E | SW | 35 | Puts in contact rocks from the Bogotá and Guaduas formations in the surroundings of Sora and north of Nuevo Colon. In addition, it puts in contact the Arenisca Tierna and Conejo formations, and repeats the stratigraphic succession of the Arenisca Tierna Formation, to the W of the municipality of Boyacá |
| Soapaga (FS) | High angle reverse | Mapped from the east of the municipality of Ciénega to the west of the municipality of Jenesano | N 50° E, with abrupt change to N 40° W | SE (southeast of the municipality of Ciénega) and SW (south of the municipality of Jenesano) | 26 (section observed in the study area) | It generates a hanging wall block made up of the Chipaque and Une formations, with synclinal and anticline folds, and a footwall block equally folded, with Paleogene rocks (Guaduas, Socha Inferior and Socha Superior formations) and Cretaceous ones of the Guadalupe Group (Arenisca Dura, Plaeners, Arenisca de Labor-Tierna formations). In the study area the end of this structure is observed |
| Machetá (FM) | High Angle Reverse with dextral transcurrent motion | Mapped south of the municipality of Turmequé | N 55° E | SE | 8 | It puts in contact the Arenisca Dura Formation, Plaeners Formation or the Arenisca de Labor-Tierna Formation with the Guaduas Formation. Together with a back thrust reverse fault located further west, they lift the Las Pavas anticline in the form of a pop up. |
| Icabuco River (FRI) | High angle reverse | Mapped east of the municipality of Tibaná | N 55° E | NE | 12 | Stratigraphically repeats the succession of the Guaduas and Arenisca Dura formations |
| Hermitaño (FH) | High angle reverse | The fault line is parallel to the Hermitaño ridge, located NE of the Guayabal police inspection | N 45° E | NW | 11 | It puts the Arenisca de Labor-Tierna Formation in contact with the Guaduas Formation, and toward the SW, near Guayabal, puts the Arenisca Dura Formation on the Guaduas Formation |
| Ventaquemada (FV) | Reverse | Mapped NE of the municipality of Ventaquemada | N 55° E | NW | 11 | It puts the Churuvita Formation in contact with the Conejo Formation |
| Viracachá (FVR) | Reverse | Located to the W of the municipalities of Viracachá, Ramiriquí and Jenesano | N 40° E | SE | 14 | To the south it puts the Conejo Formation with the basal rocks of the Guadalupe Group and the Plaeners Formation, and to the north it repeats the succession of the base of the Guadalupe Group |

bone remains and moldic porosity in the rock due to dissolution of benthic foraminifera (*Siphogenerinoids*).

The stratigraphic range of the base of the Guadalupe Group goes from the upper Santonian to lower Campanian, which is established by the ammonites collected in the following localities (Etayo Serna, 2015): 1) La Batea quarry, municipality of Samacá: *Bevahites* sp. cf. *Bevahites costatus* (Collignon, 1948); 2) the road that leads from Jenesano to Boyacá: *Hauericeras* sp. cf. *H. gardeni* (Baily, 1855); 3) Cuchilla del Gavilán, municipality of Motavita: *Submortoniceras uddeni* (Young, 1963)?, cephalopods representing the lower Campanian; 4) *Submortoniceras* sp. nov. aff. *S. tequesquitense* (Young, 1963) is at the base of the "Lidita Superior Formation" (*sensu* Montoya and Reyes, 2003b), and according to the biostratigraphic study by Etayo Serna (2015), this genus represents the base of the Campanian stage. Consequently, in the first layers at the base of the Guadalupe Group, the Santonian-Campanian limit must be found, and its stratigraphic range would be mainly lower Campanian. The thickness measured in the Vereda El Salitre stratigraphic section is 100 m, in Alto del Gavilán, 75 m, and in Siatoca village, 112 m (Terraza et al., 2016).

### 5.1.2. Arenisca Dura Formation (Pérez and Salazar, 1978)

This formation crops out on the flanks of the Chivatá syncline, in the core of the Las Pavas anticline, on the flanks of the Ramiriquí syncline and in other minor folds. At the base it is composed of layers that range from medium to very thick. These are composed of phosphate quartzarenites with a grain that varies from very fine to fine, locally calcareous, grayish-orange in color, with moderate to good selection and highly bio-disturbed. The layers are occasionally interspersed with thin layers of medium gray claystones. It is common to observe remains of fish (scales, spines and teeth), peloids, phosphate remains and phosphate intraclasts. Medium layers of phosphorites with *wackestone* and *packstone* texture of peloids, bioclasts and phosphatic intraclasts, and thin layers of siltstones and mudstones of medium dark gray color are interspersed and there are *Inoceramus* sp. fossils and calcareous concretions.

In the intermediate part, it is composed of an alternating medium and thick layers of slightly phosphatic brownish-gray mudstones and thin and medium layers of siltstones and very fine-grained quartzarenites, occasionally containing peloids and fish remains. Toward the top, there are slightly calcareous fine-grained phosphatic quartzarenites interspersed with siltstones, claystones, porcellanites and siliceous siltstones of dark yellowish-brown and very pale orange colors. Occasionally, there are medium and thick layers of phosphorites with a packstone texture of peloids and bioclasts of moderate dark gray and pale yellowish-brown colors.

