Volume 3

Chapter 13

The Morales Formation (New Unit): Record of Fluvial–Lacustrine Environments and the Beginning of the Miocene Explosive Volcanism in the Patía Sub–basin (SW Colombia)

https://doi.org/10.32685/pub.esp.37.2019.13
Published online 26 November 2020

Andrés F. GALLEGO–RÍOS[1], Andrés PARDO–TRUJILLO[2]*, Guillermo A. LÓPEZ–PLAZAS[3], and Sebastián ECHEVERRI[4]

1 geoand22@hotmail.com
Universidad de Caldas
Departamento de Ciencias Geológicas
Calle 65 n.° 26–10
Manizales, Colombia

2 andres.pardo@ucaldas.edu.co
Universidad de Caldas
Instituto de Investigaciones en Estratigrafía (IIES)
Grupo de Investigación en Estratigrafía y Vulcanología (GIEV)
Manizales, Colombia

3 guillermolopez.geo@gmail.com
Universidad de Caldas
Departamento de Ciencias Geológicas
Calle 65 n.° 26–10
Manizales, Colombia

4 juansebasecheverri@gmail.com
Universidad de Caldas
Instituto de Investigaciones en Estratigrafía (IIES)
Grupo de Investigación en Estratigrafía y Vulcanología (GIEV)
Manizales, Colombia
Universidad Nacional de Colombia
Grupo de Investigación en Geología y Geofísica (EGEO)
Medellín, Colombia

* Corresponding author

Supplementary Information:
S: https://www2.sgc.gov.co/LibroGeologiaColombia/tgc/sgcpubesp37201913s.pdf

Abstract The sedimentary rocks of the Patía Sub–basin (SW Colombia) record the Cenozoic geologic evolution of western Colombia from the Paleogene to the Holocene. In this research, we report a new Miocene stratigraphic unit near Mercaderes town (Cauca Department). A 563 m–thick sequence is described in detail and divided from bottom to top into three lithological assemblages. (I) The upper segment of the conglomeratic member of the Esmita Formation is formed by 33 m–thick beds of clast–supported lithic conglomerates interbedded with lenticular litharenites, with trough and planar cross–bedding. They are interpreted as braided river deposits. (II) The Morales Formation, which is defined in this work, presents 470 m thick composed mainly of parallel laminated gray–black mudstones interbedded with thin sandstone beds, with parallel and ripple laminations, graded bedding, and soft–sediment deformation structures. Plant fragments, pollen, and spores are common. Towards the top, sandstone and polymictic conglomerate beds increase. They are interpreted as lake, marsh, and crevasse splay deposits adjacent to fluvial channels. (III) The bottom of the Galeón Formation is composed by 7 m thick of sandstones and conglomerates rich in volcanic fragments accumulated in a fluvial environment with simultaneous volcanic activity.

The petrographic study (conventional and heavy minerals) identifies mainly litharenites and feldspathic litharenites, whose fragments suggest igneous (volcanic and plutonic), sedimentary (mudstones and sandstones), and metamorphic (high–pressure metamorphic rocks and graphitic schists) sources, which are correlated with the basements exposed at the present in the Central and Western Cordilleras.

We review a volcaniclastic sandstone obtained from the bottom of the Galeón Formation that provides the youngest population of U/Pb ages in detrital zircons of ca. 15.4 Ma, interpreted as the depositional age. The sudden increase in volcanic components allows us to interpret this time as the onset of strong volcanism in the basin, which continues currently in the Central Cordillera. This age and new palynological studies suggest a Burdigalian – early Langhian (ca. 19–15.4 Ma) age for the Morales Formation, which improves the chronostratigraphy of the region. Lower Miocene mud–dominated successions have been described in different basins of Colombia (the Cauca–Patía,

Citation: Gallego–Ríos, A.F., Pardo–Trujillo, A., López–Plazas, G.A. & Echeverri, S. 2020. The Morales Formation (new unit): Record of fluvial–lacustrine environments and the beginning of the Miocene explosive volcanism in the Patía Sub–basin (SW Colombia). In: Gómez, J. & Mateus–Zabala, D. (editors), The Geology of Colombia, Volume 3 Paleogene – Neogene. Servicio Geológico Colombiano, Publicaciones Geológicas Especiales 37, p. 395–415. Bogotá. https://doi.org/10.32685/pub.esp.37.2019.13

Middle and Upper Magdalena, Llanos, and Caribbean Basins) and can be related to a regional period of tectonically induced accommodation.
Keywords: *Patía Sub–basin, Morales Formation, middle Miocene, stratigraphy, petrography, provenance, vulcanism.*

Resumen Las rocas sedimentarias de la Subcuenca Patía (SW de Colombia) registran la evolución geológica cenozoica del oeste de Colombia desde el Paleógeno hasta el Holoceno. En este trabajo se reporta una nueva unidad estratigráfica del Mioceno cerca de la población de Mercaderes (departamento del Cauca). Se describe en detalle una secuencia de 563 m de espesor y se divide de base a techo en tres conjuntos litológicos. (I) La parte superior del miembro conglomerático de la Formación Esmita está formada por 33 m de estratos gruesos de conglomerados líticos clastosoportados intercalados con estratos lenticulares de litoarenitas, con estratificación inclinada planar y en artesa. Estos estratos se interpretan como depósitos de un río trenzado. (II) La Formación Morales, que se define en esta investigación, tiene 470 m de espesor y se compone principalmente de lodolitas de color gris–negro con laminación plana paralela intercaladas con estratos delgados de areniscas, con laminación *ripple* y plana paralela, gradación normal y estructuras de deformación sinsedimentaria. Son frecuentes los restos de plantas, polen y esporas. Hacia su parte superior se presenta un incremento en estratos de areniscas y conglomerados polimícticos. Esta unidad se interpreta como depósitos de lagos, pantanos y de desbordamiento adyacentes a canales fluviales. (III) La base de la Formación Galeón está compuesta por 7 m de areniscas y conglomerados ricos en fragmentos volcánicos acumulados en un ambiente fluvial con actividad volcánica simultánea.

En el estudio petrográfico (minerales convencionales y pesados) se identificaron principalmente litoarenitas y litoarenitas feldespáticas, cuyos fragmentos sugieren fuentes ígneas (volcánicas y plutónicas), sedimentarias (lodolitas y areniscas) y metamórficas (rocas de alta presión y esquistos grafitosos) que se correlacionan con los basamentos expuestos en las cordilleras Central y Occidental.

Se revaluó una arenisca volcanoclástica obtenida en la base de la Formación Galeón que proporcionó la población más joven de circones detríticos con edades U–Pb de ca. 15,4 Ma, interpretadas como la edad de depósito. El repentino aumento de los componentes volcánicos permite interpretar esta edad como el inicio de un fuerte vulcanismo en la cuenca, el cual continúa hoy en día en la cordillera Central. Esta edad y los nuevos estudios palinológicos sugieren una edad Burdigaliano–Langhiano temprano (ca. 19–15,4 Ma) para la Formación Morales, lo que mejora la cronoestratigrafía de la región. Se han descrito sucesiones lodosas del Mioceno inferior en diferentes cuencas de Colombia (Cauca–Patía, Valle Medio y Valle Superior del Magdalena, Llanos y el Caribe). Estas pueden estar relacionadas con un periodo de acomodación originado por la tectónica.
Palabras clave: *Subcuenca Patía, Formación Morales, Mioceno medio, estratigrafía, petrografía, procedencia, vulcanismo.*

