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Review article

Motavita Formation, new lithostratigraphic unit in the central region of the Eastern Cordillera, Colombia

Formación Motavita, nueva unidad litoestratigráfica en la región central de la Cordillera Oriental, Colombia

Roberto **Terraza Melo** ✉, Germán **Martínez Aparicio** ✉
Servicio Geológico Colombiano, Bogotá, Colombia

Abstract

A new lithostratigraphic unit is formally proposed for the upper Cretaceous in the central region of the Eastern Cordillera of Colombia called the *Motavita Formation*, made up of cherts, porcellanites, mudstones, siltstones and subordinate quartzarenites, with levels of abundant benthic foraminifera of the family *Siphogenerinoididae* and beds of potentially exploitable phosphates. The geological cartography done by the Servicio Geológico Colombiano (SGC) in the last 20 years, supported by ammonite biostratigraphy and the correlation of stratigraphic sections, allowed us to infer important lateral lithological changes at the base of the Guadalupe Group, from the eastern hills of Bogotá, where sandstones dominate (Arenisca Dura Formation), up to the municipality of Motavita, where the fine-granular siliceous rocks of the new proposed *Motavita Formation* prevail. The type section of the new *Motavita Formation* corresponds to a composite stratotype made up of a holostratotype and a parastratotype. In the Alto del Gavilán holostratotype (municipality of Motavita) the lower limit appears with the underlying Conejo Formation of the upper Santonian. In the parastratotype of the La Batea quarry (Samacá municipality), the upper limit is observed with the overlying Plaeners Formation of the upper Campanian. The new *Motavita Formation* replaces the "Plaeners Formation" of Renzoni (1967) and Etayo (1968a, b) and the "Lidita Superior Formation" of Montoya and Reyes (2003a, 2005). The chronostratigraphic interval ranges from the upper Santonian to the lower Campanian, being predominantly from the lower Campanian. Regionally, it can be recognized from the north of Nemocón (Cundinamarca department) to the municipalities of Tasco and Paz del Río in the Boyacá department.

Keywords: *Motavita Formation, Eastern Cordillera, upper Cretaceous, fine-granular rocks and siliceous, phosphates*

Resumen

Se propone formalmente una nueva unidad litoestratigráfica para el Cretácico superior en la región central de la Cordillera Oriental de Colombia denominada Formación Motavita, constituida por cherts, porcelanitas, lodolitas, limolitas y cuarzoarenitas subordinadas, con niveles de abundantes foraminíferos bentónicos de la familia *Siphogenerinoididae* y capas de fosfatos potencialmente explotables. La cartografía geológica adelantada por el Servicio Geológico Colombiano (SGC) en los últimos 20 años, soportada con bioestratigrafía de amonitas y la correlación de secciones estratigráficas, permitió inferir importantes cambios litológicos laterales en la base del Grupo Guadalupe, desde los cerros orientales de Bogotá, donde dominan las arenitas (Formación Arenisca Dura), hasta el municipio de Motavita, donde prevalecen las rocas finogranulares silíceas de la nueva *Formación Motavita* propuesta. La sección tipo de la nueva *Formación Motavita* corresponde a un estratotipo compuesto conformado por un holoestratotipo y un paraestratotipo. En el holoestratotipo del Alto del Gavilán (municipio de Motavita) aparece el límite inferior con la infrayacente Formación Conejo del Santoniano superior. En el paraestratotipo de la cantera La Batea (municipio de Samacá), se observa el límite superior con la suprayacente Formación Plaeners del Campaniano superior. La nueva *Formación Motavita* sustituye a la "Formación Plaeners" de Renzoni (1967) y de Etayo (1968a, b) y a la "Formación Lidita Superior" de Montoya y Reyes (2003a, 2005). El intervalo cronoestratigráfico va del Santoniano superior al Campaniano inferior, siendo predominantemente del Campaniano inferior. Regionalmente, se puede reconocer desde el norte de Nemocón (departamento de Cundinamarca) hasta los municipios de Tasco y Paz del Río en el departamento de Boyacá.

Palabras clave: *Formación Motavita*, Cordillera Oriental, Cretácico superior, rocas finogranulares y de composición silícea, fosfatos.

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1. Introduction

The geological cartography carried out by the Colombian Geological Service (CGS) in the last 20 years, in the central region of the Eastern Cordillera, particularly in the Sabana de Bogotá and sheet 209-Zipaquirá (Montoya and Reyes, 2003a, 2005), has recognized the Lidita Superior Formation at the base of the Guadalupe Group. The Lidita Superior Formation (De Porta, 1965; Cáceres and Etayo, 1969) is a unit of the stratigraphy of the Upper Magdalena Valley that is well recognized both in the subsoil and on the surface and constitutes a guide level for the geological cartography of that region.

Montoya and Reyes (2003b), assign the Lidita Superior Formation to the lower Campanian, based on the fossil fauna found on the top of the Conejo Formation (municipality of Ubaté), corresponding to *Texanites (Texanites)* cf. *quinquenodosus* (Redtenbacher) cf. Kennedy et al. (1981); *Glyptoxoceras* sp. cf. *crispatum* (Moberg) cf. Kennedy *et al*. (1995); *Eulophoceras* sp. indet. cf. Kennedy *et al*. (1995) and *Baculites* sp. Indet., and based on upper Campanian ammonites *Nostoceras (Nostoceras) liratum* sp. (Hyatt, 1984) and *Exiteloceras jenneyi* (Whitfield, 1887), and Maastrichtian dinoflagellates (*Andalusiella polymorpha*, Malloy 1972) collected from the overlying Plaeners Formation by Föllmi *et al*. (1992) near to Tausa municipality.

Likewise, Terraza *et al*. (2010a) on the sheet 210 - Guateque (NW sector, grid 210: A1) and Terraza, *et al*. (2016) on phosphate exploration in the surrounding area of Tunja, identify and map the Lidita Superior Formation at the base of the Guadalupe Group, following the nomenclature of Montoya and Reyes (2003a, 2005). Martínez (2018) and Martínez *et al*. (2020) refer to this unit informally as the "Guadalupe Group base" and provide a detailed description of it.

However, it is preferable to restrict the Lidita Superior Formation to the Upper Magdalena Valley (UMV), for the following reasons:

1) Almost sixty years ago, Julivert (1962, p. 11-12), expressed the inconvenience of relating the siliceous levels of the UMV (Lidita Inferior and Lidita Superior formations of the Olini Group) with the siliceous levels of the Guadalupe Group, without being clear about the age of these levels, a situation that still persists today:

"Es evidente que los niveles de liditas de la región del Magdalena no guardan ninguna relación en cuanto a unidades litoestratigráficas se refiere con los niveles de porcelanitas asociados en mayor o menor grado con las areniscas que forman el Guadalupe del área de la Sabana, por consiguiente los nombres Primera y Segunda Lidita (o Lidita Superior e Inferior) no deben ser usados fuera del área en que estas liditas se manifiestan como unidades litológicas netas y por tanto no deben ser usadas en el área de la Sabana. [*sic*]". (Julivert, 1962, p. 11-12).

2) Renzoni (1967), in the J-12 Tunja quadrangle (sheet 191-Tunja, Renzoni *et al*., 1967 and sheet 171-Duitama, Renzoni and Rosas, 1967) divides the Guadalupe Group from old to young into Plaeners Formation (unit Kg2) and Labor y Tierna Formation (unit Kg1), and interprets that the Arenisca Dura Formation (unit Kg3), which represents the basal unit of the Guadalupe Group in the Sabana de Bogotá, is probably included in the upper sandstone layers of the Conejo Formation in this sector (table 1).

However, the biostratigraphic study by Etayo (2015) in the work area contradicts the interpretation of Renzoni (1967), because paleontologically it documents interdigitation in some sites (e.g., in the stratigraphic section of Alto del Volador to the NW of Garagoa) between segments of the Arenisca Dura Formation and segments of the Lidita Superior Formation of Montoya and Reyes (2003b) at the base of the Guadalupe Group. In other words, there is a lateral change in facies between the quartz sandstones predominant in the Arenisca Dura Formation and the fine-granular siliceous and muddy facies dominant in the Lidita Superior Formation. In this context, the Lidita Superior Formation of Montoya and Reyes (2003b) can be considered as a heteropic unit coeval with the Arenisca Dura Formation outcropping in the Sabana de Bogotá and hills to the east of it.

3) The biostratigraphic study by Etayo (2015) also indicates that the fine-textured siliceous rocks named by Etayo (1968b, p. 47) as the Plaeners Formation in the Villa de Leiva region and nearby areas, an contiguous zone to our work area (see figure 1, table 1), do not correspond to this unit but to the Lidita Superior Formation of Montoya and Reyes (2003b, p. 66; 2007, p. 34). Renzoni (1967) in the J-12 Tunja quadrangle also uses the Plaeners Formation in the same sense as Etayo (1968a, b). It is then concluded that the Plaeners Formations of Renzoni (1967) and Etayo (1968a, b) and the Lidita Superior Formation of Montoya and Reyes (2003b) represent the same lithostratigraphic unit and therefore are in stratigraphic synonymy.

As can be seen, the rocks at the base of the Guadalupe Group of the study area are completely different from the rocks present at the base of the Guadalupe Group of the Sabana de Bogotá represented in the sandstones of the Arenisca Dura Formation (Pérez and Salazar, 1978).

In accordance with the above, and in accordance with the International Stratigraphic Guide (Salvador, 1994, chapter 5D2, p. 38; North American Stratigraphic Code, 2005, chapter 23b, p. 1567), it is best to name a new lithostratigraphic unit for this sector of the Eastern Cordillera, which in this article is proposed as the

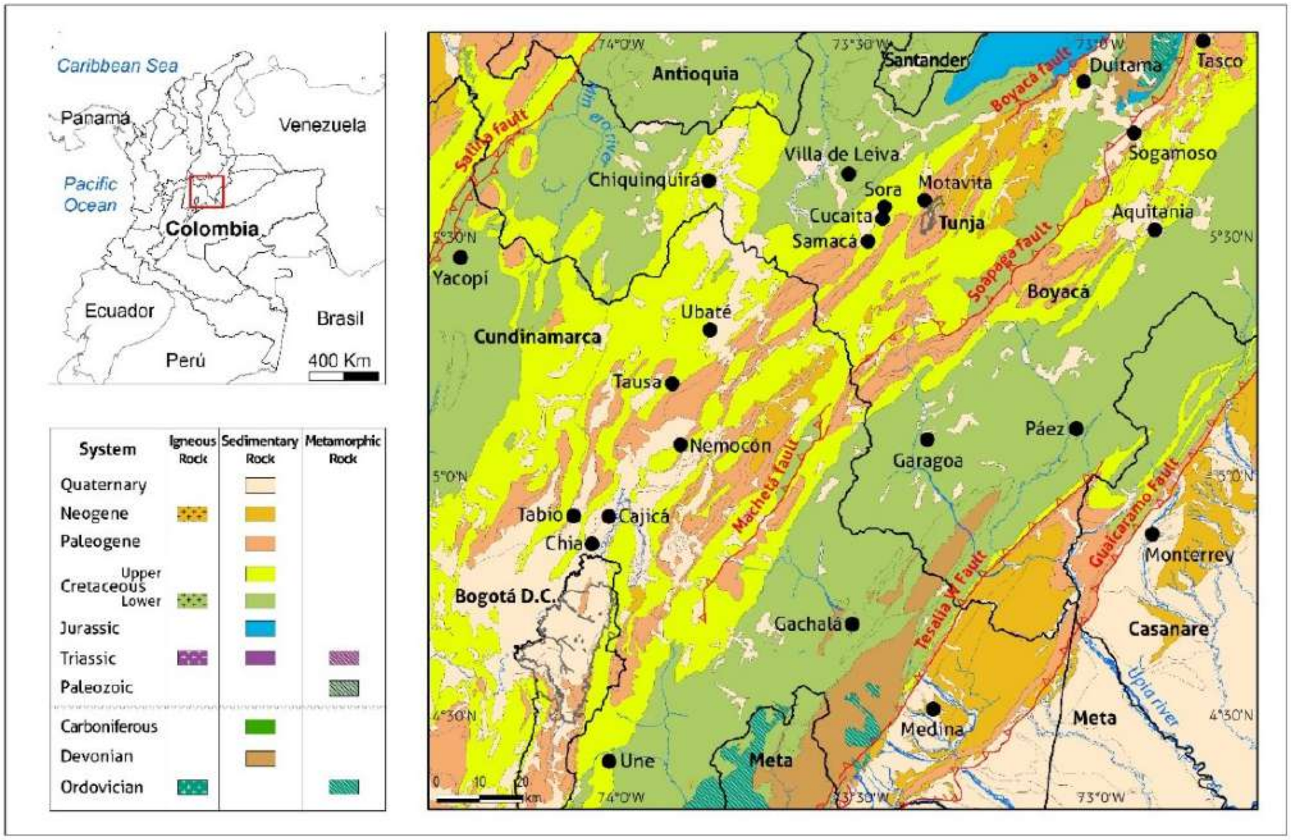

Figure 1. Regional geological map of the central zone of the Eastern Cordillera where the study area is located Source: taken from Gómez et al. (2015)

Table 1. Stratigraphic nomenclature used for the Guadalupe Group in the central region of the Eastern Cordillera.