The stratigraphic range of the Arenisca Dura Formation goes from the upper Santonian to the lower Campanian, which is established based on the presence of ammonites *Bevahites* sp. cf., *Bevahites costatus* (Collignon, 1948) from the Lower Campanian, collected on the road that leads to the village of El Escobal in the municipality of Ramiriquí; *Plesiotexanites* sp. juv. cf. *P. shiloensis* (Young, 1963) and *Plesiotexanites* sp. juv. gr. *P. stangeri* (Baily, 1855) from upper Santoniano, collected in Alto de San Pedro found in the municipality of Jenesano. Montoya and Reyes (2003b) date the Arenisca Dura to the lower Campanian based on correlations with the "Lidita Superior" (equivalent to siliceous fine-grained facies at the base of the Guadalupe Group, from Martínez et al., 2020). This is an interpretation consistent with Etayo Serna (2015), which paleontologically demonstrates the interdigitation between segments of the Arenisca Dura Formation and segments of the "Lidita Superior Formation" (*sensu* Montoya and Reyes, 2003b, p. 98) at the base of Grupo Guadalupe. Therefore, it can be affirmed that the "Lidita Superior" presented by Montoya and Reyes (2003b) represents an example of heterotopic coetaneous facies from the Arenisca Dura Formation. Therefore, it can be assigned a stratigraphic range similar to that of the siliceous fine-grained facies present at the base of the Guadalupe Group (Martínez et al., 2020), that is, mainly lower Campanian.

### 5.1.3. Plaeners Formation (Pérez and Salazar, 1978)

This formation crops out as elongated strips with a NE–SW orientation and occupies the western flank of the Cómbita syncline, the eastern flank of the Tunja syncline, the flanks of the San Francisco anticline, the cores of the San Francisco and Úmbita synclines, and other minor folds. The unit is easily recognized because it generates a morphological depression between the Arenisca Dura Formation or the base of the Guadalupe Group and the overlying Arenisca de Labor-Tierna Formation. The Plaeners Formation is constituted at the base by medium to very thick layers of claystones that are light gray and grayish yellow colors, fissile, interspersed with medium and thick layers of siliceous siltstones and prominent sandy mudstones. There is an abundance of benthic foraminifera of the genus *Siphogenerinoides*. Alternations of medium layers of siliceous siltstones, chert, porcellanites and occasionally phosphorites appear.

In the surroundings of the municipality of Jenesano, in the middle part of the succession, there are very thick and massive layers of bivalve *wackestone* with terrigenous sediments of brownish-gray and pale yellowish-brown colors. Bivalve shells are disarticulated. Toward the top they are thin, medium and thick layers of very fine- and fine-grained quartzarenites, there are some calcareous with fragments of bivalve shells; interspersed with thin layers of mudstones, siltstones and occasionally claystones. Additionally, limestone with *wackestone* texture of bivalve fragments and phosphorites with a *packstone* texture of peloids and remains of phosphate fish. Calcareous and siliceous concretions are sporadically observed, which are ellipsoidal in shape and 5-10 cm in diameter. Finally, secondary gypsum is found in the mudstones and horizontal burrows are observed at the base of some sandstone layers.

In the northern and central-western sectors of the study area, the Plaeners Formation overlies the siliceous fine-grained facies at the base of the Guadalupe Group. To the south and center-east, it overlies the Arenisca Dura Formation.

The following ammonites fauna was obtained from the Plaeners Formation: *Exiteloceras jenneyi jenneyi* (Whitfield, 1880), *Libycoceras* sp. inc. and *Sphenodiscus* sp. Inc? from the upper Campanian (Etayo Serna, 2015). The bivalve *Abruptolopha abrupta* (D'Orbigny y Boussingault, 1842) was also obtained from the Campanian (Etayo Serna, 2015), for which the unit is ascribed to the upper Campanian. This formation has a thickness of 172 m in the section measured south of Soracá and 159 m in the section that was measured north of the municipality of Jenesano (Terraza et al., 2016).

#### *5.1.4. Arenisca de Labor-Tierna Formation (Pérez and Salazar, 1978)*

In the study area, it crops out as elongated strips with a NE–SW orientation, mostly truncated by reverse fault systems that affect and obliquely cut the stratigraphic succession. This unit appears on the eastern flank of the Arcabuco anticline, the eastern flank of the Tunja syncline, the flanks of the San Francisco anticline, San Francisco syncline, Cómbita syncline and Úmbita syncline. In some sectors, such as Alto del Volador, to the NW, the Arenisca de Labor Formation is separated from the Arenisca Tierna Formation by a thin clayey interval, which can only be mapped locally. In the rest of the study area, this interval does not appear; therefore, these units are grouped into a single cartographic unit.

Morphologically, the Arenisca de Labor-Tierna Formation generates a continuous edge. At the base, it is composed of siltstones, sandy siltstones and siliceous siltstones, which are present in thin tabular layers. In the middle, it consists of a succession of medium- to very thick layers of fine- and very fine-grained quartzarenites, are slightly glauconitic, very light orange–yellow and yellowish-gray colors, are micaceous and generally friable. Occasionally, medium-sized layers of very fine-grained phosphatic quartzarenites with peloids, are observed. In the upper part of the unit, thick and very thick layers of quartzarenites appear with grains that vary from mediumto coarse, pale greenish yellow color, are friable and contain very thick cross lamination that are tangential to the base. Horizontal burrows are also observed toward the base of some sandstone layers.