1. Introduction

The Patía Sub–basin (SW Colombia, Figure 1) is filled by Cenozoic (Eocene – Holocene) siliciclastic sedimentites thicker than ca. 3000–4700 m (Barrero et al., 2006; Ruiz, 2002), which overlie a basic igneous and volcanic–sedimentary Cretaceous basement (Barrero et al., 2006; Borrero et al., 2012; Ruiz, 2002). Hydrocarbon seeps have been found in Cenozoic deposits (Grosse, 1935), revealing an active petroleum system. However, there are few studies about the paleoenvironment, age, and origin of these deposits, which makes it difficult to determine the paleogeography and the distribution of rocks of economic interest, and to correlate events of regional significance (e.g., tectonic events). The Universidad de Caldas, in agreement with the Agencia Nacional de Hidrocarburos (ANH), performed geological mapping around the town of

Mercaderes (Cauca Department) in 2010 in order to identify potential hydrocarbon source, reservoir, and seal rocks. New stratigraphic, petrographic, and geochemical data obtained along Morales Creek (south of Mercaderes town) on the eastern flank of the Mercaderes Syncline were obtained to investigate the paleoenvironment, provenance, and age of the stratigraphic units (Figure 1). In this chapter, we describe a new siliciclastic unit with a thickness of 470 m, named the Morales Formation. It overlies the conglomeratic member of the Esmita Formation and is overlain by the volcaniclastic Galeón Formation (Figure 2; León et al., 1973). Its facies and paleontological content suggest that fluvial–lacustrine deposits accumulated during the Miocene.

2. Geological Framework

The Patía Sub–basin is a N–NE–oriented elongated depression ca. 140 km in length separating the Central and Western Cordilleras of SW Colombia (Figure 1a). It is limited to the east and west by the Romeral and Cali–Patía Fault Systems, respectively (Barrero et al., 2006). To the north, the Tambo–Popayán paleohigh separates it from the Cauca Sub–basin (Ruiz, 2002). The sedimentary fill comprises ca. 3000–4700 m–thick, clastic sedimentary successions (Barrero et al., 2006; Ruiz, 2002), which were discordantly deposited over a Mesozoic basement (Barrero et al., 2006). The basement comprises Jurassic? – Cretaceous mafic and ultramafic plutonic and volcanic rocks (Figure 1a; e.g., Quebradagrande, Los Azules, and Barroso–Amaime Complexes; Orrego et al., 1996). In some cases, these igneous rocks are associated with marine sedimentary rocks (e.g., pelagic, hemipelagic, and turbiditic deposits; e.g., Pardo–Trujillo et al., 2002). The volcanic rocks of the Barroso–Amaime Complex include massive and pillow basalts with plateau and arc–related geochemical affinities (Kerr et al., 1998; Nivia, 2001; Rodríguez & Arango, 2013). According to Barrero et al. (2006), the basement originated from the oblique collision of oceanic rocks against the NW margin of South America, which generated thrusting, folding, and clastic marine sedimentation. The collision migrated from Ecuador to the N of Antioquia (Colombia) during the Late Cretaceous – Paleocene (Barrero et al., 2006; Kerr et al., 1997; Moreno–Sánchez & Pardo–Trujillo, 2003; Pindell & Kennan, 2009; Villagómez et al., 2011). Currently, the Western Cordillera is composed of plateau basalts and Upper Cretaceous sedimentary deposits (Pardo–Trujillo et al., 2002, 2020), with mylonitic deformation in some cases (Nivia, 2001). The plateau sequences are intruded by Paleogene – Neogene tonalitic plutons (Gómez et al., 2015b). To the east of the basin, in the western border of the Central Cordillera, four different structural complexes crop out, limited by faults with a N40°E trend (Maya & González, 1995); from west to east, they are (Figure 1a; Orrego et al., 1996) as follows: (1) Cretaceous basalts, tuffs, gabbro, and ultramafic igneous rocks (Los Azules Complex); (2) Cretaceous metamorphic rocks (amphibolic and black schists, quartzites, and local blueschists; Arquía Complex); (3) Lower Cretaceous volcanic and marine sedimentary rocks (Quebradagrande Complex); and (4) Permian, Triassic, and Jurassic igneous and metamorphic rocks (Cajamarca Complex) (Blanco et al., 2014).

During the Eocene – Oligocene, the sedimentation in the Patía Sub–basin was related to transcurrent tectonics along the continental margin, linked to the oblique subduction of oceanic terranes beneath the irregular continental margin of South America (Barrero et al., 2006). During the Neogene, volcanic activity increased and significantly impacted the sedimentation in SW Colombian basins (e.g., Tumaco and Cauca–Patía; Echeverri et al., 2015). According to geochronological data, the Miocene volcanism and magmatism migrated from the W (Western Cordillera) to the axis of the Central Cordillera, where it is currently located, probably due to changes in the angle of the subduction zone (Echeverri et al., 2015). Neogene hypabyssal rocks that cut the sedimentary sequences are very common in the Patía Sub–basin (González, 2010; Ruiz, 2002). The Eocene – Miocene sedimentary units were affected by thrust and fold systems with western vergence involving the oceanic basement associated with the late Miocene – Pliocene Andean orogenic pulse (Barrero & Laverde, 1998). In contrast, the Pliocene? – Quaternary units are horizontal and form terraces at different topographic levels.

No consensus regarding the age and nomenclature of these units exists (Figure 2). Grosse (1935) was one of the pioneers who studied the Cenozoic deposits of the basin. He named these rocks from bottom to top as follows: (1) "Eoterciario", composed of quartz–rich conglomerates, sandstones, and mudstones with some characteristic coal beds in this interval; (2) "Medioterciario inferior", composed of sandstones, conglomeratic sandstones, and conglomerates interbedded with mudstones, some of them with gastropods and lamellibranches; (3) "Medioterciario superior", composed of tuffaceous sandstones, claystones, tuffs (agglomerates), and conglomerates; (4) "Neoterciario" (Pliocene?), composed of clays, tuffs, agglomerates, and tuffaceous sandstones, although Grosse (1935) pointed out the difficulty of recognizing the last two units due to their lithological similarities; and (5) Quaternary, represented by the "Capas Túficas de Mercaderes". The author indicated that this unit can be differentiated because it is not folded and partially covers the former units with an angular unconformity. Grosse (1935) did not indicate a precise age for the "Eoterciario" and "Medioterciario" units.

León et al. (1973) formally defined the Esmita Formation (Figure 2) along the Esmita River, located ca. 51 km to the NE of Mercaderes town; this unit overlies the Mosquera Formation in transitional contact. The authors divided the unit, from bottom to top, into three informal members: (1) fossiliferous silty, (2) sandy, and (3) conglomeratic. They indicated