<table>
<tr><th>Sabana de Bogotá
Hettner (1892)</th><th colspan="2">Sabana de Bogotá
Hubach (1957)</th><th>Sabana de Bogotá
Bürgl (1959, 1960)</th><th colspan="2">Villa de Leyva
Etayo (1968a, b)</th><th colspan="2">J-12 Tunja Quadrangule
Renzoni (1967)</th><th>Sabana de Bogotá
Pérez & Salazar (1978)</th><th colspan="2">Near Tausa
Föllmi *et al* (1992)</th><th>Sheet 209 Zipaquirá
Montoya & Reyes (2003a, b, 2005)</th><th colspan="2">Tunja and nearby areas
This work (2023)</th></tr>
<tr><td>Stage of Guaduas</td><td colspan="2">Guaduas Fm.</td><td>Guaduas Fm.</td><td colspan="2">Guaduas Fm.</td><td colspan="2">Guaduas Fm.</td><td>Guaduas Fm.</td><td colspan="2">Guaduas Fm.</td><td>Guaduas Fm.</td><td colspan="2">Guaduas Fm.</td></tr>
<tr><td rowspan="11">Stage of Guadalupe</td><td rowspan="8">Guadalupe Superior Fm.</td><td>Arenisca Tierna</td><td>Arenisca Tierna</td><td rowspan="5">Unnamed Formations</td><td>Arenisca Tierna</td><td colspan="2" rowspan="5">Labor and Tierna Fm. (Kg1)</td><td>Arenisca Tierna Fm.</td><td rowspan="8">Fm. Guadalupe</td><td rowspan="2">Tierna Upper Plaeners Labor</td><td rowspan="2">Labor – Tierna Fm</td><td rowspan="8">Grupo Guadalupe</td><td rowspan="2">Arenisca de Labor and Tierna Fm.</td></tr>
<tr><td rowspan="4">Arenisca de Labor and Plaeners</td><td>Upper Plaeners</td><td rowspan="4">Claystones and Siltstones set</td><td>Arenisca de Labor Fm.</td></tr>
<tr><td>Arenisca Dura</td><td rowspan="3">Plaeners Fm.</td><td rowspan="3">Lower Plaeners</td><td rowspan="3">Plaeners Fm</td><td rowspan="3">Plaeners Fm.</td></tr>
<tr><td>Plaeners and Claystones</td></tr>
<tr><td rowspan="2">Unnamed Sandstone</td></tr>
<tr><td rowspan="3">Arenisca Dura</td><td colspan="2" rowspan="3">Plaeners Fm.</td><td colspan="2" rowspan="3">Plaeners Fm. (Kg2)</td><td rowspan="3">Arenisca Dura Fm.</td><td rowspan="3">Raizal = A. Dura Upper Chert</td><td rowspan="3">Arenisca Dura/Lidita Superior</td><td rowspan="3">Motavita Fm. (new unit)</td></tr>
<tr><td>Plaeners and Sandstones</td></tr>
<tr><td>First Lidite</td></tr>
<tr><td colspan="2" rowspan="3">Guadalupe Inferior Fm.</td><td>Unnamed Sandstone</td><td rowspan="3">Conejo Fm.</td><td>Segment C</td><td rowspan="3">Fm. Conejo</td><td>Same as Arenisca Dura (Kg3)</td><td rowspan="3">Villeta Group</td><td colspan="2" rowspan="3">Villeta Fm.</td><td rowspan="3">Conejo Fm</td><td colspan="2" rowspan="3">Conejo Fm</td></tr>
<tr><td>Plaeners and Sandstones</td><td rowspan="2">Segment B Cucaita Member</td><td rowspan="2"></td></tr>
<tr><td>Second Lidite</td></tr>
</table>

Motavita Formation and to abandon the "Plaeners Formation" of Renzoni (1967) and Etayo (1968b p. 47) as well as the " Lidita Superior Formation" of Montoya and Reyes (2003b, 2005, 2007) and with this avoid the synonymies that were being presented, which obviously generate a lot of confusion among geologists when they carry out geological cartography because they do not know which lithostratigraphic nomenclature is correct for this area of the Eastern Cordillera.

This work has a double purpose, on the one hand, to try to document the lateral facies changes that occur at the base of the

Guadalupe Group from its type section in the eastern hills of Bogotá to the area of Tasco and Paz del Río in the department of Boyacá; and the other objective is to standardize the stratigraphic nomenclature at the base of the Guadalupe Group in the central region of the Eastern Cordillera.

The name Motavita comes from the homonymous town in the department of Boyacá, a term chosen because it has not been previously applied to another Cretaceous unit of Colombia (Julivert, 1968) and because fine-textured siliceous facies that characterize this new lithostratigraphic unit crop out very well in the vicinity of this municipality. In the neighboring municipalities of Samacá, Sora and Cucaita there are many quarries for construction materials that are extracted from this formation. The base and subbase material used in the unpaved tertiary roads in the rural areas of these municipalities comes from this unit.

Above the new *Motavita Formation*, the Plaeners Formation and Arenisca de Labor and Tierna Formations *sensu stricto* of the Sabana de Bogotá (Pérez and Salazar, 1978) are recognized, included by Renzoni (1967) in unit Kg1 y Kg2 (see table 1). Consequently, the Guadalupe Group of the study area is constituted from base to top by the *Motavita*, Plaeners and Arenisca Tierna or Arenisca de Labor and Tierna formations (which outcrop towards the SE side of the area).

Physiographically, these units generate notorious morphological contrasts in the landscape that allow them to be easily mapped in a similar way to the geoforms that the Guadalupe Group originates in the Sabana de Bogotá and hills to the east of it. The Arenisca Dura Formation or the *Motavita Formation* is recognized because its lithology generates escarpments, the Plaeners Formation forms valleys or plains, and the Arenisca Tierna Formation (or the Arenisca de Labor and Tierna Formation) shows prominent geoforms (figure 2).

2. Regional geological context

The study work is located in the central region of the Eastern Cordillera, an area called by Kammer et al. (2020) as the "middle segment of the Eastern Cordillera". Geographically it involves the territory known in Colombia as the Cundiboyacense plateau (high and flat lands between the departments of Cundinamarca and Boyacá) where the Sabana de Bogotá and the valleys of Ubaté, Tunja, Duitama and Sogamoso are located.

The Eastern Cordillera can be considered as a folded and faulted foreland belt adjacent to the Guiana Shield (*sensu* Kroonenberg, 2019). It is an asymmetric and bivergent belt (Mora and Parra, 2008) resulting from the Neogene inversion (Andean Phase) of a Mesozoic and Cenozoic back-arc basin with predominantly SE tectonic transport (Sarmiento, 2001; Mora and Parra, 2008; Branquet *et al*., 1999; Horton et al., 2020). The evolution and structural style of the "middle segment of the Eastern Cordillera" are detailed and discussed by Kammer *et al*. (2020).

The core of the Eastern Cordillera is formed by Precambrian migmatitic rocks, Paleozoic sedimentary, igneous, and metamorphic rocks, and Jurassic intrusive and extrusive igneous rocks (Gómez *et al*., 2015) (figure 1). Tectonic controls, transversal and longitudinal, have allowed the exhumation of a thick sequence of Cretaceous sediments with different facies and thicknesses in the axial zone of the mountain range, just where our study area is located.

Rocks from the Cenozoic and unconsolidated deposits from the Quaternary partially cover the region, making it difficult to recognize some of the structures in the area. The zone is strongly folded and faulted with transcurrent faulting regionally associated with subvertical or high-angle faults at depth (Acosta *et al*., 2007; Horton *et al*, 2020).

The stratigraphic succession involved corresponds to the upper Cretaceous, specifically to the rocks present at the base of the Guadalupe Group formally designated as the Arenisca Dura Formation (Pérez and Salazar, 1978) and its facial equivalent of fine texture and siliceous composition, which is proposed in this article as the *Motavita Formation*. The Guadalupe Group at the type locality of the eastern hills of Bogotá is constituted from base to top of the Arenisca Dura, Plaeners and Arenisca de Labor y Tierna formations (Table 1). The new proposed *Motavita Formation* is made up of cherts, porcellanites, mudstones, siltstones and subordinate quartzarenites, with abundance of benthic foraminifera of the *Siphogenerinoididae* family and potentially mineable phosphate beds, and represents a facial change of the Arenisca Dura Formation outcropping in the Sabana de Bogotá and its surroundings. The cherts and porcellanites of the *Motavita Formation* are possibly of biogenic origin, as will be seen later.

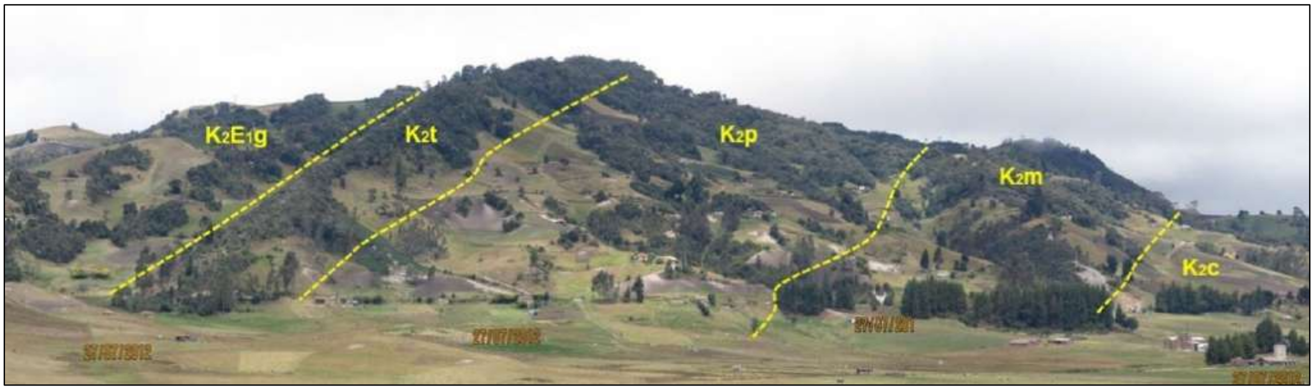

Figure 2. Characteristic geomorphology of the Guadalupe Group units in the study área. The Motavita (K2m) and Arenisca Tierna (K2t) formations show steep geoforms that alternate with valleys or depressions originated by the Conejo (K2c), Plaeners (K2p) and Guaduas (K2E1g) formations. View to the SW from the Quebrada Honda village in the municipality of Motavita (N= 1 115 657, E= 1 080 404, Z= 3 081, Azimuth= 215°)

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3. Method

The stratigraphic sections were measured with Jacob's stick. The readings were made to the nearest decimeter with an approximate error of 3% (±0.05 m for each 1.5 m long stick). The description in the field was on a centimeter and decimetric scale, using a 10x magnifying glass. The main aspects such as color, texture, composition, internal and external forms of the layers, biogenic and inorganic sedimentary structures, fossil content and degree of bioturbation were represented on previously designed formats. The field description was refined with microscopic analysis of thin sections. The term "massive" was used when the sedimentary rock appeared homogeneous or lacked internal structure, that is, macroscopically it did not show obvious internal stratification or lamination.

For the field description, the following terminologies were used, both in outcrops or hand samples and in thin sections:

The form of partitioning of the rock was compared with the proposal of McKee and Weir (1953). In the geometry (shape) of laminae, sets of laminae, beds or sets of beds, the terminology proposed by Campbell (1967) was used. The selection of particles in sediments or clastic sedimentary rocks, the shape of the strata and the types of contact between beds were defined with the Compton (1985) diagrams. Dunham's (1962) classification system based on depositional texture was applied to calcareous rocks. Folk's (1951, 1954, 1959, 1962, 1980) guidelines were followed to classify terrigenous rocks according to their texture and composition, define the degree of textural maturity, and to recognize important petrographic aspects of calcareous sedimentary rocks as a complement to Dunham's classification (1962).

The thicknesses of beds and laminae were compared with the proposal of Ingram (1954) and Campbell (1967) (adapted by Reineck and Singh, 1975). The term "medium" was used as a synonym for "mediam" in the description of thicknesses of beds or laminae of intermediate size between very thin and very thick. The shape of sedimentary particles was compared with the diagrams of Krumbein and Sloss (1969). The degree of bioturbation was defined with the graphs of Moore and Scruton (1957). The roundness of sedimentary particles was specified with the scale of Powers (1953). The lenticular and flasser bedding types were compared with the diagrams proposed by Reineck and Wunderlich (1968).

In the description of hand samples, the diagrams of Terry and Chilingar (1955) were used to volumetrically estimate percentages of minerals or particles. In the orientation of shells or remains of shells present in the strata, the terminology of Kidwell *et al*. (1986) was utilized. Fürsich (1995) was followed to identify the types of shell concentrations, showing the different accumulations of shells in epicontinental seas, the main factors that control them and their distribution on a seabed profile, referred to the base level of the waves in calm time and in stormy time. For example, the proximal tempestite or shells concentrations due to proximal storm flow originates between the base level of the waves in calm weather and the base level in stormy weather. The establishment of the color of the rock, in wet or dry samples, was carried out with the color chart of the The Geological Society of America (1995).

For sedimentary rocks with a mixture of terrigenous detrital particles and siliceous and calcareous authigenic components (mixed rocks), the general classification of sedimentary rocks by Williams *et al*. (1982) was used, which uses terms not considered by other classification system, such as chert, calcareous chert, porcellanite, siliceous limestone, clayey limestone, siliceous claystone, etc., useful and practical in petrographic, macroscopic in the field and microscopic in the laboratory description. For phosphatic rocks (5-50% phosphates) and phosphorites (>50% phosphates) the proposal of Cook and Shergold (1986), which it is based on Dunham (1962) classification of calcareous rocks modified for phosphorites.

To complement the description and classification of siliceous rocks as cherts and porcellanites or impure cherts (with >50% diagenetic or primary silica), the textural terminology of Dunham (1962) was used. As an example, a fossiliferous chert of benthic foraminifera with a wackestone texture is cited, which represents an impure chert with fossils of benthic foraminifera in a proportion of 10-50%, with a texture similar to that of a limestone with a wackestone texture in the system of Dunham.

4. Results

4.1 Holostratotype of the *Motavita Formation*

The stratigraphic column measured in the Alto del Gavilán (Sote Panelas village, to the NW of the municipality of Motavita, department of Boyacá) on the IGAC 191-Tunja sheet at scale 1: 100,000, grid B4, sheet 191-I-B at scale 1: 25,000, was chosen as holostratotype. The starting coordinates are N= 1 111 734, E= 1 076 950 and Z= 2 977 m.a.s.l. and the ending are N= 1 111 594, E= 1 077 100 and Z= 3 172 m.a.s.l. with MAGNA-Bogotá origin (figure 3). The stratigraphic continuity with the underlying unit (Conejo Formation) was taken into account because the Motavita-Plaeners geological contact was not observed with the overlying unit (Plaeners Formation), which is observable in the parastratotype of the La Batea quarry in the municipality of Samacá.