The thickness of this unit is variable. In some sectors, it is between 10 and 12 m, and in other places, it does not exceed 60 m. The ammonite fauna found on the top of the Plaeners Formation in the section of Vereda El Salitre of the municipality of Soracá is typical of the upper Campanian. In the Sutatausa area, Sarmiento (1992), by means of palynology, assigned the Guaduas Formation to the upper Maastrichtian-Paleocene, for which the Arenisca de Labor-Tierna Formation is restricted to the lower Maastrichtian.

### 5.2 Lithostratigraphic correlation

To visualize the lateral facies changes in the lithostratigraphic units and the layers rich in phosphates, two lines of correlation were made in the study area (Figure 3). The first, to the north, was between the municipalities of Motavita and Toca, where five stratigraphic sections were included: Alto del Gavilán (S1), Puente de Boyacá (S2), Vereda El Salitre (S3), Vereda Siatoca (S4) and Vereda Peñas (S5); the second, to the south, was between the municipalities of Samacá and Ramiriquí, with four stratigraphic sections: La Batea (S6), La Cascajera (S7), Alto del Volador (S8) and Vereda El Escobal (S9).

At the base of the Guadalupe Group, siliceous fine-grained facies predominate to the north and southwest of the study area, in the vicinity of the municipalities of Samacá, Tunja, Soracá, Siachoque, Toca and Boyacá, which are underlain by the Conejo Formation. In the southeastern sector, to the east of the Soapaga fault, in the municipalities of Tibaná, Jenesano, Ramiriquí, Ciénega and Viracachá, the quartzarenites facies characteristics of the Arenisca Dura Formation dominate (Figures 4 and 5). In this area, the Conejo, Simijaca and San Rafael formations do not appear, and the Chipaque Formation is clearly recognized, overlaying the Une Formation.