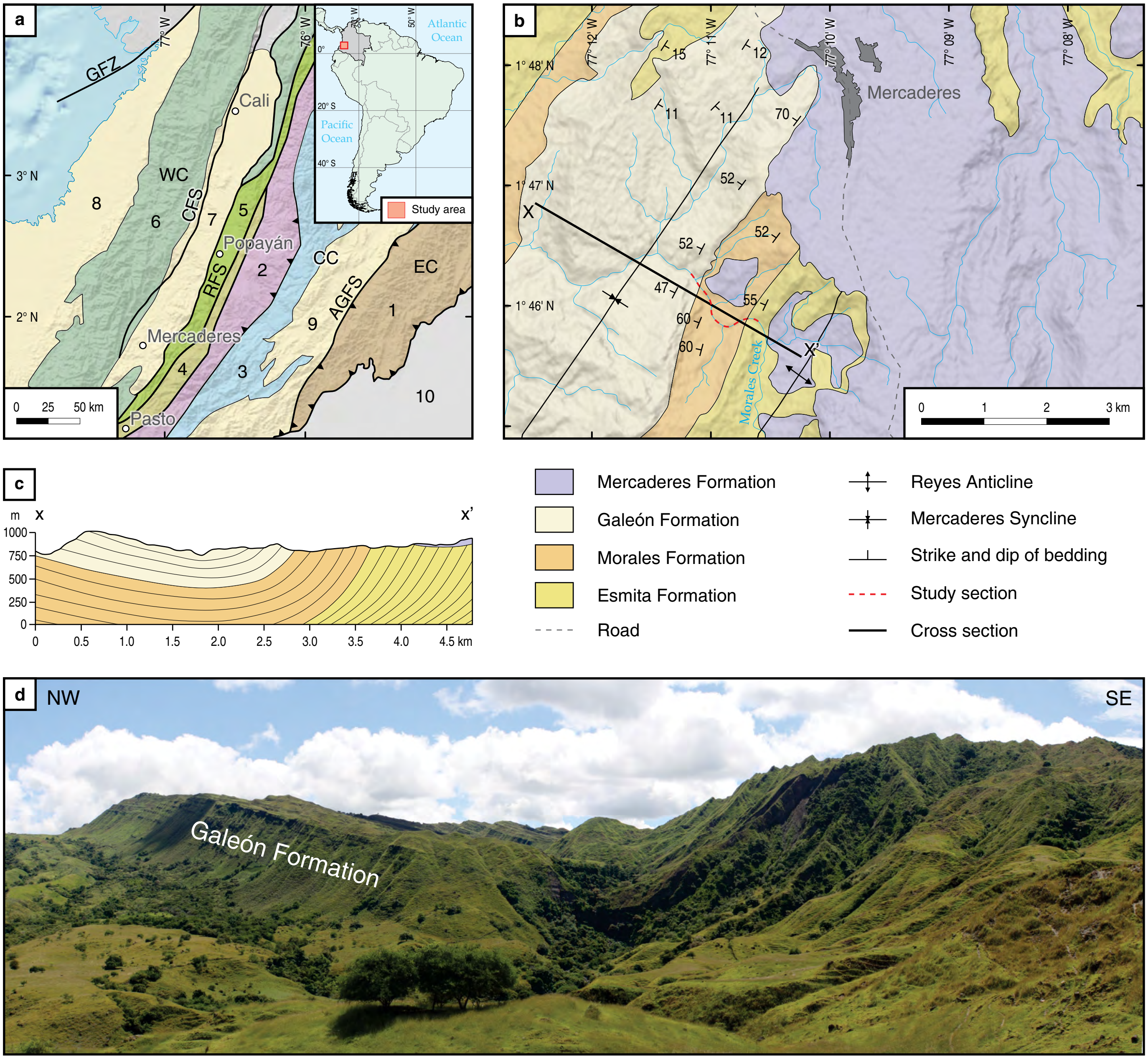

Figure 1. (a) Location of SW Colombia in South America, and simplified geological map showing the main geological units without the Pliocene – Quaternary volcanic cover (modified from Gómez et al., 2015a): (1) Precambrian metamorphic rocks (Garzon Massif); (2) Cajamarca Complex; (3) Jurassic plutonic and volcanic rocks; (4) Quebradagrande Complex; (5) Arquía Complex; (6) Cretaceous mafic and ultramafic volcanic and plutonic rocks, including the Barroso–Amaime and Los Azules Complexes (Orrego et al., 1996), and marine sedimentary rocks (mainly in the Western Cordillera); (7) Patía Sub–basin; (8) Tumaco Basin; (9) Upper Magdalena Valley Basin; (10) Caguán–Putumayo Basin. (WC) Western Cordillera; (CC) Central Cordillera; (EC) Eastern Cordillera; (AGFS) Algeciras–Garzón Fault System; (RFS) Romeral Fault System; (CFS) Cali–Patía Fault System; (GFZ) Garrapatas Fault Zone. **(b)** Geological map of the study area (Universidad de Caldas fieldwork map performed in 2010). **(c)** Geologic cross–section that shows the stratigraphic relations of the various units. **(d)** Morphology of the Galeón Formation on the axial axis of the Mercaderes Syncline.

a Miocene age based on fossil marine mollusks (*Mytilus* sp., *Balcis* sp., *Bittium* sp., *Rissoina sagraiana*, and *Neverita nereidis*) found in the lower and middle members. Duque–Caro (1973, written communication, in León et al., 1973) suggested a late Miocene age based on the presence of *Ammonia beccarii* (Figure 2). The authors indicated shallow brackish water marshes as the depositional environment. The Esmita Formation is overlain by the Galeón Formation. It was initially named Galeón's Formation by Keizer et al. (1955, unpublished, in van der Hammen, 1958). Van der Hammen et