The Alto El Gavilán section is located on the western flank of the Cómbita Syncline (see geological map by Terraza *et al*. (2016). A thickness of 141.6 m was measured, of which 66.0 m correspond to the top of the Conejo Formation and the remaining 75.6 m to the *Motavita Formation*, of which about 8 m are covered at the base of segment D (figure 4). The section has an average strike of N60°E and a dip of 36° SE.

Martínez (2018) and Martínez et al. (2020) make a more detailed lithological description of this stratigraphic section with a good photographic illustration of it, for which the reader is referred to consult these works. These authors informally refer to the *Motavita Formation* as the "base of the Guadalupe Group".

The lithological description of the holostratotype of the *Motavita Formation* from the work of Martínez et al. (2020) is excerpted below.

Conejo Formation (Renzoni, 1967; Etayo, 1968a, b): Starts at coordinates N= 1 111 734, E= 1 076 950 and Z= 2,977 m.a.s.l.

Segment A (m0.0-m35.4). In the lower part (m0.0-m6.9) quartzarenite with a very fine texture, color 10Y8/2, mature, highly bioturbated, in medium and very thick tabular beds with continuous parallel flat stratification, massive, locally with non-parallel wavy lamination dashed. In the middle part, mudstones (m6.9-m9.3) of color N8 and claystones (m9.3-m24.3) of color 5YR4/1 in thin beds with continuous parallel flat bedding and very thin, discontinuous, parallel flat lamination.

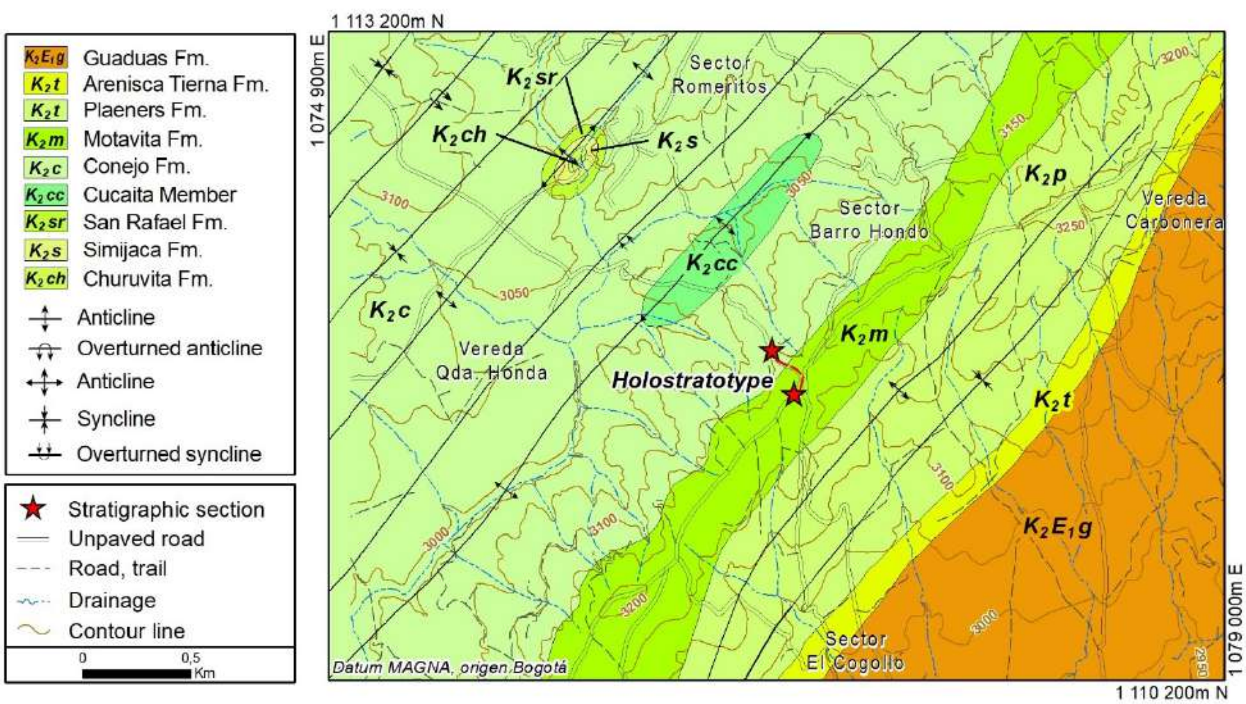

Figure 3. Location and local geology of the holostratotype of the *Motavita Formation*. Source: geology adapted from Terraza et al. (2016)

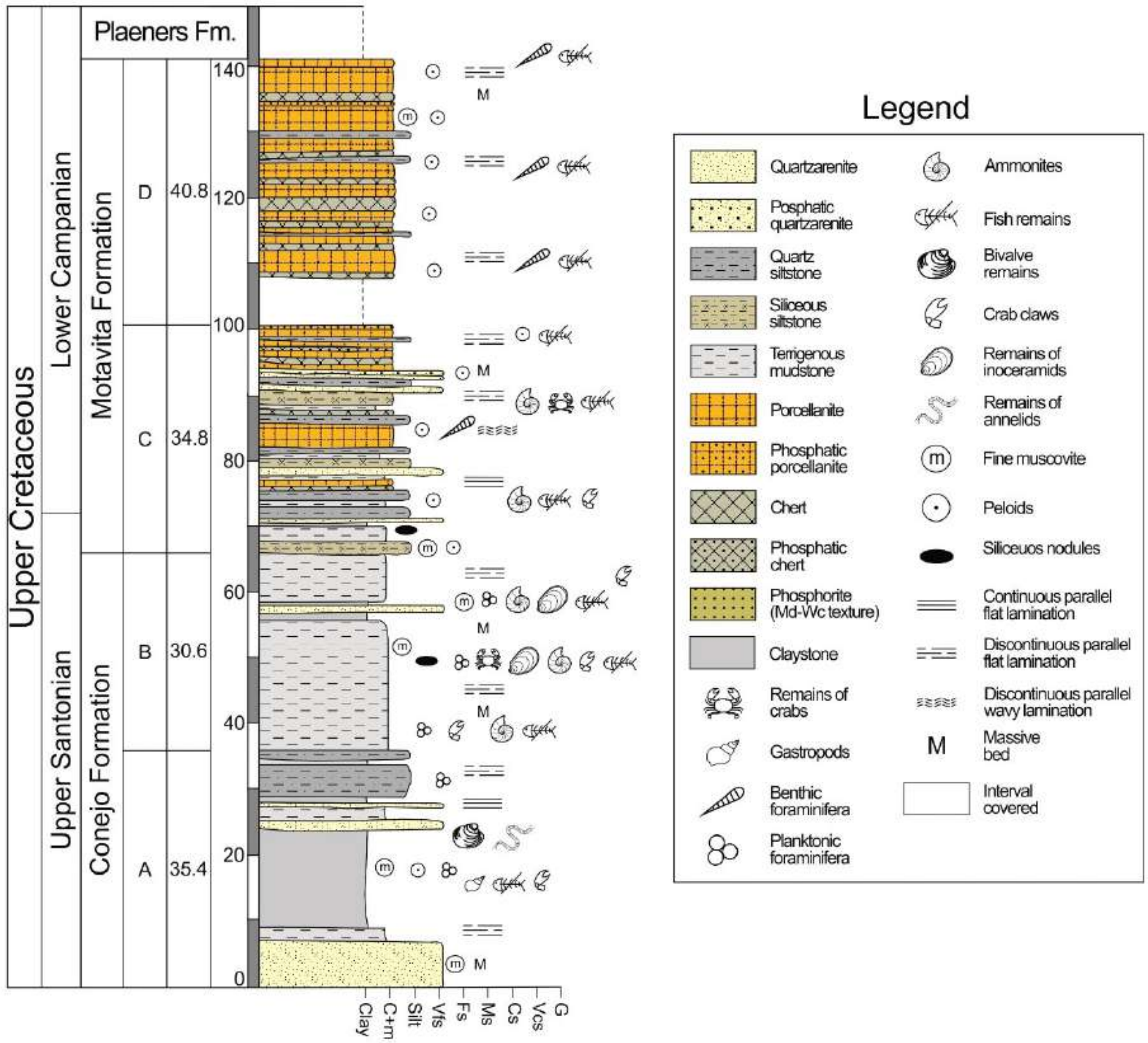

Figure 4. Holostratotype of the *Motavita Formation* in the stratigraphic section of Alto del Gavilán. Graphic scale: meters

The upper part (m24.3-m35.4) is made up of a 1.7 m tabular bed of very fine quartzarenite of color 10Y8/2, with discontinuous parallel flat thin lamination; a 2 m bed of 5YR6/4 colored mudstone with discontinuous parallel planar very thin lamination; a 0.5 m bed of quartzarenite similar to the previous one; a 1.2 m bed of N8 color claystone with discontinuous parallel planar thin lamination. The segment ends with 5.7 m of thin to very thick beds of 5YR4/1 colored quartz clayey siltstone with continuous parallel planar bedding and discontinuous parallel planar lamination, with some beds of claystone similar to the previous one interbedded. Planktonic foraminifera, fish remains, gastropods, crab claws, peloids, micas and iron oxides are observed in this segment. The rock is weathered.

Segment B (m35.4-m66.0). Mudstone of color N4 to 5YR3/4 weathered in thin to very thick beds with continuous parallel planar bedding, massive or with parallel planar discontinuous lamination, with high to moderate bioturbation; sporadically, it is interbedded with claystone of color 5YR2/2 and medium to very thick, tabular beds of very fine quartzarenite of color N6, bioturbated. In this segment, ammonites such as *Cocuyites cocuyensis* (Etayo-Serna, 1985), *Paratexanites* sp. inc., *Placenticeras* sp.? and the bivalves *Meretrix eufaulensis* (Conrad, 1860)? and *Platyceramus* ex gr. *P. cycloides* (Wegner, 1905), fossils assigned to the upper Santonian (Etayo, 2015). Concretions with iron oxides, siliceous nodules, planktonic foraminifera, crab claws, fish remains, organic matter and micas were also observed.

<u>*Motavita Formation*</u>*:* Starts at coordinates N= 1 111 665, E= 1 076 996 and Z= 3 179 m.a.s.l.

Segment C (m66.0-m100.8). The contact with the Conejo Formation is concordant and sharp. This segment begins with 1.7 m of siliceous siltstone of color 10Y8/2, in thin and medium beds with continuous parallel planar bedding and discontinuous parallel planar thin lamination; 7.7 m of mudstone and claystone of color 5YR4/1 follow in thin beds very thinly laminated in a discontinuous parallel flat shape, with siltstone nodules; medium and thin beds of siliceous siltstone of 5YR8/1 and 5YR4/1 color follow with ammonite fossils such as *Submortoniceras* sp. cf. uddeni (Young, 1963) from the lower Campanian (Etayo, 2015), interbedded with thin tabular beds of N8 mudstone with discontinuous parallel planar lamination; the rock is weathered.

The segment continues with 1.5 m of thin and medium beds of porcellanite and chert color 5YR4/1 with continuous parallel planar bedding and discontinuous parallel planar thin lamination. There follows a 5.7 m package made up of thinly laminated quartz siltstone; very fine quartz sandstone, somewhat fossiliferous, in tabular beds, and quartz siltstones with sporadic beds of interbedded porcellanite; the rock is N8 or 5YR8/1 in color and occurs in thin to medium beds with parallel planar bedding. There are 3.4 m of medium and thin beds of 5YR4/1 colored porcellanite with discontinuous parallel planar stratification and discontinuous non-parallel wavy lamination. Internally, the layers present chert nuclei and sandy concretions.

This is followed by a very thin bed of ferruginous siltstone of color 5R4/2; 0.9 m of 5YR4/1 colored siltstone in thin and medium beds with discontinuous parallel planar very thin lamination; 1.8 m of thin and medium layers of porcellanite and fossiliferous chert of color 5YR6/1 with wackestone texture, rich in benthic foraminifera and silicified peloids, finely laminated in a discontinuous parallel planar shape, with sporadic interbedded layers of quartzarenite and siliceous siltstone.

It follows a 1.2 m fossiliferous level composed of 5Y8/1 colored mudstone in medium and thick beds with discontinuous parallel planar bedding and ammonite impressions (*Submortoniceras* uddeni, Young, 1963?) suggesting the lower Campanian (Etayo, 2015), with silicified peloids, remains of fish and crabs. Subtabular thin to medium beds of N8 colored sandy mudstone with high bioturbation follow. The segment culminates with 7.8 m consisting of a thick, massive bed of slightly fossiliferous quartzarenite of color N8; several thin beds of 10Y8/2 colored porcellanite with continuous parallel flat bedding and sporadic beds of interlayered chert; above is siliceous siltstone of color 10Y8/2 in thin to medium tabular beds, with an interbedded median tabular bed of silicified peloid chert with wackestone texture and color N8. Thin and medium beds of 10Y8/2 colored porcellanite with discontinuous parallel flat lamination continue; finally follows a medium, tabular bed of peloid phosphatic porcellanite with a wackestone texture, color 5Y7/2, without internal lamination (massive). This segment is characterized by presenting benthic foraminifera, ammonite impressions, crab and fish remains, silicified peloids, micas and iron oxides.

Segment D (m100.8-m141.6). N8-N9 and 5YR8/1 colored porcellanite in thin to medium beds with continuous parallel planar bedding and discontinuous parallel planar thin to very thin lamination, interbedded with chert, 10R4/2 color ferruginous siltstone, 5B9/1 color quartz siltstone, and some beds of siliceous siltstone. Towards the top of the segment there are medium and thin tabular beds of wackestone-textured fossiliferous porcellanite with abundant benthic foraminifera, color N8-N9 and discontinuous, flat parallel lamination, with interbedded beds of chert. Above the last layer of porcellanite, a zone covered with a valley morphology continues that corresponds to the Plaeners Formation. This segment is characterized by the presence of silicified benthic foraminifera of the *Siphogenerinoididae* family, fish remains, silicified peloids, micas and iron oxides.