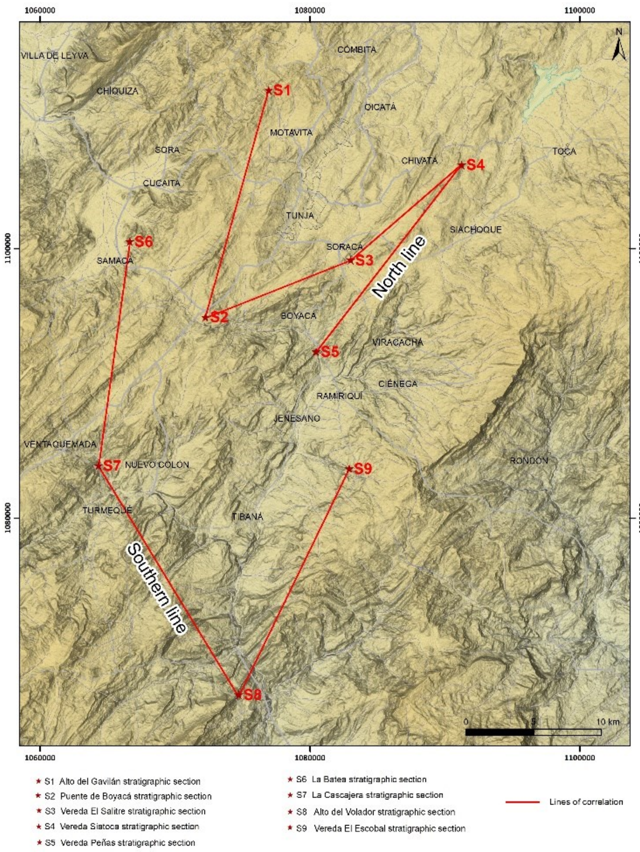



**Figure 3.** Shows the correlation lines of the stratigraphic sections.

Source: digi-tal terrain model taken from https://vertex.daac.asf.alaska.edu/

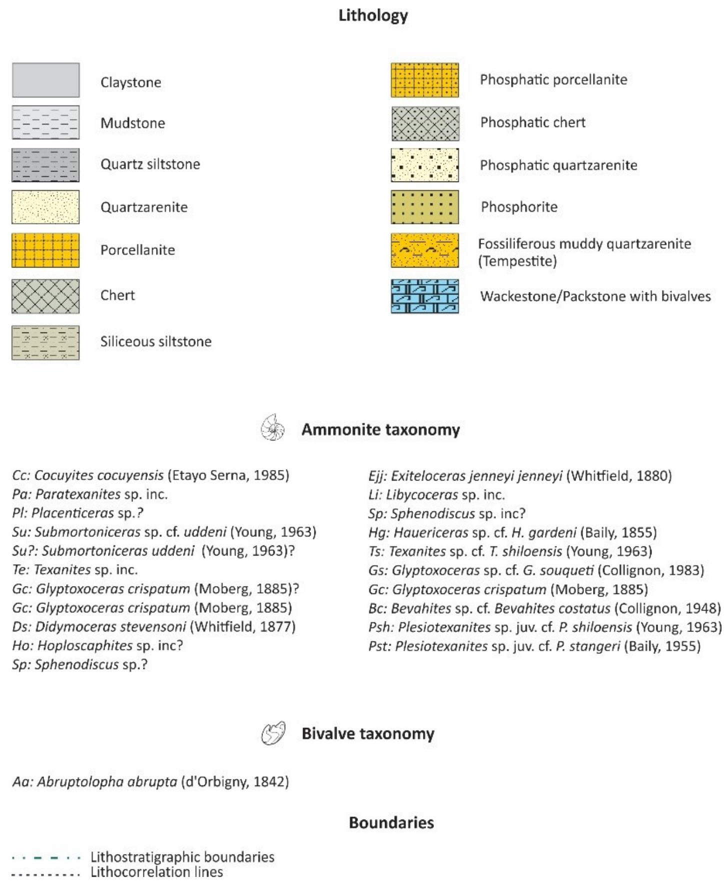



**Figure 4.** Conventions for figures 5 and 6

For the lithostratigraphic correlation along the north line (S1-S5) (Figures 4 and 5), layers of quartzarenites and fossiliferous siltstones that contained the bivalve *Abruptolopha abrupta* (D'Orbigny, 1842) from the Campanian (Etayo Serna, 2015) were taken as a guide. These were located on the top of the Plaeners Formation, approximately 19 meters from the contact with the Arenisca de Labor-Tierna Formation, in the sections of Vereda El Salitre (S3) and Vereda Peñas (S5). The interval corresponding to the Arenisca Dura Formation and equivalent fine-granular siliceous facies at the base of the Guadalupe Group was moored by correlating layers of bivalve wackestone, some phosphorites, quartzarenites, and siltstones (Figure 5).

For the lithostratigraphic correlation along the southern line (S6-S9) (Figures 4 and 6), layers of very fine-grained quartzarenites located stratigraphically above the occurrence of the *Bevahites* sp. cf. *Bevahites costatus* (Collignon, 1948) ammonites were taken as a guide, which were found in the lower part of the siliceous fine-grained facies at the base of the Guadalupe Group, in the La Batea section (S6), approximately 46 m from the contactwith the Conejo Formation and in the lower part of the Arenisca Dura Formation in the Vereda El Escobal section (S9). These sandstone layers can also be identified in the La Cascajera (S7)and Alto del Volador (S8) stratigraphic sections. Additionally, a stratigraphic interval composed of porcellanites, siltstones, phosphorites and quartzarenites was taken into account, whichwas located in the La Batea and La Cascajera stratigraphic sections and can be identified in the Alto del Volador and Vereda El Escobal sections. This interval is located above the aforementioned ammonite level in the upper part of the Arenisca Dura Formation (Alto del Volador and Vereda El Escobal sections) in the equivalent siliceous fine-grained facies of the base of the Guadalupe Group (La Batea and La Cascajera sections). This interval contains the largest number of phosphorite and phosphate rock layers, with thicknesses between 10 cm and 1.1 m (Figure 6).

For the correlation along the southern line, a stratigraphic interval was also used that was located in the intermediate part of the Plaeners Formation of the La Batea section, which composed of thin to medium-sized, tabular layers of porcellanite with intercalations of claystones, where alternate four layers between thin to medium thickness of phosphorites with packstone texture that contain peloids. These porcellanites can be identified in the La Cascajera and Alto del Volador sections (Figure 6).

From the correlation along the north line, at the base of the Guadalupe Group, there is an increase in the thickness and number of phosphorite layers toward the east, with three layers in the sections of Alto del Gavilán and Puente de Boyacá and up to 12 layers in the section of the Vereda Peñas, with thicknesses that vary between 10 cm and a maximum of 75 cm. In the southern correlation line, in the siliceous fine-grained facies at the base of the Guadalupe Group, 20 phosphorite layers are recognized (La Cascajera section), which towards the east decrease to four layers (Vereda El Escobal section), where they appear in the Arenisca Dura Formation. The thickness of the phosphorite layers varies between 5 cm and a maximum of 2.6 m.