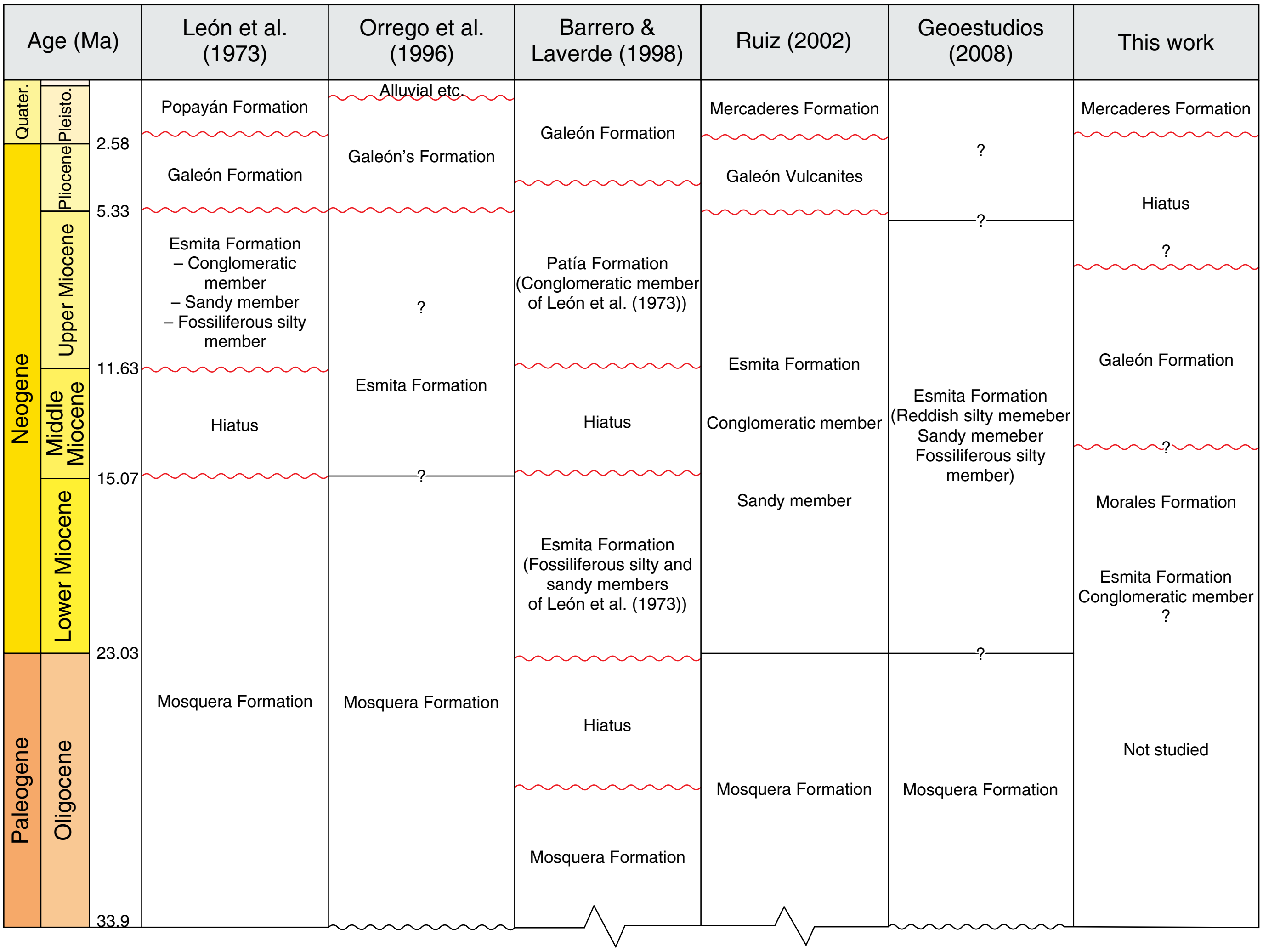

Figure 2. Different stratigraphic nomenclatures and ages proposed for the Cenozoic deposits of the Patía Sub–basin.

al. (1955, in León et al., 1973) suggested an early Pliocene age for this unit.

Orrego et al. (1996) described the Mosquera and Esmita Formations (Figure 2) in the 387–Bolívar geologic map to the west of the study area. They pointed out that the Esmita Formation stratigraphy is different from that described by León et al. (1973) in the 386–Mercaderes geologic map. Among the differences, they mentioned the presence of a sequence of purple siltstones and claystones interbedded with sandstones located in the upper part of the Esmita Formation. Orrego et al. (1996) indicated that this discrepancy is probably related to mistakes in stratigraphic interpretation due to structural problems. They proposed a detailed revision of the stratigraphy and structural geology of the area. An Oligocene – Miocene age was proposed for the Mosquera Formation, and a middle – late Miocene age was indicated for the Esmita Formation based on stratigraphic relationships and regional correlations.

Barrero & Laverde (1998) performed an analysis of seismic lines and regional geological information from the Cauca–Patía Basin. They restricted the name Esmita Formation to the fossiliferous silty and sandy members of León et al. (1973), and indicated an Oligocene – early Miocene age (Figure 2). The conglomeratic member was called the Patía Formation, following Murcia et al. (1981), and a late Miocene – early Pliocene age was suggested. Finally, they mentioned the upper Pliocene – Holocene Galeón Formation (Figure 2).

In the Mercaderes area, the Servicio Geológico Colombiano (Ruiz, 2002) employed the following stratigraphic terms from base to top: Mosquera Formation, Esmita Formation, Galeón Vulcanites, and Mercaderes Formation (Figure 2). He identified two members of the Esmita Formation, which from base to top are the (1) sandy member and (2) conglomeratic member (Figure 2). The lithological and paleontological data of the sandy member suggest a transitional–continental environment, where sandstones and conglomerates accumulated in fluvial channels. Ruiz (2002) suggested an early Miocene (Aquitanian) age based on the presence of *Lymnaea* found in Matacea Creek. He indicated that the conglomeratic member of the Esmita Formation is disconformably overlain by the Galeón Vulcanites (equivalent to the Galeón Formation) of Pliocene – early Pleistocene age (León et al., 1973). The Pleistocene Mercaderes Formation (Ruiz, 2002) is composed of volcanic and volcaniclastic deposits and covers the previous units above an angular unconformity.

Geoestudios (2008; Figure 2) described the Esmita Formation in three sections: El Boquerón, Guanabanal, and La Despensa Creeks. They identified the fossiliferous silty and sandy members of León et al. (1973) in the lower and middle parts of the unit. At the top, they defined a reddish siltstone member that could be correlated with the sequence of purple siltstones and claystones interbedded with sandstones mentioned by Orrego et al. (1996). The authors suggested muddy tidal plains, tidal channels, and fluvial environments for the unit. Palynologic studies performed at La Despensa Creek indicated a late Oligocene to middle Miocene age for the Mosquera and Esmita Formations (Geoestudios, 2008).

3. Methods

The studied rocks were described in well–exposed outcrops along Morales Creek using Jacob's staff (Patacci, 2016). This method allowed the identification of sedimentary facies and the interpretation of the depositional physical processes (Figure 3; Table 1). The Morales Formation was defined following the procedures for establishing stratigraphic units in the International Stratigraphic Guide (Murphy & Salvador, 1999). The facies identified were classified with a code based on their granulometry and sedimentary structures, according to Miall (2006). Subsequently, facies associations and architectural elements were identified in order to interpret the depositional environments (Table 2) and their variations over time.

From the 65 collected samples, 15 were used for petrographic analysis: 4 from the Esmita Formation, 10 from the Morales Formation, and one from the base of the Galeón Formation. The analyses were conducted in the Sedimentary Petrography Laboratory of the Instituto de Investigaciones en Estratigrafía (IIES) of the Universidad de Caldas and followed the Gazzi–Dickinson method (Ingersoll et al., 1984). The composition and texture of the clasts, such as grain size, roundness, and calibration, were measured. The Folk (1974) nomenclature was used to classify the sandstones. To improve the interpretation of the provenance of sediments, the heavy mineral fractions (densities > 2.82 g/cm^3) of four samples were analyzed. The heavy fractions were concentrated with sodium polytungstate (density of 2.9 g/cm^3); subsequently, thin sections were assembled using a resin with a refractive index similar to that of Canadian balsam (n = 1539). More than 300 grains per slide were counted using the ribbon counting method. The mineralogical identification was realized according to Mange & Maurer (1992). The data were represented on bar charts to visualize and group the populations and interpret their origin. Finally, the petrographic data were integrated into the regional geology in order to interpret source rocks.

We reviewed the U/Pb Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA–ICP–MS) detrital zircon ages of the Galeón Formation reported by Echeverri et al. (2015), and decomposed the ages on the relative probability diagrams employed by Density Plotter (Vermeesch, 2013). The morphology of zircon grains was revealed by cathodoluminescence imaging and described in terms of the growth rates of the crystal faces relative to each other. To assess zircon morphology, we implemented the characterization described by Corfu et al. (2003).

To determine the amount and type of organic matter contained in the deposits of the Morales Formation, total organic carbon (TOC) and pyrolysis analyses were performed on 5 samples using the LECO and Rock–Eval techniques, respectively, in the laboratories of Schlumberger (Colombia).

4. Results

4.1. Definition of the Morales Formation in SW Colombia

The term Morales Formation is proposed to include the fine–grained unit that overlies the conglomeratic member of the Esmita Formation and underlies the Galeón Formation (Galeón Vulcanites of Ruiz, 2002) in the Mercaderes area (Figure 3). This unit differs in lithology and geomorphology from the adjacent units (Esmita and Galeón Formations; Figure 3) and therefore, can be mapped separately on a 1:25 000 map. The most important features of the unit are described below.

4.2. Stratotype and Type Locality

The proposed stratotype crops out four kilometers to the southwest of Mercaderes town, along Morales Creek on the eastern flank of the Mercaderes Syncline (Figure 1b, 1c, 1d). Its geomorphological expression as a valley allows the unit to extend up to 9.2 km towards the SW, along the eastern and western flanks of the Mercaderes Syncline and to the west of Arboledas town (Cauca Department). To the north, it is covered by the volcaniclastic deposits of the Mercaderes Formation (Figure 1). The origin of the name comes from Morales Creek, a Patía River tributary. The map base 386–IV of the Instituto Geográfico Agustín Codazzi (2005) was used.