4.2 Parastratotype of the *Motavita Formation*

The parastratotype of the *Motavita Formation* is located in the La Batea quarry (municipality of Samacá, El Venado neighborhood group, Tibaquira village, La Batea sector) with starting coordinates N= 1 100 504, E= 1 066 662 and Z= 2 677 m.a.s.l. and coordinates ending N= 1 100 820, E= 1 066 341 and Z= 2 666 m.a.s.l. with MAGNA-Bogotá origin (figure 5), on the IGAC 191-Tunja plate at 1: 100,000 scale, grid D2, and 191-I-C plate at 1: 25,000 scale.

The parastratotype of the *Motavita Formation* is located on the eastern flank of the Samacá Syncline or the western flank of the Cucaita Anticline (figure 5; see geological map by Etayo, 1968a and geological map by Renzoni *et al*., 1967, grid D2). A thickness of 267 m was measured, of which 64.5 correspond to the upper part of the Conejo Formation, 129.8 m to the *Motavita Formation* and 72.7 m to the overlying Plaeners Formation. The section has an average strike of N27°E and a dip of 44° to the NW. Unfortunately, the last 9.3 m of the highest part of the Conejo Formation (underlying unit) and the base of the *Motavita Formation* (first 31.5 m) are covered (figure 6), however, in the type section of the Alto del Gavilán these covered intervals can be observed.

Conejo Formation (Renzoni, 1967; Etayo, 1968a, b): Starts at coordinates N= 1 100 504, E= 1 066 662, and Z= 2 677 m.a.s.l.

Segment A (m0.0-m27.8). At the base (m0.0-2.6) fine quartzarenite, color 10YR6/2, submature, calcareous cement, 1-3% bivalve remains, <1% muscovite, thin to medium massive beds or with remnants of lamination wavy non-parallel dashed; between m1.5-m2.6 the sandstone is nodular in appearance and contains 7-10% of bivalve remains. The rest of the segment is mudstone of color N1-N5, 5YR4/1 or 10YR6/2, with poorly developed lamination, medium to thick, flat parallel discontinuous, stratified in thin beds of flat parallel discontinuous; there are fish scales and crab claws.

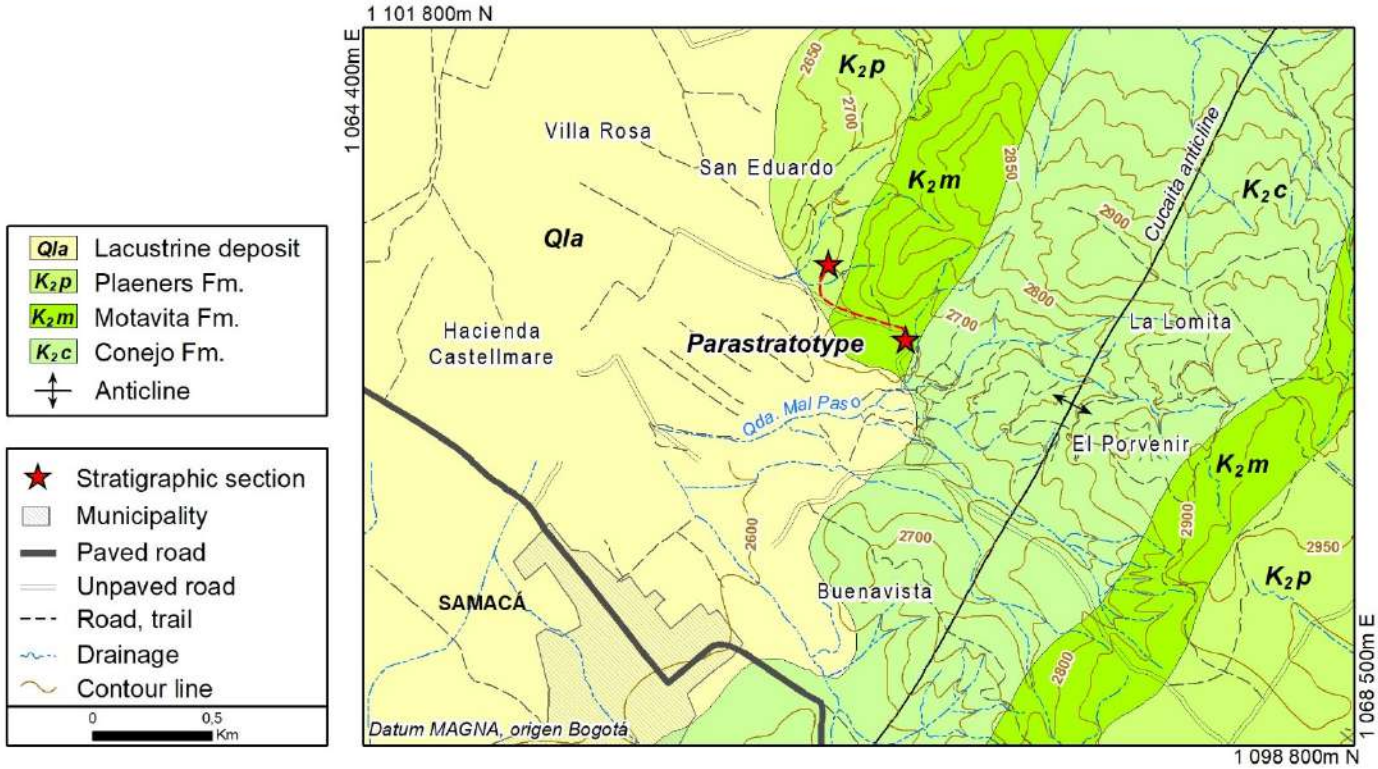

Figure 5. Location and local geology of the parastratotype of the *Motavita Formation*. Source: geology adapted from Etayo (1968a)

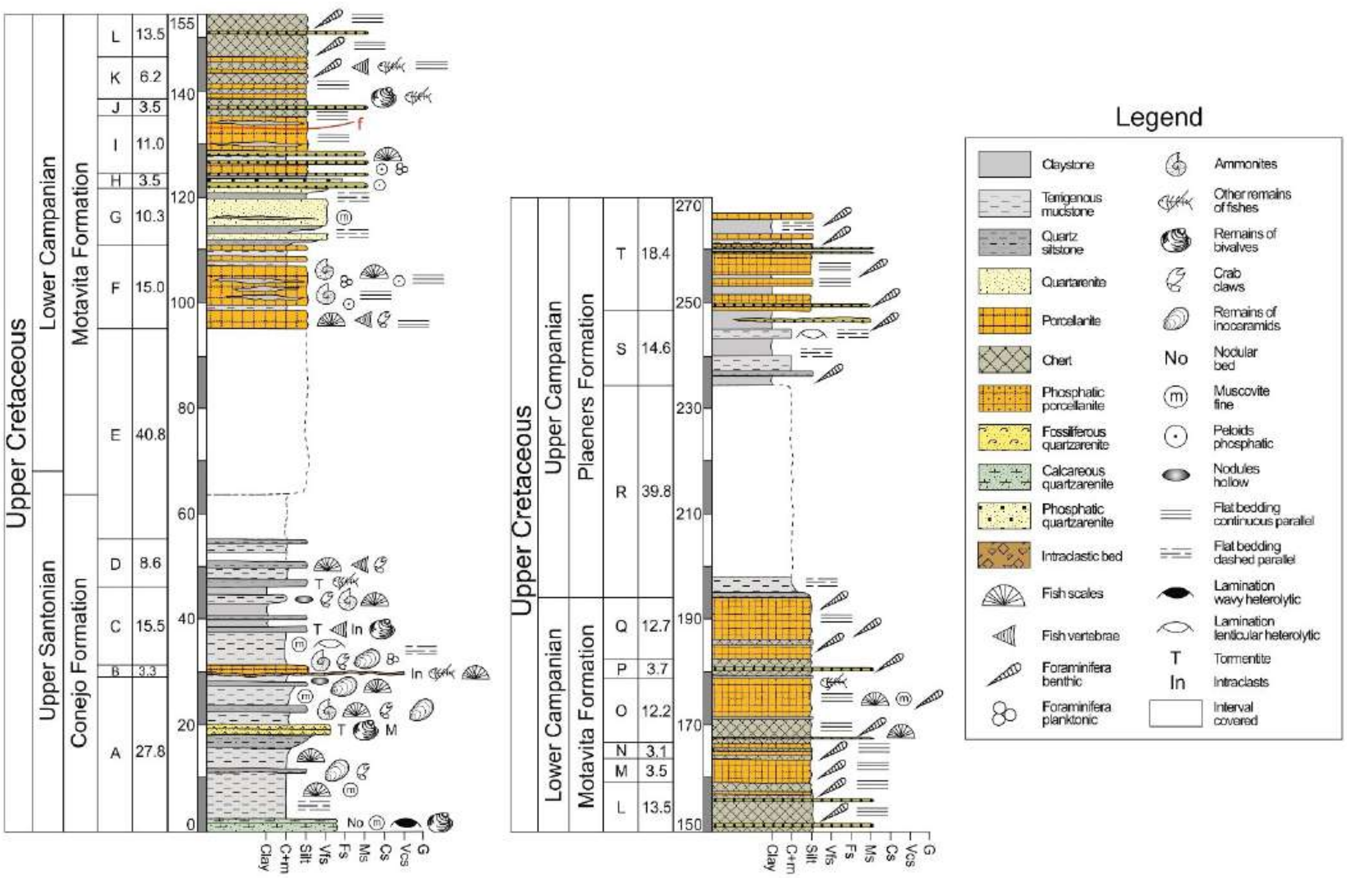

Figure 6. Parastratotype of the *Motavita Formation* in the stratigraphic section of the La Batea quarry Graphic scale in meters

There are interpositions of quartzose siltstones (m11.0-11.5, m21.0-m22.6) weathered (figure 7), with inoceramide fossils, ammonite impressions, crab claws or other bivalve remains. Between m16.5-m19.3 there is a coarsening upward sequence of mudstone to very fine quartz sandstone that ends with a 30 cm bed of immature fossiliferous quartz sandstone, with 20-25% remains of floating bivalves, with a net and irregular base, and below a bed of 0.7 m of immature, massive quartzarenite, with 10-15% of floating bivalve remains in the sandy framework. In m21.7 it was found *Platyceramus cycloides* (Wegner, 1905) and *Texanites* sp. cf. *T. shiloensis* (Young, 1963), fossils assigned to the upper Santonian-Lower Campanian? and in m21.0 *Glyptoxoceras* sp. cf. *G. souqueti* (Collignon, 1983) from the upper Santonian (Etayo, 2015).

Figure 7. Tabular beds of weathered quartz siltstones interbedded in gray mudstones

Segment B (m27, 8-m31,1). Laminated silty porcellanite, color N2-N5 and 10YR6/6, in thin continuous parallel flat beds, hard, prismatic partition, to the top with ammonites, crab claws, inoceramids and planktonic foraminifera. At the base (m28.3-m28.8) mudstone of N5 color is interbedded, overlain by a 10 cm bed, with an irregular and net base, of fossiliferous intraclastic mudstone (intraclasts of clay of color N8 of very coarse sand size and of porcellanite of color N9 with a size of up to 1 cm in diameter and fragmented remains of fish) with hollow concretions. *Glyptoxoceras crispatum* (Moberg, 1885) (m28.9) from the Santonian (Etayo, 2015) was found.

Segment C (m31.1-m46.6). Weathered mudstone, color N5 and 5YR4/1, with thin to medium bedding and lamination, discontinuous, flat parallel, micaceous (<1-2% muscovite), in the middle part with lenticular lamination by granulometry (thin laminae of quartz silt interbedded); the lower part of the segment is covered (m31.1-m31.5). In the upper part (m39.2-m39.8) there are interbedded two beds of 20 cm each of fossiliferous siltstones with 35-40% poorly calibrated and floating remains of fish vertebrae, intraclasts and fragments of bivalves, possibly tormentites. Between m39.8-m42.7 and m45.0-m46.6 there are claystones of color 5YR4/1 and N4-N5, weathered, soft, with stratification and lamination similar to mudstones.

Between m40.2-m40.5 there is an interbedded layer of 30 cm of quartz siltstone, argillaceous, micaceous (1-2% muscovite), with vertebrae and fish scales and crab claws; between m45.0-m46, 6 frequent lenticular lamination is observed (thin laminae of quartz silt interbedded every 1 to 2 cm stratigraphically). Towards m39.8 and 44.5 there are impressions of ammonites. At m39.7 *Platyceramus cycloides* (Wegner, 1905) was found and at m45.0 *Cocuyites cocuyensis* (Etayo, 1985) from the Santonian (Etayo, 2015).

Segment D (m46.6-m55.2). Mudstone of color N4 and 10YR6/2 with interpositions of fossiliferous quartz argillaceous siltstone, in thin discontinuous layers of flat parallel shape and thin to medium flat parallel discontinuous lamination; the rock is weathered. An interval covered between m51.0-m54.0 is presented. The siltstones are found at the top and in the lower part, are fossiliferous (5-10% of fish remains such as vertebrae, bone fragments and scales), of color 5YR4/1, porous and light. In the lower part of the segment, at the top and base of a siltstone package (m46.6-m47.8), there are two layers of 20 and 30 cm of siltstones, with 10-15% the upper layer and 30-35% the lower layer, of fish remains (vertebrae, bone fragments, and scales) and crab claws, floating in the silty framework, possibly correspond to tormentites. It was found at m49.5 *Sphenoceramus* sp. inc.? of the upper Santonian (Etayo, 2015).

Segment E (**m55.2-m96.0**). Covered interval. In this segment, the geological contact between the Conejo and *Motavita* formations is inferred, manifest at approximately meter m64.5, due to a morphological change between a depressed area corresponding to the top of the Conejo Formation (m55.2-m64.5) and a hill slightly prominent, covered by fragments of porcellanite from the lower part of the *Motavita Formation*, which is located between meters m64.5 and m96.0 (figure 8).