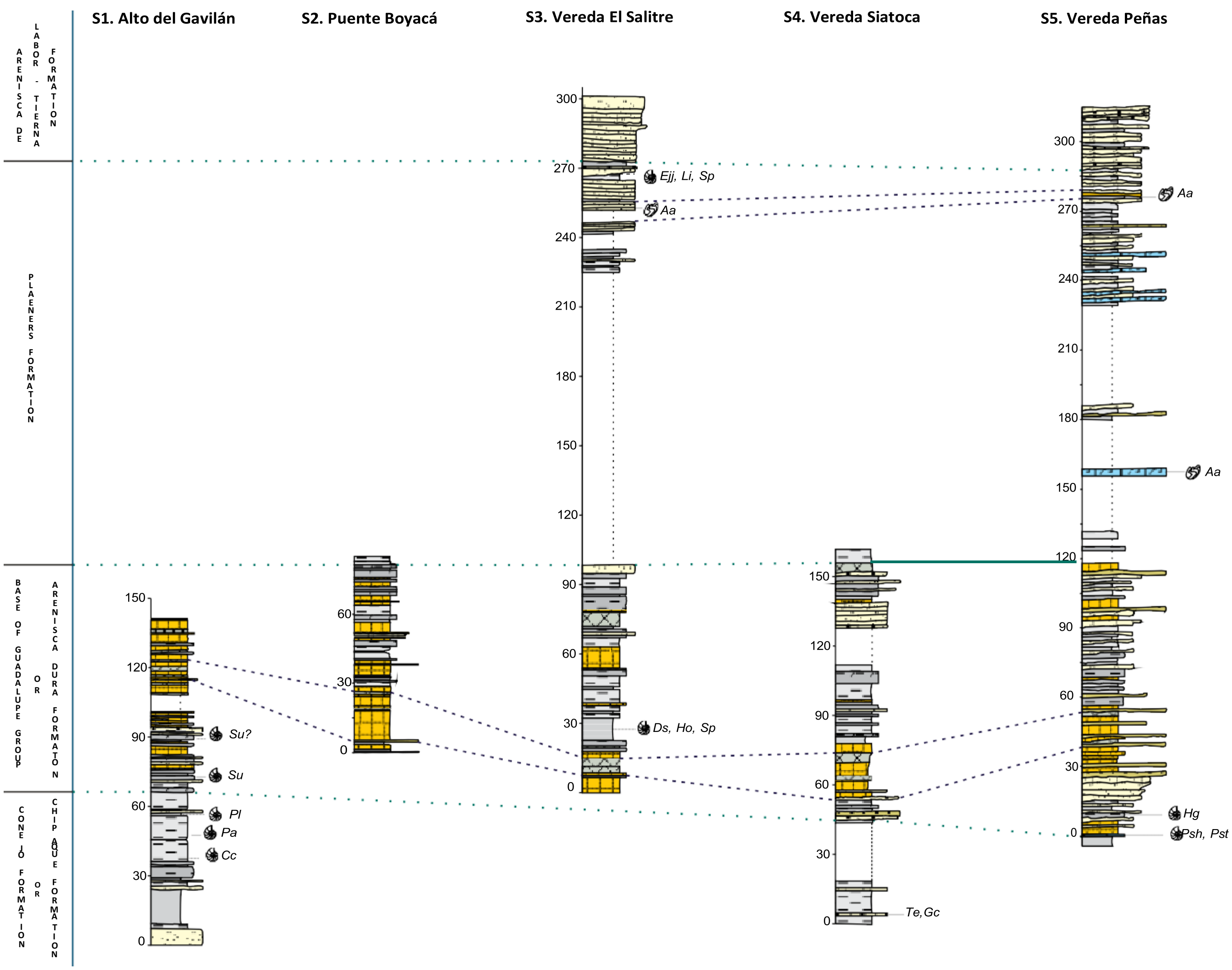



**Figure 5.** Lithostratigraphic correlation along the north line, municipalities of Motavita and Toca.
Source: Terraza et al. (2016).