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Figure 3. Stratigraphic log of the studied section with locations of samples analyzed. (Q) quartz; (F) feldspar; (L) lithic fragments, the main components for classification of sandstones in percentages. The pink arrows and the numbers indicate the facies associations. See Tables 1, 2 for the descriptions and interpretations of lithofacies.

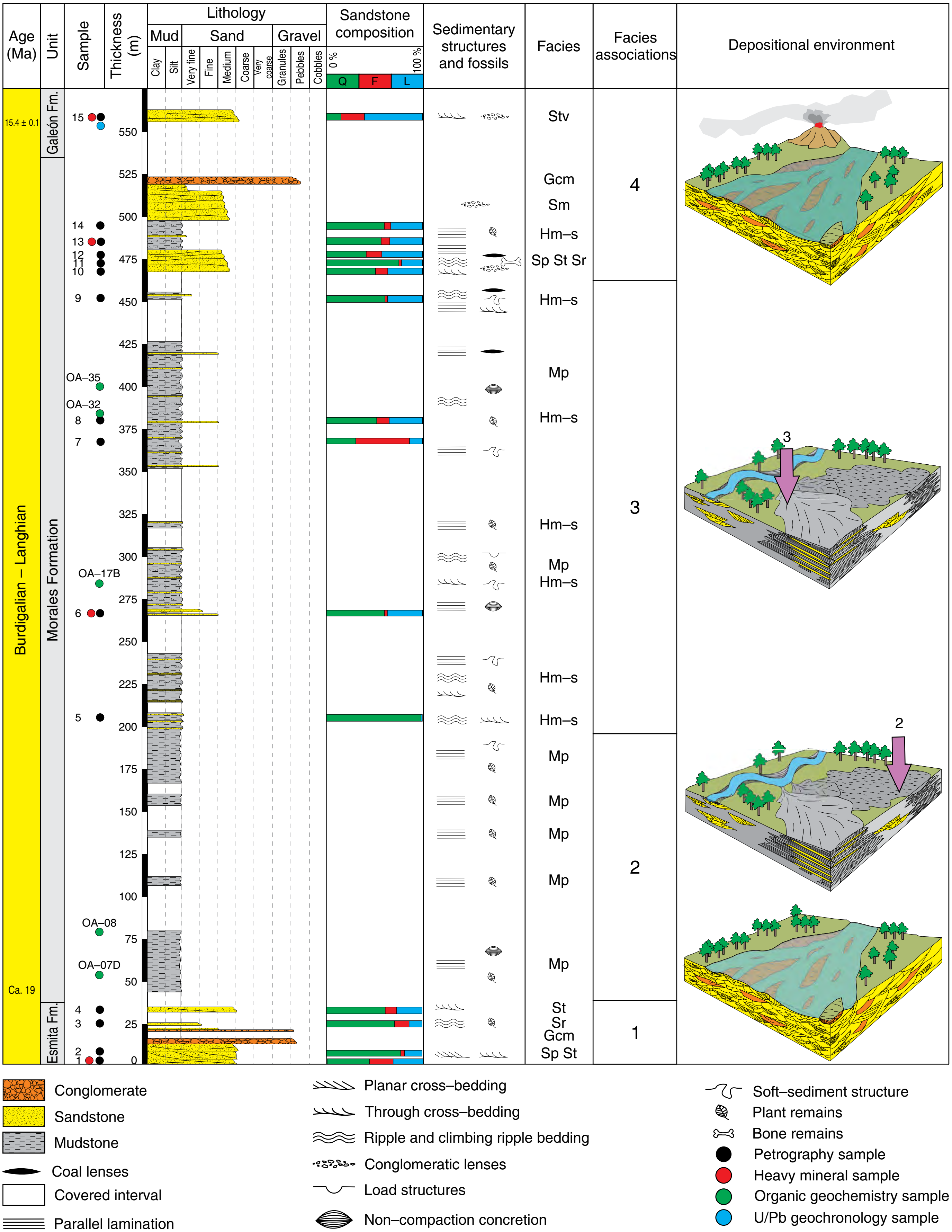

Age (Ma)
Unit
Sample
Thickness (m)
Lithology
Mud
Sand
Gravel
Clay
Silt
Very fine
Fine
Medium
Coarse
Very coarse
Granules
Pebbles
Cobbles
Sandstone composition
0 %
100 %
Q
F
L
Sedimentary structures and fossils
Facies
Facies associations
Depositional environment
15.4 ± 0.1
Ca. 19
Burdigalian – Langhian
Galeón Fm.
Morales Formation
Esmita Fm.
15
14
13
12
11
10
9
OA–35
OA–32
8
7
OA–17B
6
5
OA–08
OA–07D
4
3
2
1
550
525
500
475
450
425
400
375
350
325
300
275
250
225
200
175
150
125
100
75
50
25
0
Stv
Gcm
Sm
Hm–s
Sp St Sr
Hm–s
Mp
Hm–s
Hm–s
Mp
Hm–s
Hm–s
Hm–s
Mp
Mp
Mp
Mp
Mp
St
Sr
Gcm
Sp St
4
3
2
1
3
2
Conglomerate
Sandstone
Mudstone
Coal lenses
Covered interval
Parallel lamination
Planar cross–bedding
Through cross–bedding
Ripple and climbing ripple bedding
Conglomeratic lenses
Load structures
Non–compaction concretion
Soft–sediment structure
Plant remains
Bone remains
Petrography sample
Heavy mineral sample
Organic geochemistry sample
U/Pb geochronology sample

Table 1. Lithofacies codes used in this research (modified from Miall, 2006).

Code	Description	Interpretation
Gcm	Tabular and lenticular strata of structureless clast–supported polymictic conglomerates; subangular to subrounded, poorly sorted clasts. Locally, they have incipient clast orientation.	Pseudoplastic debris flow, longitudinal bedforms, lag deposits, sieve deposits (Miall, 2006).
Sp	Tabular and lenticular strata of medium–grained feldspathic lithic sandstones and conglomerates with planar cross stratification.	Migration of transverse bedforms associated with unidirectional Newtonian flows under low–flow conditions (Miall, 2006).
St	Tabular and lens–shaped strata of medium–grained feldspathic lithic sandstones, poorly to moderately sorted, with trough cross stratification. The top of the sequence features volcanic fragments and conglomeratic lenses (Stv).	Migration of sinuously crested and linguoid dunes under lower flow regime (Miall, 2006).
Sr	Tabular and lenticular beds of medium–grained lithic sandstones, with ripple and climbing ripple laminations.	Migration of ripples, in some cases with constant sand inflow, under lower flow regime (Miall, 2006).
Sm	Tabular and lenticular beds of structureless, medium–grained lithic sandstones, with local conglomeratic lenses.	Hyper–concentrated sediment flow deposits near the bottom of the channel (Miall, 2006).
Hm–s	Heterolithic facies. Thin beds of mudstones and fine– to very fine–grained sandstones. The mudstones have parallel lamination. The sandstones have ripple and climbing ripple laminations, normal grading and soft–sediment deformation structures (e.g., slumped, convoluted).	Particle settlement from suspension that alternated with low–energy currents; the deformation structures may be related to high sediment load and/or seismic activity (Potter et al., 2005).
Mp	Dark gray–black mudstones with parallel laminations, soft–sediment deformation structures and calcareous concretions.	Low–energy settings, settlement of particles from suspension in anoxic environments (Miall, 2006).

Table 2. Architectural elements in fluvial deposits (modified from Miall, 2006 and Potter et al., 2005).