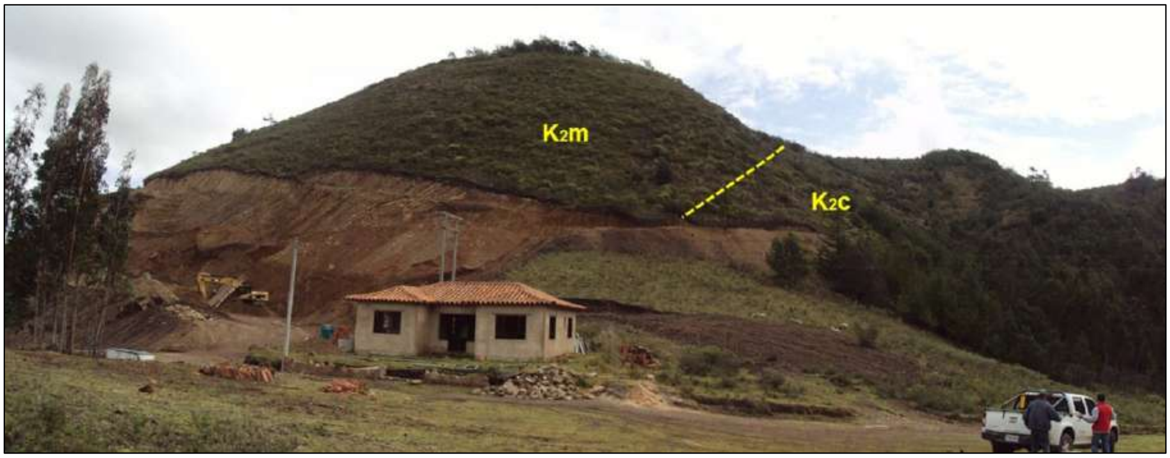

Figure 8. Approximate geological contact between the Conejo (K2c) and Motavita (K2m) formations

Figure 9. Porcellanites with some intercalations of claystone in lentiform beds; the rock is weathered and takes on a yellowish coloration.

Segment F (m96.0-m111.0). In the lower and middle part (m96.0-107.7) laminated porcellanite, color 5YR4/1 and 5YR6/1, slightly phosphatic (1-3% of phosphatic peloids), in layers of 4-20 cm, 2-5 cm or 1-10 cm with flat parallel continuous layering internally with thin to medium flat parallel discontinuous lamination. At the base (m96.0-m97.5) there are 0.5 cm thick levels enriched in phosphatic peloids up to 20%. Fossil remains of fish (scales and vertebrae) and crab claws, impressions of ammonites, and occasionally planktonic foraminifera are common. There is a 20 cm nodular bed of interbedded black chert (m103.3) and another 50 cm of siliceous mudstone (m99.5), as well as several thin lenticular layers (approximately 10 cm) of weathered claystone of color 10YR6/ 6 between m102.0 and m106.0 (figure 9).

The upper part of the segment (m107.7-m111.0) is made up of porcellanite similar to the previous one with interbedded beds of laminated siliceous mudstone colored 5YR4/1 and 5YR8/1, weathered, in medium and thick layers (between 30-50 cm) in tabular form. It was found at m107.5 *Bevahites* sp. cf. *B. costatus* (Collignon, 1948) from the lower Campanian (Etayo, 2015).

Segment G (m111.0-m121.3). Sandy, made up of three coarsening upward sequences, the lower (m111.0-m111.8) of mudstone to quartz sandstone with a very fine texture, and the intermediate (m111.8-m120.0) and upper (m120.0-121.3), from quartz siltstone to very fine quartz sandstone. The quartz sandstone is 5YR6/1 and 10YR8/6 in color, weathered, muscovitic (1%), mature, in tabular layers of 2-30 cm or 3-15 cm, with discontinuous parallel flat stratification and equally flat thin to medium lamination dashed parallel; locally they contain 7-10% (m121.0) or 3-5% (m111.59) of phosphatic peloids. The siltstone at the base of the segment (m111.8-m112.5) is argillaceous, with 1-2% phosphatic peloids and contains impressions of ammonites. In the middle part of the segment (m117.2) there are thin lenticular layers of weathered sandy claystone of color 10YR6/6.

Segment H (m121.3-m124.8). Phosphatic, color N4-N5, made up of 1.3 m of massive phosphorite with peloids and a packstone texture (figure 10). Three 20 cm layers follow, the upper and lower layers of clay separated by a layer of porcellanite. This is followed by 0.8 m of fine-textured, mature, phosphatic quartzarenite (15-40% phosphatic peloids), followed by 20 cm of phosphorite similar to the previous one, and the segment ends with two 20 cm layers of 5YR2/1 color phosphorite each one, with a similar texture to the previous one, separated by a 20 cm layer of quartzous siltstone.

Segment I (m124.8-m135.8). Porcellanite color 5YR4/1 and N6-N8, in 1-4 cm, 2-10 cm or 2-20 cm beds, tabular, with continuous parallel flat stratification and discontinuous parallel thin to medium flat lamination. In the upper part (m131.5-m135.5) there are 1 cm x 1.5 m black chert lenses and 30 cm long pockets of white clay. Between m132.0 and m133.0 there appears a decimetrically folded porcellanite zone with crushed rock caused by a local fault.

In the lower and middle part (m124.8-m132.0) the rock shows moldic porosity (15-20% or 10-15%) possibly due to the dissolution of foraminifera, 3-5% of floating phosphatic peloids in the fine-granular support siliceous rock and interpositions of 10-30 cm layers of nodular or lenticular black chert, and 10-35 cm layers of peloid phosphorites of packstone texture.

Figure 10. Massive bed of 1.3 m of gray phosphorite with packstone texture

Segment J (m135.8-m139.3). Black N1 chert in 2-7 cm beds with continuous parallel planar bedding and parallel planar discontinuous thin lamination, locally fossiliferous (15-20% of fish remains between m136.9 and m38.4). In the lower part the chert shows moldic porosity? from 25 to 30%; in the middle part, two layers of 12 and 25 cm of peloid phosphorite with a packstone texture are interbedded.

Segment K (m139.3-m145.5). Alternation of N1 black chert and 10YR8/2 porcellanite in beds of 2-4 cm (chert) and 10-15 cm (porcellanite) with continuous parallel flat bedding and discontinuous parallel thin to medium flat lamination. The porcellanite shows moldic porosity of 20-25% due to the dissolution of phosphatic peloids; levels with remains of fish bones or remains of bivalves are observed.

Segment L (m145.5-m159.0). N1, 5YR6/1, 5Y2/1 or 10YR6/6 colored chert in 4-15 cm, 2-7 cm or 3-10 cm beds, with continuous flat parallel bedding and discontinuous parallel flat medium to thin lamination (figure 11), fossiliferous, with 20-25% of benthic foraminifera of the family *Siphogenerinoididae*, locally up to 35%, distributed in laminae 1-8 mm thick. At various levels, these microfossils are dissolved, causing moldic porosity, or they can be seen silicified. Tabular layers of fossiliferous porcellanite are interbedded every 1.5 to 3.0 m, 20 to 50 cm thick, weathered, with 20-25% moldic porosity due to the dissolution of benthic foraminifera (family *Siphogenerinoididae*). In the upper part (m154.5) and middle part (m151.1) there are 5-13 cm beds of peloidal phosphorite with a packstone texture.

Segment M (m159.0-m162.5). Colored porcellanite 10YR6/2 and 10YR8/2 in 4-15 cm layers with continuous parallel flat bedding and discontinuous parallel flat medium to thin lamination, hard, fossiliferous, with 5-7% of benthic foraminifera of the family *Siphogenerinoididae*, locally with levels 10 and 30 cm thick and with contents of 30-35% of dissolved or silicified foraminifera.

Figure 11. Light brown weathered chert with continuous parallel planar bedding that is common in the upper part of the Motavita Formation

Segment N (m162.5-m165.6). Chert alternated with porcellanite in 5-30 cm layers, tabular, with continuous parallel flat bedding and discontinuous parallel flat medium to thin lamination. The rock is N6 and 5YR6/1 in color and contains 3-5% benthic foraminifera; at the base (m162.7) there is a 30 cm bed of porcellanite with 30-35% dissolved foraminifera.

Segment O (m165.6-m177.8). In the upper part (m170.7-m177.8) N9 and 10YR7/4 color porcellanite in 1-10 cm beds with continuous flat parallel bedding, thin to medium flat discontinuous parallel lamination, slightly fossiliferous (1-3% of benthic foraminifera of the family *Siphogenerinoididae*) and somewhat micaceous (<1% muscovite). In the lower part (m165.6-m170.7) chert color 10YR8/2 and N4, in 10-35 cm beds with stratification and lamination similar to porcellanite, with 1-2% phosphatic remains and 1-3 % of benthic forams (family *Siphogenerinoididae*), hard, dense, locally with fish scales. At m167.4 there is a 6 cm bed of peloid phosphorite with a packstone texture and at m170.7 one of laminated siliceous siltstone.

Segment P (m177.8-m181.5). Chert of color N5, N9 and 10YR8/2, hard, in slightly sinuous layers of 5-20 cm or tabular 5-40 cm and 5-15 cm (figure 12), with continuous flat parallel bedding and thin lamination to median discontinuous parallel flat, slightly fossiliferous, with 1-3% benthic foraminifera of the family *Siphogenerinoididae*; between m178.8-m179.7 contains 3-10%. In the middle part (m179.7) there is a 20 cm bed of phosphorite with a wackestone texture, porous, with 40% of dissolved phosphates. In the lower part (m178.1) a 30 cm bed of laminated quartz siltstone is interbedded with ovoid-shaped concretions filled with clay-sandy material.

Segment Q (m181.5-m194.2). N5-N6 color porcellanite, hard, in beds of 3-15 cm and 1% of benthic foraminifera of the family *Siphogenerinoididae* in the upper part, beds of 2-6 cm and 1-3% of benthic foraminifera in the middle portion, and 10-20 cm beds with 10-15% benthic foraminifera and 1-2% phosphatic peloids at the base. The bedding is flat parallel continuous with faint discontinuous lamination, thin to medium, flat parallel. In the middle part (m184.5-m186.0) a set of 2-6 cm beds of fossiliferous chert is interbedded with 7-10% of silicified benthic foraminifera of the family *Siphogenerinoididae*, some of which are dissolved.

Figure 12. Weathered chert, light gray and yellowish, in tabular, slightly sinuous median layers

Plaeners Formation (Hubach, 1931; Julivert 1961; Renzoni 1962; Pérez and Salazar, 1978): Starts at coordinates N= 1 100 534, E= 1 066 429, and Z= 2 669 m.a.s.l.

Segment R (m194.2-m234.0). The geological contact with the porcellanites of the *Motavita Formation* is rapid gradual, varying from porcellanite to quartz siltstone and terrigenous mudstone in approximately 30 stratigraphic cm (figure 13). A large part of the segment is covered and only the first 1.3 m exposed, made up of massive terrigenous mudstone of 5YR4/1 color in thin layers with discontinuous parallel flat bedding.

Segment S (m234.0-m248.6). Claystone with terrigenous mudstone intercalations. The rock is N5-N9, 5YR5/6 or 10YR8/2 in color, weathered, in thin massive layers, with discontinuous parallel flat stratification (figure 14). The terrigenous mudstones present traces of muscovite (<1%) and 25-30% of quartz silt in thin interbedded laminae (lenticular heterolithic lamination). In the lower part (m236.3-m236.8) a 50 cm massive quartz siltstone package is interbedded with <1% benthic foraminifera. In the upper part (m247.5-248.6) three lenticular layers of peloid phosphorite with a packstone texture are interbedded, 9 to 20 cm, with an irregular and net base, fossiliferous (10-20% of benthic foraminifera of the family *siphogenerinoididae*.

Figure 13. Transitional geological contact between the *Motavita Formation* (K2m) and Plaeners Formation (K2p)

Segment T (m248.6-m267.0). 5YR8/1, 5YR4/1 or 5YR5/6 colored porcellanite with N4-N5 or 5YR4/1 clay intercalations. The porcellanite is in tabular layers of 2-5 cm or 3-10 cm with continuous parallel flat bedding and discontinuous lamination, thin to medium, parallel flat in shape, with variable concentrations of benthic foraminifera of the family *Siphogenerinoididae* (5-7%: m266-m267.0, 15-20%: m261.5-m262.1, 1%: m258.0-m259.4, 20-25%: m255.1-m258.0, 3-5%: m253, 0-m254.8; 7-10%: m248.6-251.2). There are 4 interbedded layers of 5 to 15 cm of peloid phosphorite with a packstone texture (m249.6, m254.0, m259.4, m260.39) as well as a 60 cm pack of porous phosphatic porcellanite in m260.3. Claystone is soft, weathered and massive; between m251.2 and m253.0 two 6 cm layers of peloid phosphorite with a packstone texture are interbedded. Between m260.9-m261.5, the porcellanite presents an interbedded set of 60 cm of fossiliferous terrigenous mudstone of color 5YR4/1 with 15-20% of benthic foraminifera of the family *Siphogenerinoididae*.

Figure 14. Weathered gray claystone in the lower part of the Plaeners Formation

4.3 Geographic extent

According to what is stated in the Introduction of this article and the analysis of the geological cartography published by the CGS, the *Motavita Formation* would extend approximately in a stripe of upper Cretaceous rock of about 120 km in length (linearly measured), oriented SW-NE in the axial region of the Eastern Cordillera, from about 10 km north of the municipality of Nemocón in Cundinamarca to the town of Duitama in the department of Boyacá, covering the NE portion of sheet 209-Zipaquirá (Montoya and Reyes, 2003a), the SE sector of sheet 190-Chiquinquirá (Fuquen and Osorno, 2005), the NW extreme of sheet 210 (Terraza *et al*., 2010a), the W side of sheet 191-Tunja (Renzoni *et al*., 1967) and the northeast region of sheet 172-Paz del Río (Ulloa *et al*., 1998c), that is, it can be recognized to the NE of the Sabana de Bogotá and in the valleys of Ubaté, Tunja, Duitama and Sogamoso.