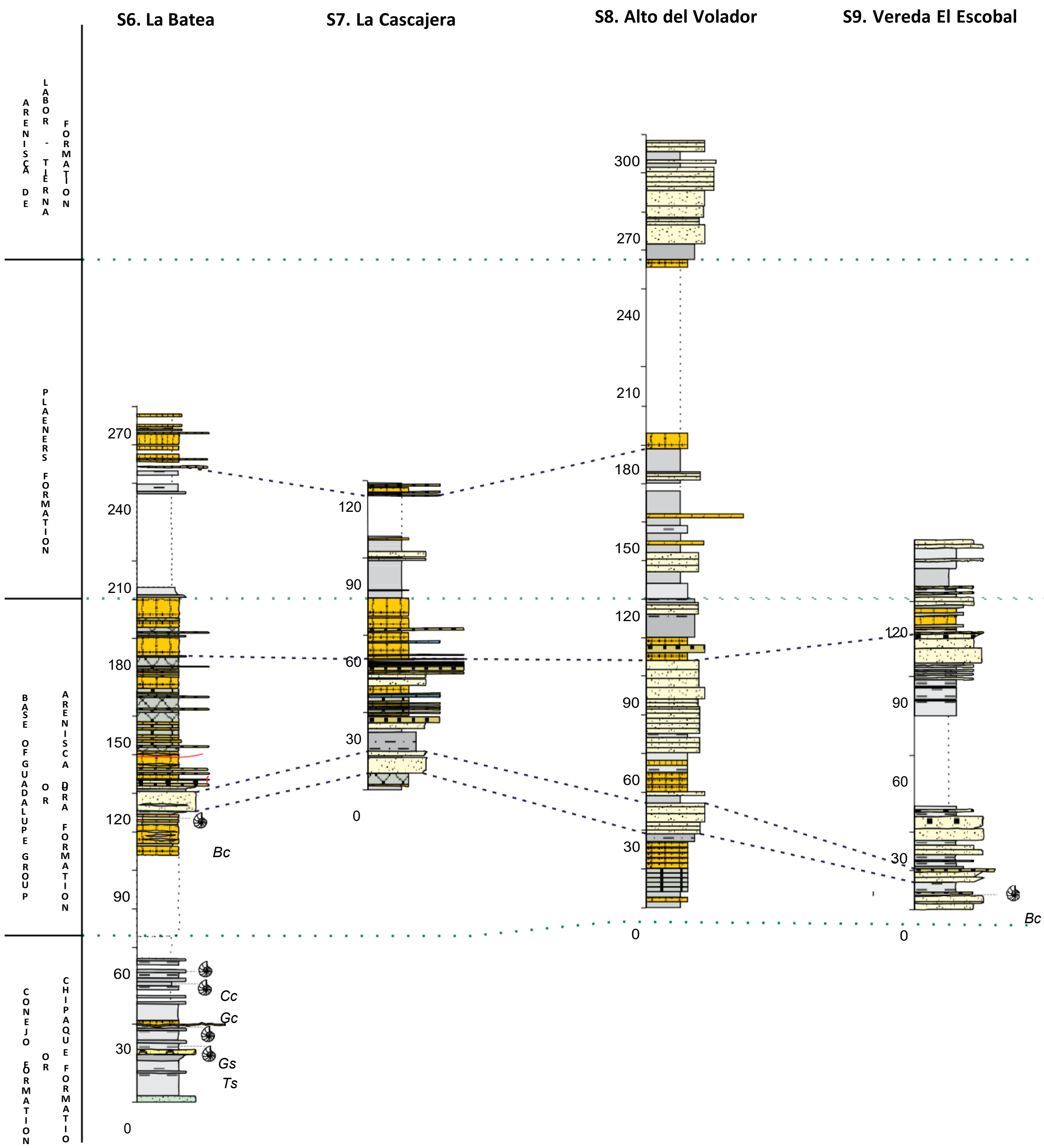



**Figure 6.** Lithostratigraphic correlation along the southern line, municipalities of Samacá and Ramiriquí
Source: Terraza et al. (2016).

## 5.3 Analysis of X-ray fluorescence data (XRF)

Through exploratory analysis of the $P_2O_5$ concentration data from the 299 phosphorite and phosphate rock samples from the units that make up the Guadalupe Group in the study area,the most appropriate interpolation method is determined. In addition, it was possible to establish that the data do not present a normal or Gaussian distribution, according to the histogram and the statistical parameters (histogram A of Table 2), which has a bias to the left. The analysis of the Voronoi map corroborated that the sampling is heterogeneous due to the difference in the sizes of the polygons, which show a NW–SE trend (Figure 7). These polygons result from grouping the data spatially according to the Voronoi mapping methodology.

The semivariogram, which is part of the exploratory analysis of the data, shows a trend in the data since it is not easy to identify the plateau and establish the range (semivariogram B of Table 2).

However, the nugget (where the curve intercepts with the Y axis) is close to 0, which indicates that the data should be interpolated. Additionally, the error analysis (root mean square), shows that inverse distance weighted (IDW) was the most appropriate method for this type of data and sampling, since the Kriging method produced a greater error. Based on the previous analysis, for the interpolation with the supervised IDW method, an ellipse with four sectors was considered, with a major axis equal to 28000 m and a minor axis of 15 000 m, and was rotated in a 45-degree direction to take into account the trend of the data (Figure 7).

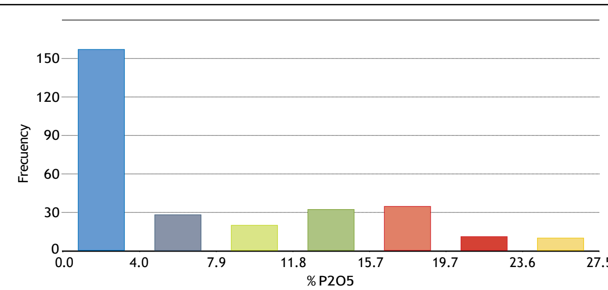
From the analysis of the map of isoconcentrations of $P_2O_5$ obtained from the interpolation (Figure 7), the following can be concluded: there are areas of high to medium potential concentrations of $P_2O_5$ greater than 6.74%, with colors ranging from dark orange to red. The ranges of values for each zone are described below. In the southwestern sector, at the level of the municipalities of Turmequé, Nuevo Colón and Tibaná, the interval oscillates between 10.8% and 27.5% $P_2O_5$; in the central-eastern zone, at the vicinity of the municipalities of Ciénega and Viracachá, they vary between 6.74% and 10.8% $P_2O_5$; in the northwestern area, at the vicinity of the municipalities of Samacá and Cucaita, the values range from 6.74% to 17.3% $P_2O_5$; and in the northeast, between the municipalities of Toca and Tuta, they vary between 6.74% and 17.3% $P_2O_5$. The other areas present $P_2O_5$ values lower than 6.74%, thus, their potential is considered low, and they are identified withpale orange, green, yellow and blue colors (Figure 7).

To validate the model, the isoconcentration map was compared with the polygon that includes the Guadalupe Group, and a great deal of agreement was observed between the areas with $P_2O_5$ potential and the lithostratigraphic units that make up the Guadalupe Group. For example, on the flanks of the Tunja syncline, at the vicinity of the municipalities of Cómbita, Motavita, Chivatá and Soracá, there are low percentages of $P_2O_5$, in these places, the layers of interest for phosphorus are less abundant and siliceous layers (porcellanites and cherts) predominate, which represents a lateral change in facies in the sedimentary succession, consistent with geological cartography and stratigraphy (Figure 7).