Number in the log of Figure 3	Lithofacies associations	Interpretation
1, 4	**Gcm, Sp, St, Sr, Sm, and a low proportion of Hm–s**	Gravel and sand bars. Common in fluvial channels with high energy and load capacity (Miall, 2006).
3	**Hm–s, Mp**	Overflow and settlement of particles from suspension in low–energy environments. Typical of floodplains, swamps, lakes, and peat bogs (Potter et al., 2005).
2	**Mp**	Swamp and shallow lake deposits with low oxygen content at the bottom. Associated with alluvial plains (Miall, 2006).

4.2.1. Coordinates

Initial point (base of the unit): E: 989 005; N: 686 417 (origin Bogotá) (1° 45' 49" N; 77° 10' 46" W). Final point (top of the unit): E: 988 477; N: 686 898 (origin Bogotá) (1° 46' 04" N; 77° 11' 02" W).

4.2.2. Stratigraphic Limits and Thickness

The lower contact is conformable with the conglomerates and sandstones of the Esmita Formation. The upper limit with the sandstones and conglomerates of the Galeón Formation is covered by recent alluvial deposits (Figure 3). The Galeón Formation shows a sudden increase in the percentage of volcanic clasts. The measured thickness in Morales Creek reaches 470 m.

4.2.3. General Description

From bottom to top, the Morales Formation consists mainly of thin beds of gray to black laminated mudstones with some intercalated thin layers of lithic sandstones (heterolithic beds). The mudstones have parallel lamination, and the sandstones have ripple and climbing ripple laminations and normal grading. The heterolithic facies have soft–sediment deformation structures (e.g., slumps and clastic injection dikes). In the upper part of the unit (last 55 m), there is an increase in tabular and lenticular, medium to thick beds of lithic sandstones and polymictic conglomerates (Figure 3; Table 1).

4.2.4. Age

The Morales Formation has relatively abundant pollen, spores, and plant remains (Martínez et al., 2013). A sample analyzed from the basal volcaniclastic beds of the Galeón Formation (Figure 4; Echeverri et al., 2015) that overlies the top of the Morales Formation shows ages between 12 and 15 Ma (Table 1 of the Supplementary Information). This sample shows three U/Pb detrital zircon peaks with a wide domain of middle Miocene ages (Langhian; 83%, 15.4 ± 0.1 Ma), which is considered the depositional age, while the Oligocene (Chattian; 6%, 25.8

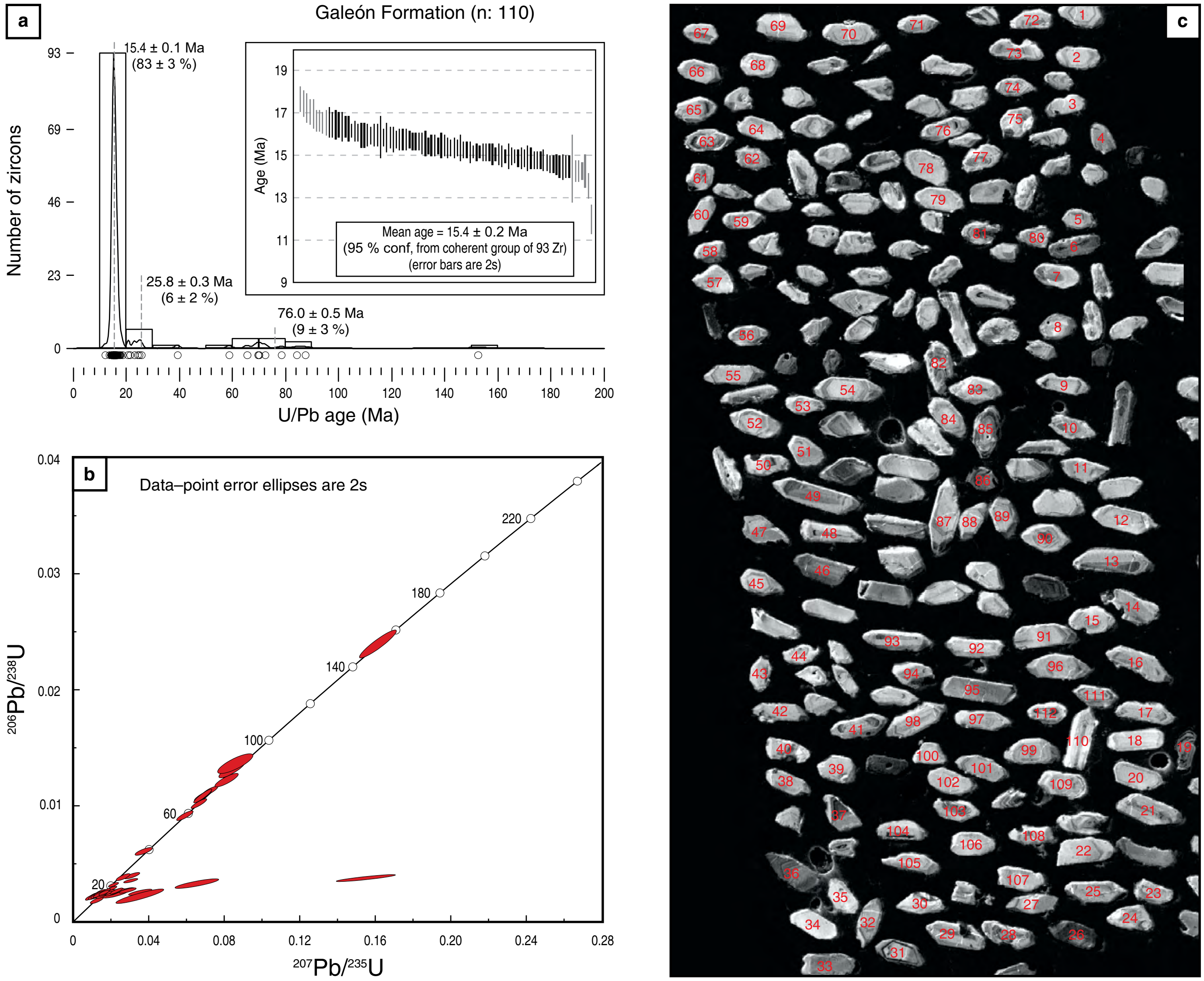


Figure 4. U/Pb LA–ICP–MS detrital zircon geochronology from the Galeón Formation (after Echeverri et al., 2015). **(a)** Probability density plot that shows the U/Pb detrital zircon peaks obtained with Density Plotter (Vermeesch, 2013). The inset shows the weighted mean age plot of the most common population of zircons. **(b)** Tera–Wasserburg concordia diagram. **(c)** Cathodoluminescence images of the detrital zircons analyzed. Red numbers indicate the dated zircons.

± 0.3 Ma) and Late Cretaceous (Campanian; 9%, 76.0 ± 0.5 Ma) ages occur less frequently (Figure 4a, 4b). In the middle Miocene population, exclusively igneous zircons, which are euhedral, subhedral, and prismatic with oscillatory zonation, are observed (Figure 4c). Additionally, Oligocene and Cretaceous populations contain zircons of igneous origin. Zircons with overgrowths associated with metamorphic events are absent. In summary, the age of the basal strata of the Galeón Formation is estimated at ca. 15.4 Ma. Additionally, the presence of *Clavatricolpites densiclavatus, Nijssenosporites fossulatus*, and *Echitricolporites maristellae* in the lower part of the Morales Formation indicates an age not older than Burdigalian (ca. 19 Ma, early Miocene), according to the zonation of Jaramillo et al. (2011) for the Llanos area (Martínez et al., 2013). Thus, the age of the Morales Formation is not older than ca. 19 Ma, and not younger than ca. 15.4 Ma.