4.4 Chronostratigraphic interval

Based on the fossils cited in the lithological description of the stratigraphic sections of the Alto del Gavilán (holoestratotype) and the La Batea quarry (parastratotype) and the fossils studied in the exploration of phosphates in the surroundings of Tunja (Etayo, 2015) and those reported by Montoya and Reyes (2003b) and Martínez *et al*. (2023), it was defined that the new *Motavita Formation* covers the upper Santonian to lower Campanian chronostratigraphic interval, being dominantly from the lower Campanian. In addition, it was determined that the Santonian-Campanian boundary must be found in the first layers of the new *Motavita Formation*.

In the following stratigraphic sections of the study area the most characteristic fossil ammonoids of the upper Santonian-lower Campanian stratigraphic interval are cited:

a) La Batea quarry, Samacá municipality: *Bevahites* sp. cf. *Bevahites costatus* (Collignon, 1948) from upper Santonian to lower Campanian.

b) Peñas village, municipality of Ramiriquí: *Hauericeras* sp. cf. *H. gardeni* (Baily, 1855) from the lower Campanian.

c) Alto del Gavilán, Motavita municipality: *Submortoniceras* uddeni (Young, 1963) and *Submortoniceras* sp. cf. (Young, 1963) from the lower Campanian.

4.5 Some important petrographic aspects

Petrographically, silicified benthic foraminifera of the genus *Orthokarstenia* are usually found in the cherts and porcellanites of the *Motavita Formation* (Cruz *et al*., 2011). Likewise, peloids, remains of bioclasts and the fine-granular matrix or support of the rock are replaced by cryptocrystalline to finely crystalline silica, suggesting an intense silicification process in the rock. Typical textures of calcareous rocks can also be recognized, which indicates that the silicification must have occurred from limestone with similar textures.

The figure 15 (A, B, C, D, E, F) shows cherts with a mudstone or packstone texture and silicified biomicrites where benthic foraminifera, peloids and some bioclasts are recognized, originally of calcareous composition, totally replaced cryptocrystalline silica a finely crystalline or chalcedony. This replacement probably occurs in the early stage of diagenesis, during shallow burial of sediments (Trewin and Fayers, 2005), when bioclasts and other allochemical grains, the matrix or support of calcareous mud and cement, undergo dissolution and then there is re-precipitation of the carbonate, to form the calcareous rock; subsequently, the substitution of carbonate by silica occurs. Less frequent is silicification from terrigenous mudstones and other siliciclastic rocks; however, they also occur in the *Motavita Formation* (figure 15G, H). Although provenance studies of the silica in the *Motavita Formation* have not been made, it is thought that the most likely source of the silica is biogenic, from the dissolution of diatom shells, radiolaria, and other siliceous microfossils (Trewin and Fayers, 2005; Boggs, 2009). These silicification processes have also been observed in other siliceous rocks of the Upper and Middle Magdalena Valley (Terraza, 2003; 2019).

More specific diagenesis studies in the *Motavita Formation* will be needed to resolve these questions, which are outside the scope of this publication.

4.6 Sedimentary environments

For the interpretation of the sedimentary environments of the *Motavita Formation*, the ramp model proposed by Burchette and Wright (1992) and the Plint (2010, p. 168) model were taken as a basis, which shows the main sedimentation environments and their hydrodynamic conditions hypothesized in a modern coastal depositional system.

Based on the association of lithologies present in the *Motavita Formation*, a shallow marine environment less than 90 m deep can be inferred if the model corresponds to a platform or less than 40 m deep if it represents a homoclinal ramp, supported by the presence of glauconite in the quartz sandstone and terrigenous mudstone facies, and by fossils of clearly marine origin such as remains of fish, bivalves, ammonites, gastropods, crabs, and benthic foraminifera in the terrigenous mudstone, claystone, chert, and porcellanite facies (figure 16).

In general, the sedimentary environments vary from the upper shoreface or internal ramp in the sandstone and quartz siltstone rocks to offshore depositional environments in the middle platform or middle ramp for the cherts, porcellanites, terrigenous mudstones and claystones, basically above the storm action level, which is inferred by the presence of interbedded layers of

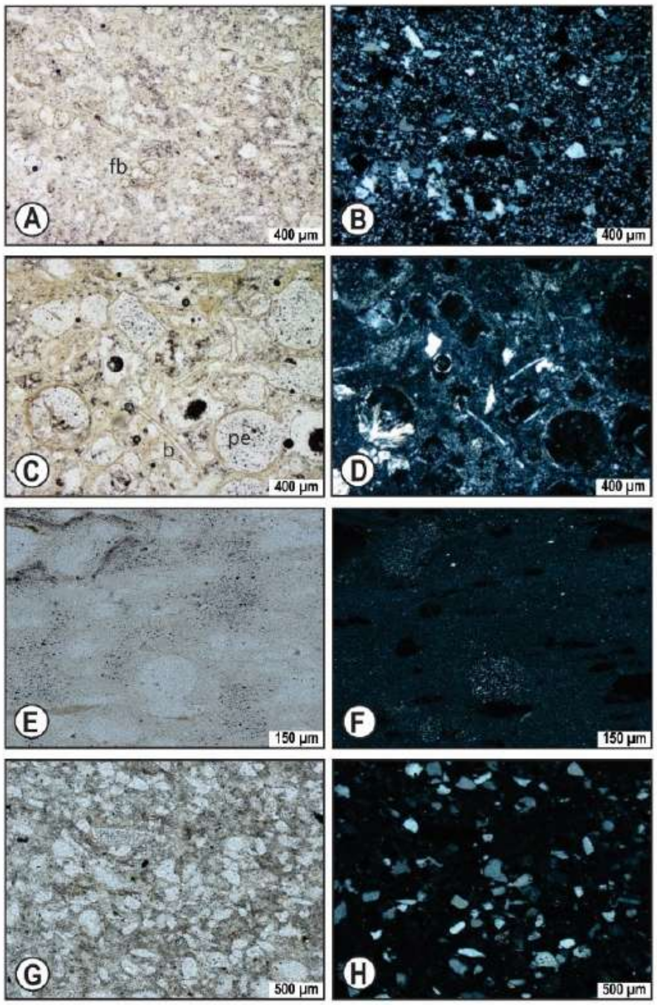

Figure 15. A and B. Fossiliferous chert with a mudstone texture showing benthic foraminifera (fb) replaced by cryptocrystalline silica; some terrigenous quartz grains float on the finely crystalline siliceous support of the rock. C and D. Chert of peloids with a packstone texture where the peloids (pe) and some bioclasts (b) are replaced by crypto-a finely crystalline silica or chalcedony; likewise, some terrigenous quartz grains can be distinguished on the matrix. E and F. Fully silicified biomicrite (fossiliferous wackestone) with benthic foraminifera floating on a support of microcrystalline silica. G and H. Silicified sandy terrigenous mudstone; quartz grains float fine to medium sand size float on microcrystalline silica. The images to the left of the figure are in parallel nicoles and to the right in crossed nicoles; all samples are of the holostratotype of the *Motavita Formation*: A and B, segment C, m83.7; C and D, segment C, m96.6; E and F, segment D, m 141.0; G and H, segment C, m74.6

allochthonous phosphates (Föllmi *et al*, 1992; Föllmi, 1996) or granular phosphates (Glenn *et al*., 1994) in the fine-granular siliceous and muddy rocks of the *Motavita Formation* accumulated by storm-induced gravity sediment flows. Beds of granular phosphorite interbedded in porcellanites, cherts, claystones, or mudstones originated in this way.

The morphological profile of the accumulation bottom must have been almost flat or with a very low slope, which is reflected in the predominance of stratification and parallel flat lamination in the sedimentary sequence.

The granular phosphorite beds interbedded or associated with sandy and silty facies probably originated from the rapid accumulation of sediments on coastal areas (shoreface or inner ramp), a process also generated by storms, similar to the model proposed by Brenner and Davis (1973) of accumulation of beds of coquinoid sandstone in coastal marine bars.

Due to their origin, the phosphorites associated with fine-granular rocks (porcellanites, cherts, claystones or terrigenous mudstones) can be accepted as proximal tempestites (*sensu* Fürsich, 1995), accumulated by the action of storm waves or proximal storm flows generated between the base level of the waves in calm weather and the base level of the waves in stormy weather. The phosphorites interbedded in sandy or silty rocks could be considered as coastal tempestites. In both cases, it is common to recognize one or more amalgamated storm events in the granular phosphorite beds (figure 17). The source of the phosphate material must come from pristine phosphate beds and the accumulation of skeletal fish remains, which were later reworked and accumulated by storms.

Granular phosphorite from shallow-water marine environments, such as that found in the *Motavita Formation*, abounded on the ancient epicontinental shelves of the South Tethys Phosphogenic Province in the upper Cretaceous-Eocene, which extended from Colombia to the Middle East (Pufahl *et al*., 2003; Pufahl and Groat, 2017). These epicontinental seas were affected by waves and important processes of coastal upwelling. In this type of granular deposits, storms were the most important agent for the reworking and accumulation of pristine phosphate in phosphorite beds. The constant syndepositional reworking of the seafloor does not allow for the accumulation of pristine phosphates (Pufhal, 2010).

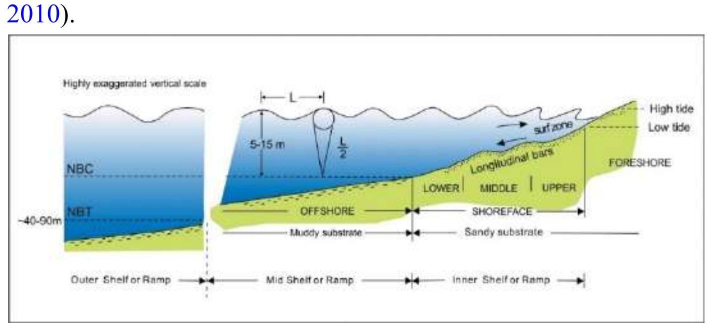

Figure 16. Inferred shallow marine sedimentary environment for the *Motavita Formation*. Hydrodynamic sedimentation conditions vary from the upper shoreface or inner ramp to the mid shelf or mid ramp in offshore areas. NBC= base level of waves in calm weather, NBT= base level of waves in stormy weather. Source: based on Plint (2010) and Burchette and Wright (1992)

Sedimentologically, the granular phosphorites are recognized by their moderately calibrated, medium-grain sandy texture, composed mainly of phosphatic peloids, fragments of fish bones and vertebrae, and phosphatized benthic foraminifera. The layers generally present net contact with the bedrock, are massive (without internal lamination) and show a packstone to wackestone texture (see figure 17).

In the chert and porcellanite layers of the *Motavita Formation* it is common to observe accumulations (pockets or tapestries in the stratification planes) of foraminifera of the genus *Orthokarstenia* (Etayo, 1968b), which suggests, according to the paleoecological interpretation of Cruz *et al*. (2011), a very dynamic infaunal environment with a degree of biodisturbance and dispersed concentration of nutrients, which is deduced by the abundance of megalospheric forms that come from an asexual mechanism that facilitates the concentration of organisms in areas limited by the concentration of nutrients. The elongated and pointed shape of the shells are indicative of anoxic and dysaerobic environments.

Figure 17. Granular phosphorite bed (P) in the lower part of the Motavita Formation (La Batea quarry parastratotype, m124.5). The contacts of the top and the base of the bed are irregular and sharp. Internally, two amalgamated storm events can be recognized (layers 1 and 2); the phosphorite is overlain by layered quartz siltstones and underlain by fine-grained phosphatic quartzarenites

The increasingly abundant presence of benthic foraminifera (e.g., *Orthokarstenia* sp.) towards the top of the *Motavita Formation* and the overlying Pleaners Formation together with the disappearance of planktonic forms that are occasionally found towards the base of the unit (e. g., m105 and m126 in the parastratotype of the La Batea quarry, figure 6), suggests a gradual shallowing of the sedimentary environment and probably an increase in oxygen levels on the water-sediment interface.

5. Discussion

The work of geological cartography and stratigraphy with the support of ammonite biostratigraphy carried out by the GSC during the last 20 years in the central zone of the Eastern Cordillera (Montoya and Reyes, 2003a, 2003b, 2005, 2007; Terraza *et al*, 2010a, 2010b; Etayo, 2015; Terraza *et al*., 2016; Martínez , 2018; Martínez *et al*., 2020; Martínez *et al*., 2023), including the comparison of stratigraphic sections at various sites in this area, allowed inferring important lateral lithological changes at the base of the Guadalupe Group from the type section in the eastern hills of Bogotá to the eastern region of Paz del Río (see figures 18, 19, 20 and 21). This basic geology work is the documentary support for the new proposed *Motavita Formation*.

It is considered that the new *Motavita Formation* solves the problem of stratigraphic nomenclature that was occurring at the base of the Guadalupe group, because there are some synonymous units such as the "Plaeners Formation" *sensu* Renzoni (1967) and Etayo (1968a, 1968b), the Lidita Superior Formation of Montoya and Reyes (2003a, 2005) and the informal unit of Martínez *et al*. (2020) and Martínez *et al*. (2023) designated as "Guadalupe Group base" in the surroundings of Tunja; really, it is the same unit, that is, the *Motavita Formation*. The idea of Renzoni (1967), who sustained that the Arenisca Dura Formation of the Sabana de Bogotá was represented in the sandstone beds of the upper part of the Conejo Formation (unit Kg3) of the J-12 Tunja quadrangle due to lateral facies changes, is also distorted; really, the Arenisca Dura Formation changes facies laterally, but it does not correspond to the sandstones of the upper part of the Conejo Formation, but to the fine-textured rocks and siliceous composition present in the overlying "Plaeners Formation" *sensu* Renzoni (1967), a unit called in this work as the *Motavita Formation*.