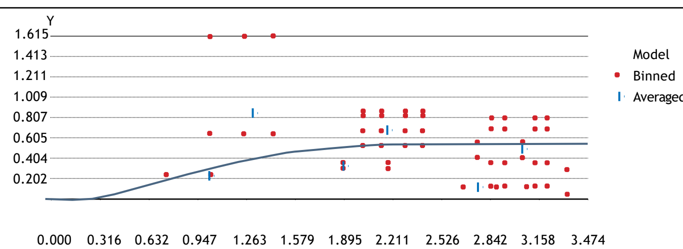
**Table 2.** Descriptive statistics of the geochemical data corresponding to the Guadalupe Group

| Parameter | Value |
|---|---|
| Medium | 7.10 |
| Typical error | 0.45 |
| Median | 3.34 |
| Mode | 0.05 |
| Standard deviation | 7.75 |
| Sample variance | 60.10 |
| Kurtosis | 2.33 |
| Asymmetry coefficient | 0.83 |
| Range | 27.47 |
| Minimum | 0.03 |
| Maximum | 27.50 |
| Sum | 2123.72 |
| Number of samples | 299 |

**A. Frequency histogram of $P_2O_5$**




**B. Semivariogram**



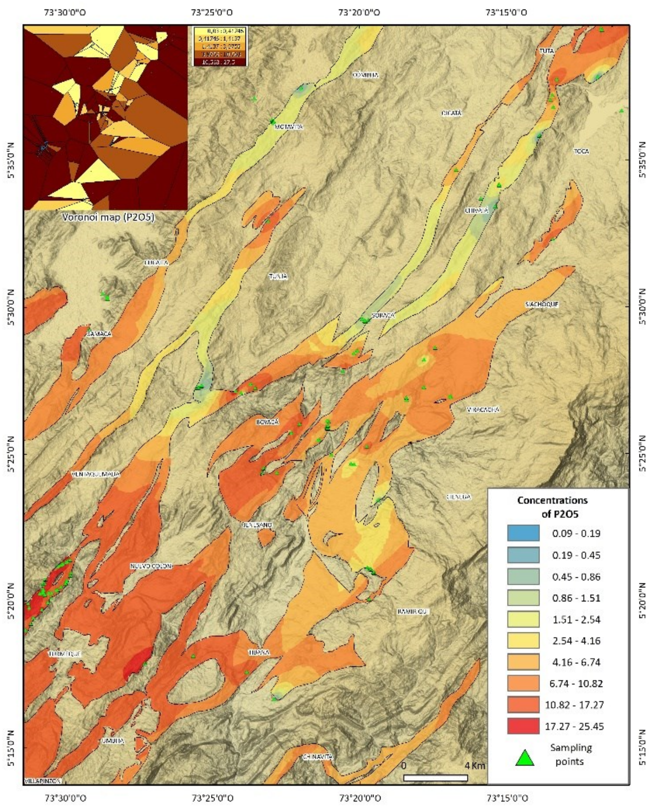



**Figure 7. Map of isoconcentrations of $P_2O_5$ corresponding to the Guadalupe Group developed by the supervised IDW method. The figure shows, in the upper left, the Voronoi map. Source: the authors; digi- tal terrain model taken from https://vertex.daac.asf.alaska.edu/**

## 6. Discussion

Since the 1940s, the Servicio Geológico Colombiano (formerly the Servicio Geológico Nacional and Ingeominas) has been conducting investigations (Bürgl and Botero, 1967; Cathcart and Zambrano, 1967; Irving, 1967; Zambrano and Mojica, 1990) on the phosphate layers in different lithostratigraphic units of the country, in which the sedimentary rocks of the Upper Cretaceous of the Eastern mountain range deserve more attention. Based on the geological cartography, the de- tailed stratigraphy and the supporting biostratigraphic studies (Etayo Serna, 2015), it was specified that the greatest potential of phosphates in the study area is at the base of the Guadalupe Group, whose stratigraphic nomenclature corresponds to the Arenisca Dura Formation by Pérez and Salazar (1978) or to the equivalent siliceous fine-grained facies at the base of the Guadalupe Group as specified by Martínez et al. (2020), and named by Renzoni (1981) and Etayo Serna (1968b) the “Plaeners Formation”, and by Montoya and Reyes (2003b, 2005, 2007) as the “Lidita Superior Formation”. However, in the overlying Plaeners Formation (Pérez and Salazar, 1978) and in the Arenisca de Labor-Tierna Formation (Renzoni, 1962; Pérez and Salazar, 1978), there is also phosphate potential, but it is of less importance (some layers of phosphates are less thick than others).

It was established that the phosphate layers found in the Guadalupe Group represent the highest Santonian to upper Campanian chronostratigraphic interval (Etayo Serna, 2015), with the most occurring in the lower Campanian (Arenisca Dura Formation, or in the equivalent siliceous fine-grained facies, or a transition between these two). The most important layers, which have maximum $P_2O_5$ values of 27.5%, were found in the siliceous fine-grained facies at the base of the Guadalupe Group. These layers vary laterally and vertically, both in thickness and in the $P_2O_5$ content, which can be seen in the lithostratigraphic correlations and in the map of isoconcentrations of the Guadalupe Group.