4.2.5. Organic Geochemistry

The TOC of the Morales Formation samples fluctuates between 0.26 and 1.08 (poor quality of source rock). The hydrogen index (HI) fluctuates between 121 and 229 (mainly gas–prone organic matter), the oxygen index fluctuates between 14 and 31, and the Tmax between 428 and 436 °C. Kerogen is mainly types II–III and has a very low remaining hydrocarbon potential (Figure 5; Table 2 of the Supplementary Information). The organic matter is mainly continental, as indicated by the contents of plant organic matter, pollen spores, and freshwater algae (Martínez

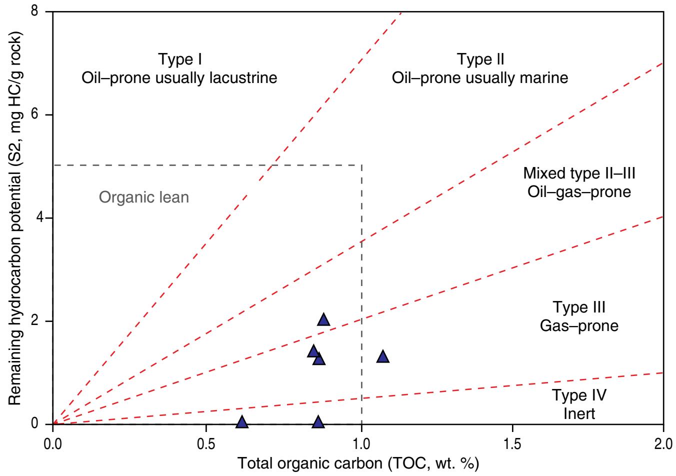


Figure 5. Remaining hydrocarbon potential vs. TOC and kerogen types of the studied samples from the Morales Formation.

et al., 2013). According to the color of the palynomorphs, the thermal alteration index (TAI) is –2 to 2 (thermally immature rocks according to Traverse, 2007).

4.3. Facies Analysis

Figure 6a shows the geomorphological expression of the units studied. Seven lithofacies are identified in this area (Table 1).

4.3.1. Gcm (Conglomerate, Clast–supported, Massive)

Tabular and lenticular thick beds of structureless (massive), poorly sorted clast–supported pebbly conglomerates, with subangular to subrounded clasts. They are composed of quartz, chert, and volcanic rock fragments (Figures 3, 6b; Table 1).

4.3.2. Sp (Sandstone, Planar Cross–stratification)

Tabular and lenticular thick beds of well to poorly sorted lithic and feldspathic medium–grained sandstones, with subrounded to subangular grains. They have planar cross–stratification marked by oriented pebbly levels. Locally, conglomerates and conglomeratic sandstones are present (Figures 3, 6c, 6h; Table 1).

4.3.3. St (Sandstone, Trough Cross–bedding)

Lenticular and tabular beds of gray poorly to moderately sorted lithic and feldspathic medium–grained sandstones, with subangular to subrounded grains and trough cross–bedding. The top of the sequence features volcanic fragments (Stv facies; Figures 3, 6d, 6e, 6f, 6h; Table 1).

4.3.4. Sr (Sandstone, Ripple Laminations)

Tabular and lens–shaped strata of gray poorly sorted lithic medium–grained sandstones, with subrounded to subangular grains. They have ripple laminations (in some cases climbing ripples) as internal structures (Figures 3, 6g, 6h; Table 1).

4.3.5. Sm (Sandstone, Massive)

Tabular beds of greenish–gray medium–grained lithic sandstones, moderately sorted, structureless (massive), with local conglomeratic lenses containing subrounded to subangular clasts (Figures 3, 6i; Table 1).

4.3.6. Hm–s (Heterolithic, Mudstone–Sandstone)

Succession of thin beds of mudstones interlayered with sandstones. The mudstones have parallel lamination. The sandstones are very fine in grain size, with parallel, trough, and climbing ripple laminations and graded beds. Load casts and soft–sediment deformation structures are also common (Figures 3, 6j, 6n, 6o; Table 1). Plant remains are frequent.

4.3.7. Mp (Mudstone, Parallel Lamination)

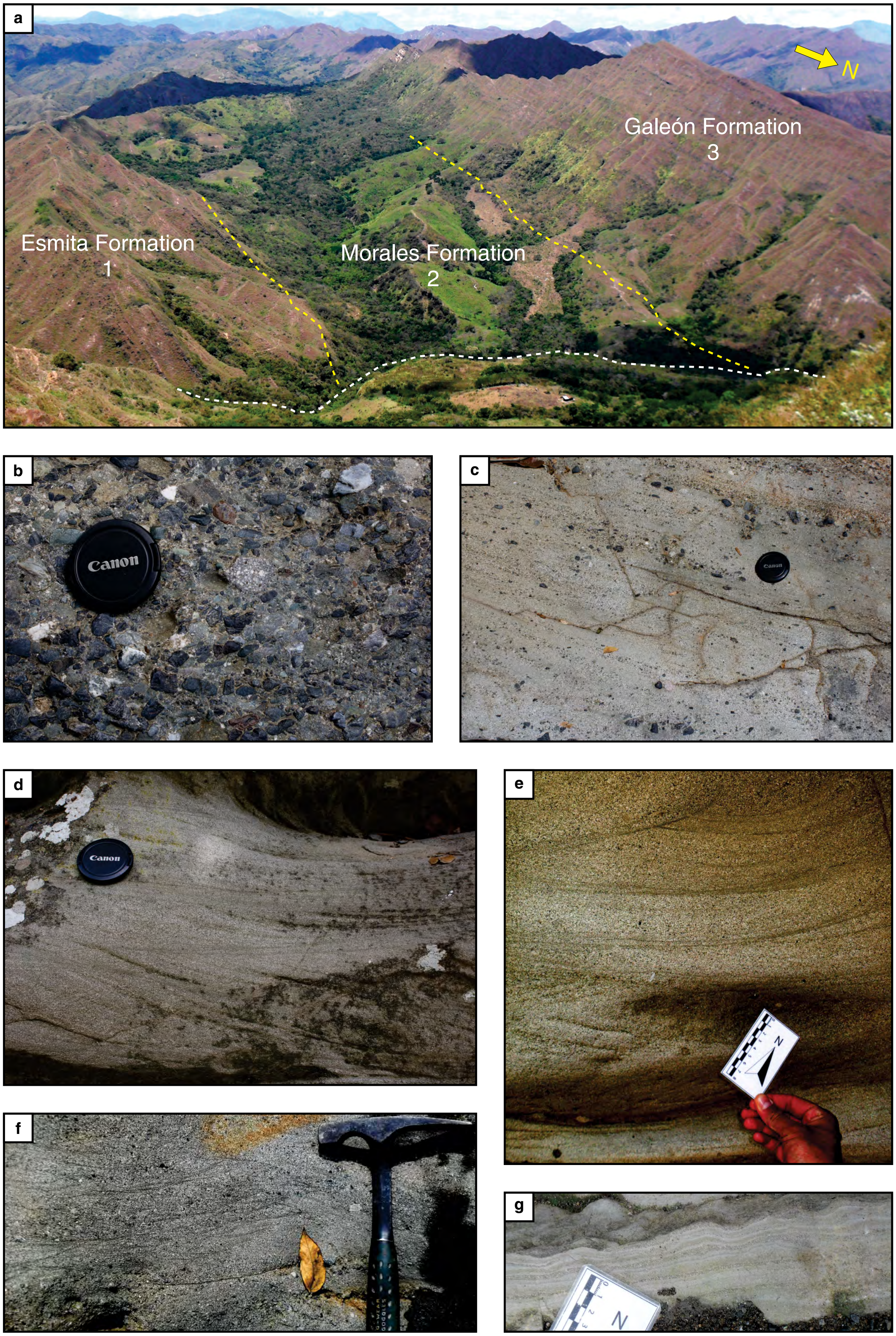
Dark gray mudstones with parallel lamination and local deformation structures and locally uncompacted calcareous concretions. It is commonly associated with the Hm–s facies (Figures 3, 6k, 6l, 6m; Table 1). Plant remains, pollen, and spores are relatively common in this facies.