Additionally, it is probable that the unit designated as "La Luna Formation" on sheet 172-Paz del Río (Ulloa *et al*., 1998c; Ulloa *et al*., 2001), constituted at the base by 30 m of quartz sandstones (some calcareous) in thin to thick beds, and at the top by 90 m of calcareous siliceous siltstones with intercalations of mudstones and calcareous mudstones in thin beds with some levels of black chert, correspond to the new *Motavita Formation*, because this "La Luna Formation" is assigned to the lower Santonian-Campanian interval, similar to the chronostratigraphic position of the *Motavita Formation*; likewise, its lithology (with the exception of the calcareous component reported) is very similar to the lithology of the new proposed *Motavita Formation*; the lower sandy segment of 30 m is considered as a tongue of the Arenisca Dura Formation, according to Ulloa *et al*. (2001), which reinforces the proposed hypothesis.

Undoubtedly, the proposed *Motavita Formation* will not solve all the stratigraphic problems of the Guadalupe Group in the study region and more detailed studies will be necessary of the units that make it up (Arenisca Dura, Plaeners *sensu stricto*, Arenisca de Labor, Los Pinos or Upper Pleaners, and Arenisca Tierna formations), of the units that overlie it (Guaduas or Socha Inferior formations) and of the units that underlie it (Conejo or Chipaque formations). Such studies should include at least 1:25,000 scale detailed geological mapping with biostratigraphic support, detailed to semi-detailed stratigraphic surveys (1:100 to 1:500 scale), petrographic and paleontological sampling, petrographic analyses, paleontological determinations of microfossils (foraminifera, pollen, dinoflagellates) and macrofossils (ammonites, bivalves) supplemented, where posible, with geochemical studies, SEM, among others.

This work is one of the great challenges that the GSC has pending with the purpose of solving all the problems of stratigraphic nomenclature and of knowing more in depth the different lithostratigraphic units of the country, knowledge that is essential, since mineral deposits, hydrocarbons, groundwater or a certain geological process such as erosion, mass movements, volcanism, hydrothermalism, etc., can be associated with these units. However, it is considered that the new *Motavita Formation* clarifies the lithostratigraphic-nomenclatural panorama at the base of the Guadalupe Group, as previously indicated.

Due to its fine-granular lithology, the new *Motavita Formation* completely blurs the Guadalupe Group, since it loses its sandy character by which it is recognized in the type area to the east of Bogotá and Sabana de Bogotá (Hubach, 1931, 1951, 1957; Pérez and Salazar, 1978), and therefore, it is recommended not to use the term Guadalupe Group in those areas where the *Motavita Formation* crops out. However, geomorphologically, the new *Motavita Formation* generates a scarp between the underlying units (Chipaque or Conejo Formation) and overlying units (Pleaners Formation *sensu stricto*), a morphology that is similar to that of the Arenisca Dura Formation in the type section in the eastern hills of Bogotá. This characteristic is important, because the morphological expression of a lithostratigraphic unit is a relevant criterion to identify it, both in the field and in satellite images and aerial photographs.

In some areas there will be a facial transition between the Arenisca Dura Formation and the new *Motavita Formation* (see figure 18) and there will be doubts about assigning a certain stratigraphic level to one or the other formation, for which reason the criteria must be based on the predominance of lithology, e. g., in the proportion of sandstones. If the domain is quartz sandstones, the interval should be included in the Arenisca Dura Formation, or the opposite, if the sandstones are subordinated to other fine-grained lithologies (cherts, porcellanites, terrigenous mudstones, and siltstones), the respective level should be assigned to the new proposed *Motavita Formation*.

A place where this duality occurs is in the section of the Guadalupe Group measured in the Alto del Volador to the NW of the municipality of Garagoa (see figure 18, section AV), along the road that leads from Pachavita to Úmbita (sheet 210-Guateque, grid C3), where the base of the Guadalupe Group is made up of equal parts of quartz sandstones and other fine-textured siliceous rocks and terrigenous mudstone; however, it was decided to assign the stratigraphic interval to the Arenisca Dura Formation considering that the quartz sandstones plus the siltstones quartz dominated the stratigraphic sequence (see figure 20 and figure 46 of Terraza *et al*., 2010b). However, the most recommendable alternative is to call it the Arenisca Dura-*Motavita Formation*, to indicate that neither of the two units can be fully recognized or that the two formations are present interdigitated, following the recommendations of the International Stratigraphic Guide. (Salvador, 1994, chapter 3B3e, p. 22). It will always be better to express doubt than to make an arbitrary designation of the lithostratigraphic nomenclature or create a new unit unnecessarily.

The differences in thickness of the *Motavita Formation* in the Alto del Gavilán holostratotype (76 m) and in the La Batea quarry parastratotype (130 m) can be attributed to regional tectonics, specifically to differences in tectonic subsidence between both places, possibly due to the movement of a paleofault synchronously with sedimentation.

The figure 18 shows the regional geographic distribution of the Arenisca Dura and *Motavita* formations and the lithological transition between them for the lower Campanian interval, according to the geological cartography published by the CGS in the central region of the Eastern Cordillera. The predominantly sandy facies corresponds to the Arenisca Dura Formation, the fine-granular siliceous and muddy facies to the *Motavita Formation*, and the transitional facies to the interdigitation between these two units, that is, to the Arenisca Dura-*Motavita Formation*, as previously stated. The figure was made without palinspastic restoration; therefore, the geographical extension of the units must be wider.

The figure 18 also includes the geographic location of several stratigraphic sections of the base of the Guadalupe Group with which two lithostratigraphic correlation lines were made, which will be discussed later. The PLL section corresponds to a stratigraphic section located in the Piedmonte Llanero (near the municipality of San Luís de Gaceno), and was referenced because it documents the sandy facies present at the base of the Guadalupe Group (Arenitas de San Antonio Formation) in this region of the country, whose detailed description can be consulted in the work of Guerrero and Sarmiento (1996).

The figures 19, 20 and 21 show two lithostratigraphic correlation lines that support the lateral facies changes between the heteropic and coeval formations Arenisca Dura and *Motavita*. To elaborate these correlations, the following stratigraphic sections of the base of the Guadalupe Group were compiled at the same graphic scale (see figure 18 for location): 1) Type section, eastern hills of Bogotá (Pérez and Salazar, 1978), 2) Chía and Tabio, Serranía de Chía (Bürgl, 1955; Julivert, 1962; Etayo, 2015), 3) Tausa

(Föllmi *et al*., 1992; Sarmiento, 2010), 3) Samacá, La Batea quarry (authors; Etayo, 2015), 4) Motavita, Alto del Gavilan (Etayo, 2015; Terraza *et al*., 2016; Martínez, 2018), 5) Garagoa, Alto del Volador (Terraza *et al*., 2010b; Terraza *et al*., 2016), 5) Ramiriquí, Peñas village (Etayo, 2015; Terraza *et al*., 2016), 6) Chivatá, Siatoca village (Etayo, 2015; Terraza *et al*., 2016) and 7) El Crucero (Vergara y Rodriguez, 1996). Geological contacts with the overlying Pleaners Formation and underlying Chipaque or Conejo Formation and available paleontological data were also taken into account.

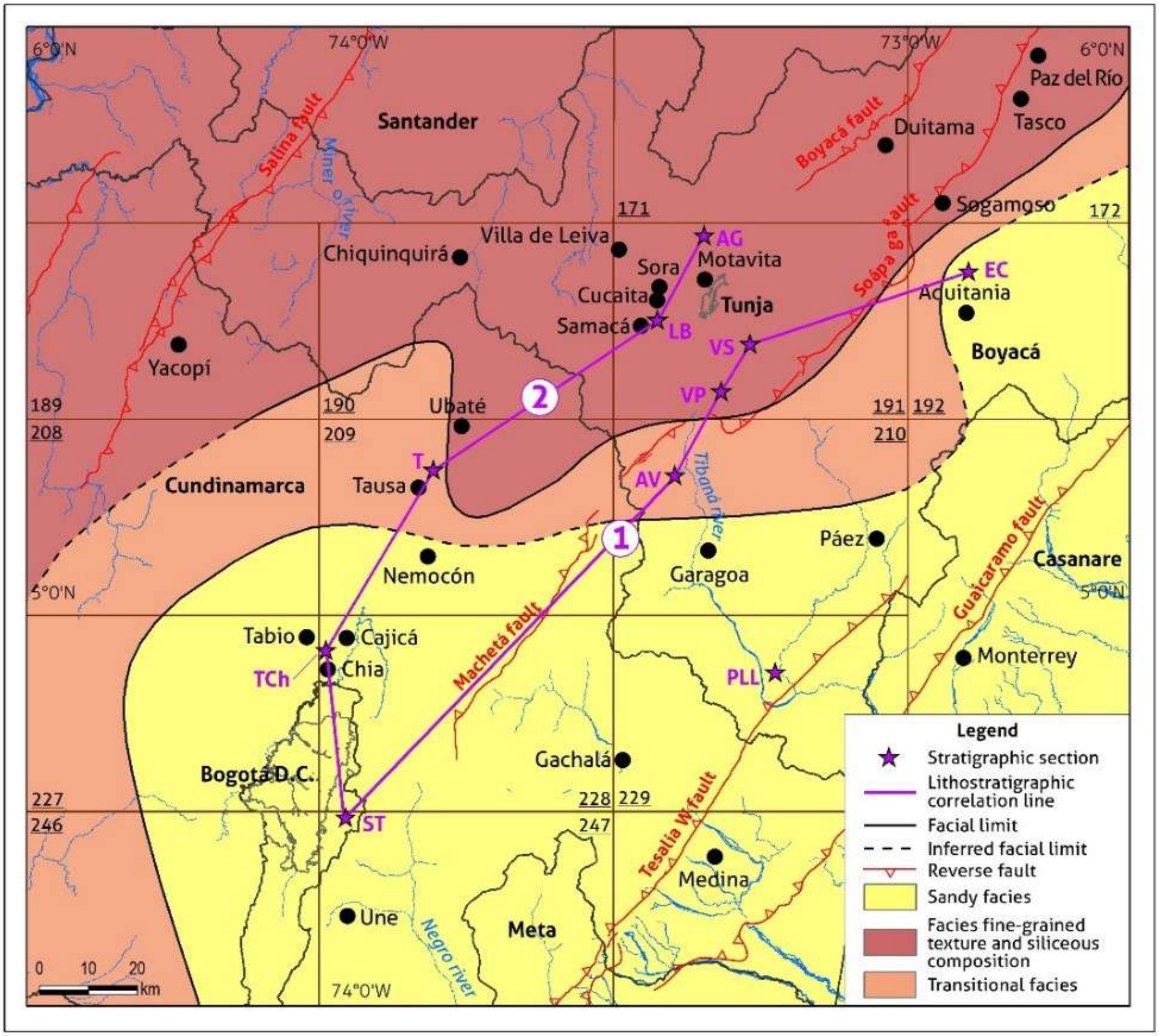

Figure 18. Geographic extension of the Arenisca Dura and *Motavita formations* for the lower Campanian interval. The figure shows the location of the stratigraphic sections of the Guadalupe Group with which the lithostratigraphic correlation lines were made: ST= Type Section, AV= Alto del Volador, VP= Peñas Village, VS= Siatoca Village, TCh= Tabio-Chía, T= Tausa, LB= La Batea Quarry, AG= Alto del Gavilán, EC= El Crucero; the PLL section= Piedmonte Llanero, was used to document the sandy facies of the base of the Guadalupe Group in this area of Colombia.
Source: GSC geological sheets 246 (Acosta and Ulloa, 1998), 247 (Patiño et al., 2011), 227 (Ulloa et al., 1998a), 228 (Buitrago and Terraza, 2008), 229 (Montoya et al., 2013), 208 (Ulloa and Acosta, 1998), 209 (Montoya and Reyes, 2003a), 210 (Terraza et al., 2010a), 189 (Rodríguez and Ulloa, 1994; Terraza et al., 2008), 190 (Fúquen y Osorno, 2005), 191 (Renzoni et al., 1967), 192 (Ulloa et al., 1998b), 171 (Renzoni y Rosas, 1967), 172 (Ulloa et al., 1998c)