The siliceous fine-grained facies at the base of the Guadalupe Group (Martínez et al., 2020), are dominant in the NW and SW of the study area. These change laterally to quartzaarenitic facies, both to the south and to the SE, places where in the Arenisca Dura Formation (Pérez and Salazar, 1978), which has its own characteristics that it presents in the eastern hills of Bogotá. However, a transition between these two units continues to coexist.

Regarding the stratigraphic nomenclature applicable to the base of the Guadalupe Group with a predominance of siliceousfine-grained facies, it is recommended to name a new lithostra-tigraphic unit for this sector of the Eastern Cordillera following the recommendations of the International stratigraphic guide (Salvador, 1994) and abandon the name “Plaeners Formation”, established by Renzoni (1967, published in 1981) and Etayo Serna (1968b, p. 47), as well as the “Lidita Superior Formation”, established by Montoya and Reyes (2003a, b, 2005a, b 2007),which is typical of the Upper Magdalena valley, because the biostratigraphic studies by Etayo Serna (2015) show that thesefacies correspond to a facies change in the Arenisca Dura For- mation of the Bogotá savanna, which was confirmed with the geological cartography and correlations.

Preliminarily, the name “Motavita Formation” is proposed for this new lithostratigraphic unit since these siliceous facies outcrop quite well in the vicinity of homonymous municipality.

In the stratigraphic sections from Alto del Gavilán (S1) and La Batea quarry (S6), located to the north and SW of Motavita (Figures 3, 5 and 6), the lithology, stratigraphic range, age and boundaries can be clearly established with the underlying Conejo Formation and with the overlying Plaeners Formation. However, it is necessary to formalize the unit through an independent publication.

## 7. Conclusions

In the study area, there are sedimentary rocks with a stratigraphic ranges from Cretaceous to Paleogene and is covered in some sectors by Neogene and Quaternary deposits.

Structurally, in the study area, the reverse faults dominate with a preferential NE–SW direction and have vergences to both the SE and to the NW, though some are strike-slip faults (the faults of Chivatá, Cormenchoque, Puente Hamaca, Viracachá, Soapaga, Machetá, Río Icabuco and Hermitaño) and with regional folds (synclines of Tunja, Cómbita and Úmbita) and local folds, they are equally oriented to the NE–SW.

The geological mapping, which was supported by ammonite biostratigraphy, made it possible to specify the limits of the lithostratigraphic units and clarify the upper Cretaceous stratigraphy represented in the Guadalupe Group. Said group, in its basal portion, is constituted by the Arenisca Dura Formation, or an equivalent stratigraphic interval constituted by siliceous fine-grained facies, or an interdigitation between these two units. It is overlayed by the Plaeners Formation, which is located in the middle part of the Group, and in the top, by the Arenisca de Labor-Tierna or the Arenisca Tierna formations.

The most economically important phosphate layers are found at the base of the Guadalupe Group, whose stratigraphic range is mainly during the lower Campanian (Etayo Serna, 2015), which coincides with other phosphate deposits found in the departments of Huila (Lidita Superior Formation of the Olini Group) and Santander (La Renta Formation, *sensu* Terraza, 2019).

The lithostratigraphic correlation clearly shows that the lateral facies changes that occur at the base of the Guadalupe Group, inferred by the biostratigraphic studies from Etayo Serna (2015). The siliceous fine-grained facies dominate in the northwest and southwest of the study area, and in the southeast and south, the quartzarenitic facies characteristic of the Arenisca Dura Formation of the Bogotá savanna prevail. However, a transition between these two units is observed.

The geostatistics from the X-ray fluorescence data (XRF) corresponding to the samples from the Guadalupe Group allowed defining four sectors of phosphate potential that vary from high to medium: 1) the southwestern sector, at the vicinity of the municipalities of Turmequé, Nuevo Colón and Tibaná, with $P_2O_5$ values between 10.8% and 27.5%; 2) the central-eastern zone, at the vicinity of the municipalities of Ciénega and Viracachá, with concentrations of $P_2O_5$ between 6.74% and 10.8%; 3) the northwestern zone, at the vicinity of the municipalities of Samacá and Cucaita, with values of $P_2O_5$ between 6.74% and 17.3%; and 4) the northeast zone, between the municipalities of Toca and Tuta, with $P_2O_5$ values between 6.74% and 17.3%.

### Supplementary data

Appendix 1. Supplementary data for this article can be found online at https://doi.org/10.32685/0120-1425/bol.geol.50.1.2023.666

### Acknowledgments

The authors acknowledge to the Directorate of Mineral Re- sources of the Servicio Geológico Colombiano for its supportof the working group; Dr. Fernando Etayo Serna for the va- luable contribution in the paleontological determination ofthe collected ammonites and the teachings on the stratigraphy,geological cartography and paleogeography of the study area;the officials of the Directorate of Laboratories of the Servicio Geológico Colombiano for the geochemical analyses and the explanation of the thin sections.

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