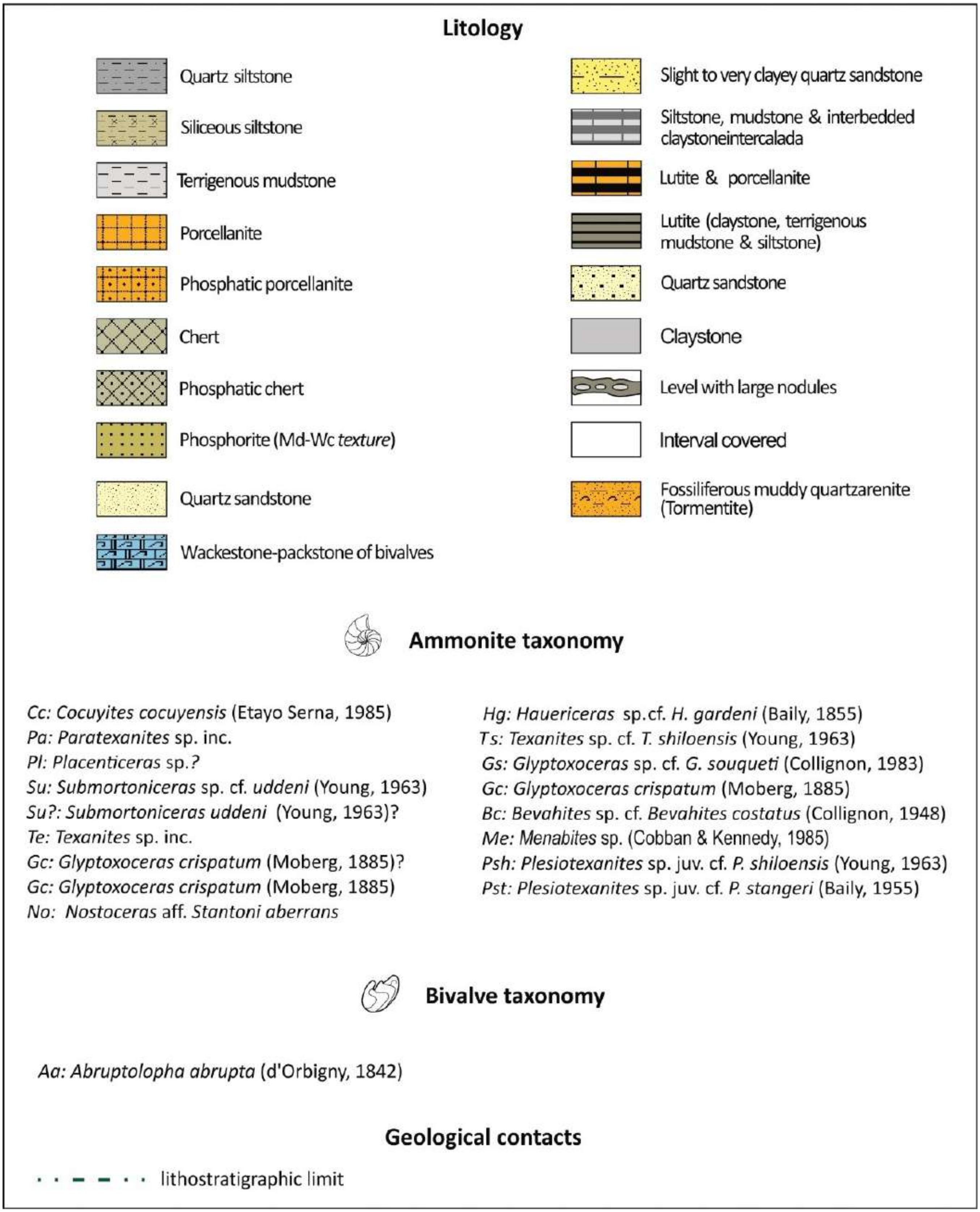

Figure 19. Legend of figures 20 and 21

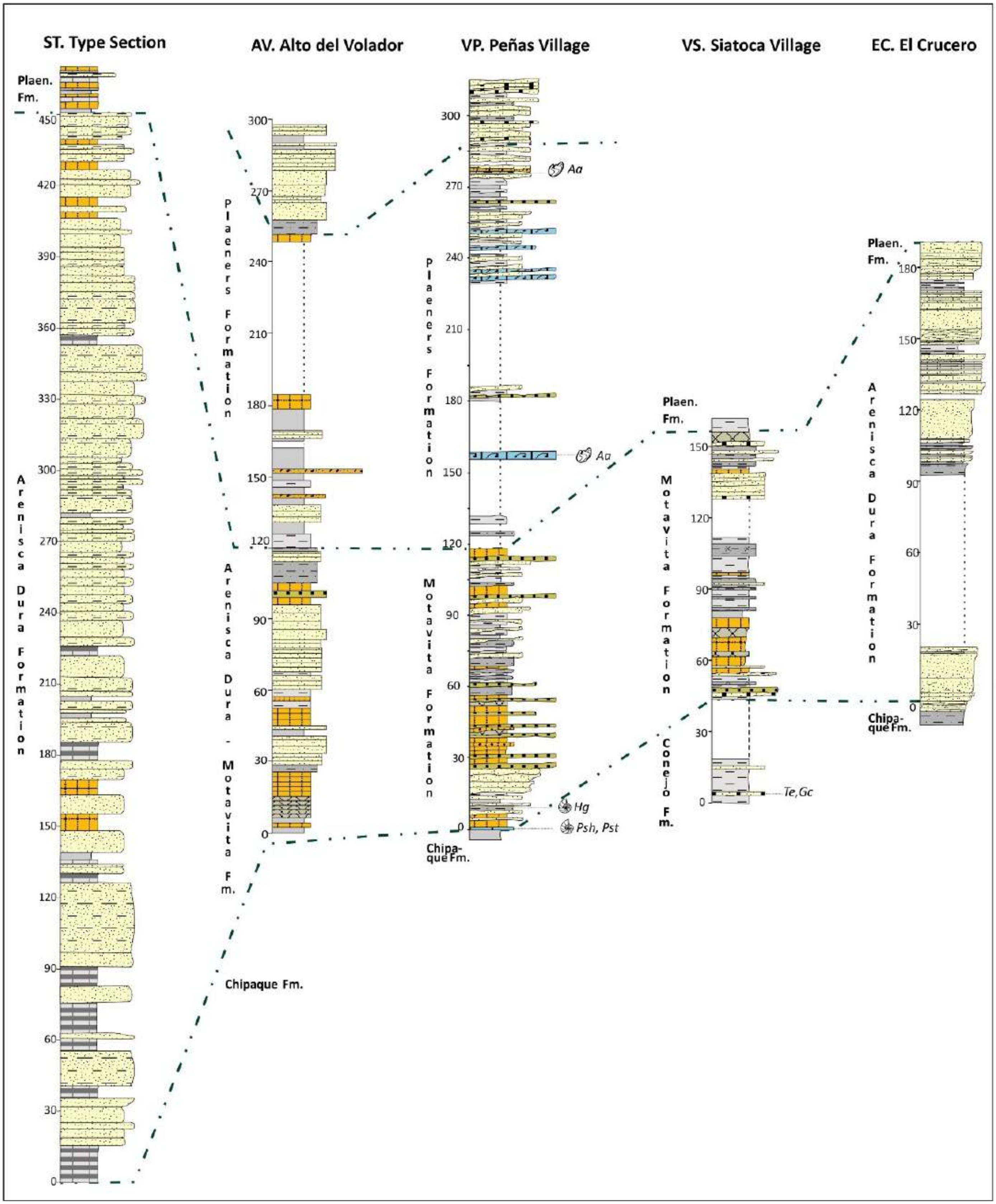

Figure 20. Lithostratigraphic correlation line 1. The location of the stratigraphic sections appears in figure 18
Source: Pérez and Salazar (1978); Vergara y Rodríguez (1996); Etayo (2015); Terraza et al. (2016); Martinez (2018), Martinez et al. (2020)

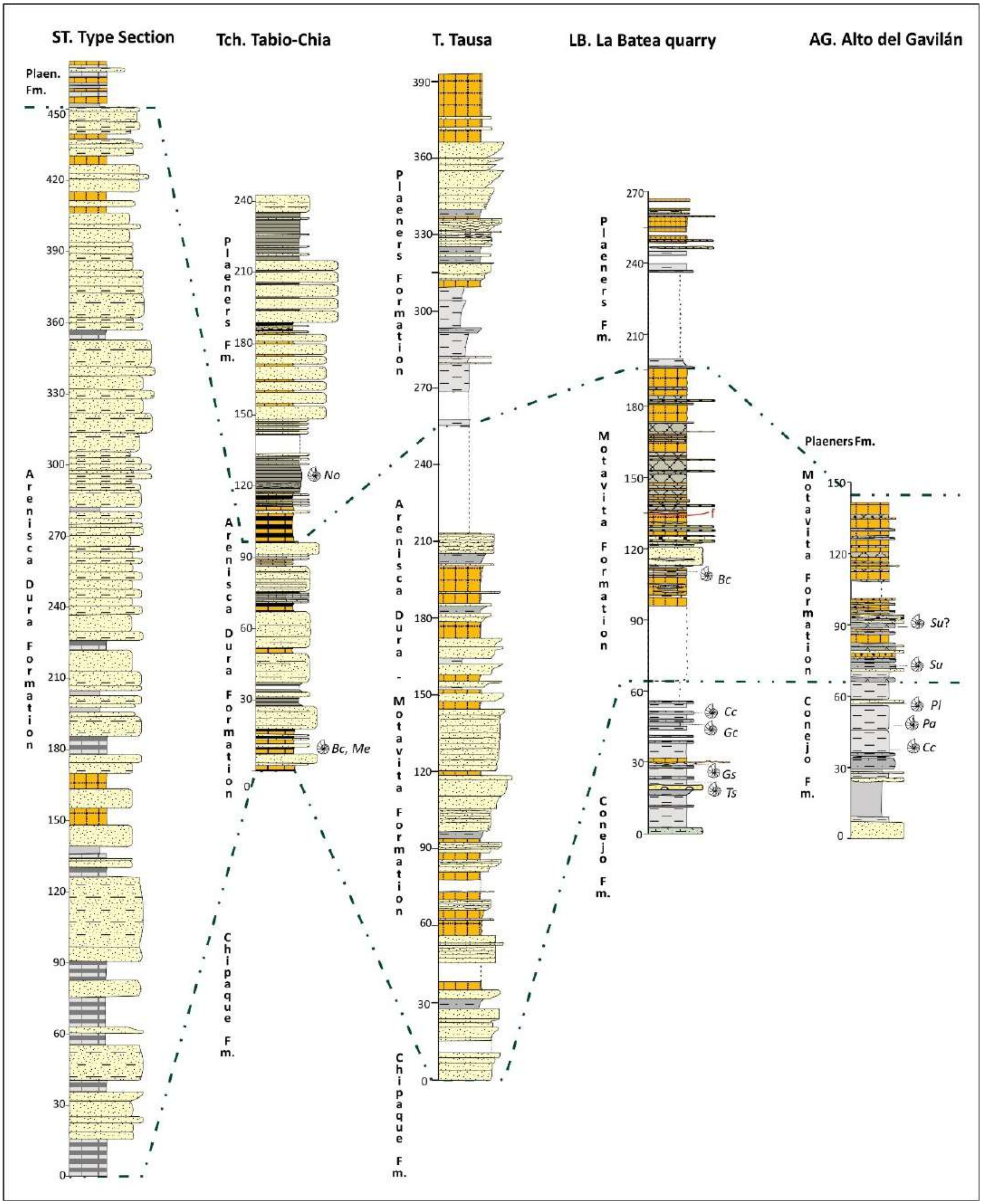

Figure 21. Lithostratigraphic correlation line 2. The location of the stratigraphic sections appears in figure 18. Source: Pérez and Salazar (1978); Föllmi et al. (1992); Sarmiento (2010); Etayo (2015); Terraza et al. (2016); Martinez (2018); Martinez et al. (2020)

6. Conclusions

The new *Motavita Formation* is stratigraphically located at the base of the Guadalupe Group and would replace the "Plaeners Formation" of Renzoni (1967) and Etayo (1968b, p. 47), the " Lidita Superior Formation" of Montoya and Reyes (2003a, 2005) and the informal unit of Martínez *et al*. (2020) designated as "Guadalupe Group base" in the surroundings of Tunja. This new unit is recognized in the NE sector of the Sabana de Bogotá, in the valleys of Ubaté, Tunja, Duitama and Sogamoso, and to the northeast of the municipality of Paz del Río.

Given that the stratigraphic limits of the new *Motavita Formation* are not exposed in a single stratigraphic section, the type section corresponds to a composite stratotype (Salvador, 1994, chapter 4B4) which is constituted by a holostratotype located in the Alto del Gavilán (figures 3 and 4) and a parastratotype in the La Batea quarry (figures 5 and 6). In the Alto del Gavilán the lower limit of the unit can be observed with the underlying Conejo Formation of the upper Santonian, from which the upper part of the unit outcrops. In the La Batea quarry, the upper limit can be seen with the overlying Plaeners Formation of the upper Campanian and the upper two-thirds of the unit outcrop; the lower third and upper part of the Conejo Formation are covered.

The lithological description of the composite stratotype was made from base to top, dividing the section into stratigraphic segments. The holostratotype is located in the escarpment known as Alto del Gavilán, located 3 km NW of the municipality of Motavita and the parastratotype in a quarry located 1.7 km NE of the municipality of Samacá in the sector called La Batea. Both municipalities are located in the department of Boyacá in the vicinity of Tunja. The two sections are separated from each other by about 16 km in a straight line with an azimuth of 43°, a direction more or less coincident with the general direction of the geological structures in that part of the Eastern Cordillera.

The new *Motavita Formation* is made of fine-textured sedimentary rocks with a siliceous composition such as cherts, porcellanites, claystones and terrigenous mudstones, quartz siltstones and some beds of fine to very fine-grained quartzarenites interbedded with abundant levels of benthic foraminifera of the family *Siphogenerinoididae* (e. g., *Orthokarstenia* sp.); medium to thick beds of potentially mineable wackestone to packstone textured phosphorite are also common.

The new *Motavita Formation* underlies concordantly and in rapid transitional contact to the Plaeners Formation *sensu stricto* (Hubach, 1931; Pérez y Salazar, 1978), intermediate unit of the Guadalupe Group, and overlies the Conejo Formation (Renzoni, 1967) or Chipaque Formation (Hubach, 1931; Renzoni, 1962) in a concordant and sharp contact.

The thickness of the new *Motavita Formation* in the section of the Alto del Gavilán (holoestratotype) is 76 m and in the section of the La Batea quarry (parastratotype) it is 130 m.

Geomorphologically, the new *Motavita Formation* generates a scarp between the Chipaque o Conejo Formation (underlying unit) and the Pleaners Formation (overlying unit), a morpholgy similar to that of the Arenisca Dura Formation in the type section in the eastern hills of Bogotá. This characteristic is important, because the morphological expression of a lithostratigraphic unit is a relevant criterion to identify it, both in the field and in satellite images and aerial photographs.

The stratigraphic interval of the new *Motavita Formation* is mainly lower Campanian. Regionally, the *Motavita Formation* can be mapped from north of Nemocón (Cundinamarca) to the municipalities of Tasco and Paz del Río, and to the east of these municipalities, in the department of Boyacá.

Wackestone and packstone textures typical of calcareous rocks are recognized in the cherts and porcellanites of the new *Motavita Formation*, suggesting a complete silicification process from limestones with similar textures.

The new *Motavita Formation* sedimented in a shallow marine depositional environment, probably less than 90 m deep if the system corresponds to a platform model or less than 40 m deep if the sedimentary environment represents a homoclinal ramp, in both cases with a dominance of waves, whose water-sediment interface was low in oxygen.

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Conflict of interest

The authors declare that they have no financial interests or competing personal relationships that could affect the work reported in this paper.

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