4.4. Facies Associations

Four facies associations are identified (Figure 3; Table 2).

→

Figure 6. Morphology and facies of the studied section. **(a)** Geomorphology of the studied stratigraphic units. The dotted line corresponds to the studied section (Morales Creek). **(b)** Structureless conglomerate with clast–supported pebbles (Gcm; Esmita Formation). **(c)** Sandstones and conglomeratic sandstones with planar cross stratification (Sp; Esmita Formation). **(d)**, **(e)** Sandstones with trough cross–bedding (St; Esmita Formation). **(f)** Sandstones and conglomeratic sandstones rich in volcanic clasts with trough cross–bedding (Stv; Galeón Formation). **(g)** Sandstones with climbing lamination (Sr; Esmita Formation).


a
N
Galeón Formation
3
Esmita Formation
1
Morales Formation
2
b
Canon
c
d
Canon
e
f
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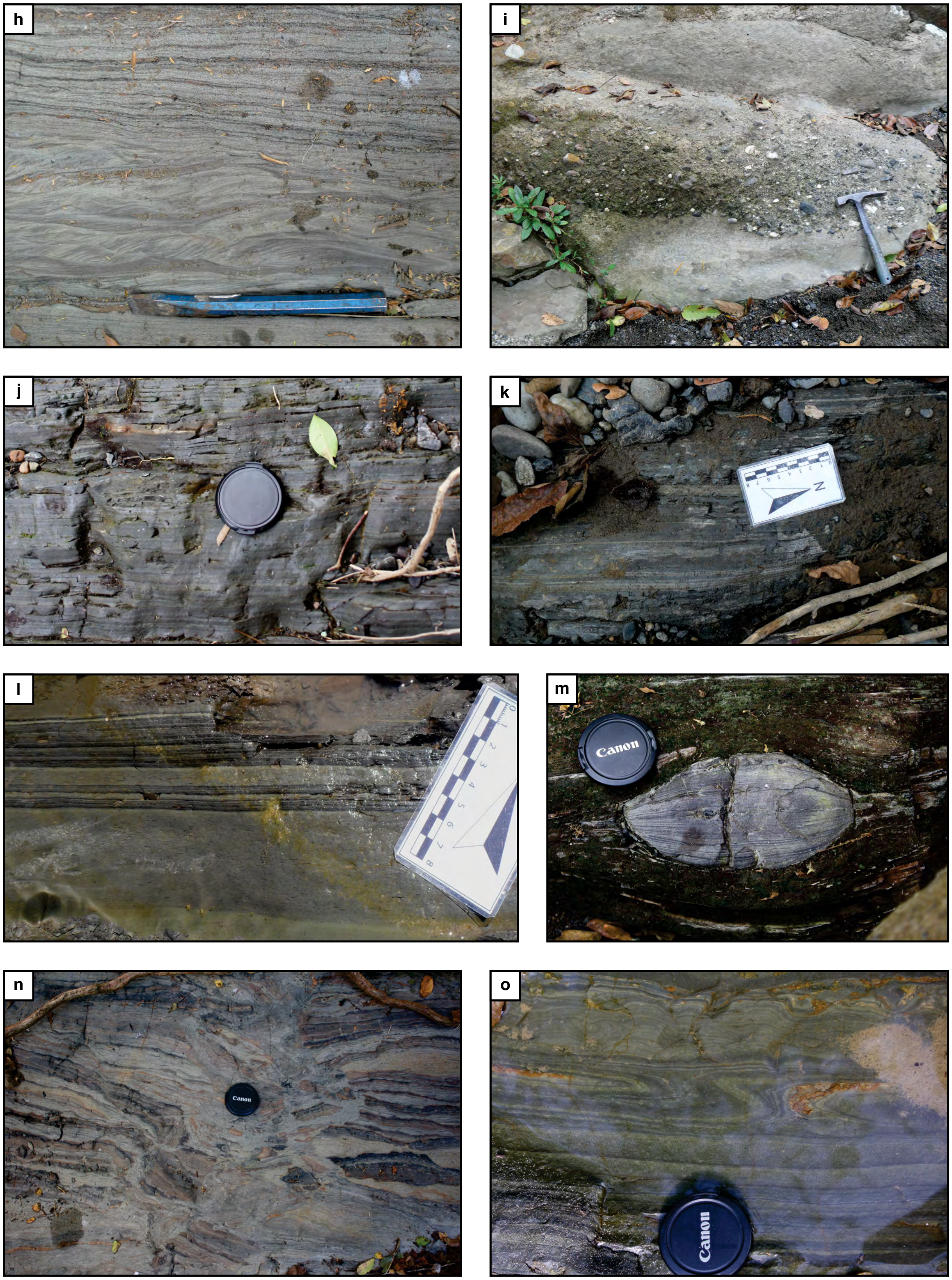

Figure 6. Morphology and facies of the studied section. **(h)** Sandstones with parallel laminations (Sp), trough cross–bedding (St), and climbing ripple lamination (Sr) (Morales Formation). **(i)** Massive sandstones (Sm) with conglomeratic lenses (Morales Formation). **(j)** Mudstones (claystones and siltstones) with parallel lamination (Morales Formation). **(k)**, **(l)** Heterolithic facies with parallel lamination (Mp) and plant debris (Morales Formation). **(m)** Early diagenetic muddy concretion (Morales Formation). **(n)**, **(o)** Soft–sediment deformation structures in heterolithic facies (convolute and slumped beds, respectively; Morales Formation) (*continued*).

4.4.1. Facies Association 1 (0–33 m; Conglomeratic Member of the Esmita Formation)

It consists mainly of amalgamated lenticular beds with the Sp, St, Sr, and Gcm lithofacies (Figure 6; Table 1), some of them with fining–upward patterns a few meters in thickness. The Gcm facies can be related to debris flow deposits associated with longitudinal fluvial bars (Miall, 2006) (Table 1). Its relations with Sp, St, and Sr facies can be associated with the deposition of dunes in abandoned channels or sand wedges at the edges of bars (Einsele, 2000). The fining–upward pattern can be related to lateral migration and sudden abandonment of channels by avulsion (Einsele, 2000). The absence of fine–grained overbank and alluvial plain deposits, as well as the random arrangement between coarse–grained lithofacies, suggests braided fluvial deposits (cf. Miall, 2006; Figure 3; Table 2).

4.4.2. Facies Association 2 (33–179 m; Morales Formation)

It is dominated by the Mp lithofacies with a low percentage of thin sandstone beds (Figure 3; Table 2). These deposits can be related to low–energy environments associated with swamps and shallow (?) lakes developed in alluvial plains, relatively far from the main channel (Figure 3; Table 2). This interpretation is also supported by the exclusive presence of continental microfossils (e.g., pollen and spores; Martínez et al., 2013). The dark gray color of this facies can be associated with anoxic–dysoxic environments (Potter et al., 2005). Continental lakes occur in areas of crustal subsidence, such as rift zones, continental sag basins, and foreland and back–arc basins (Einsele, 2000).

4.4.3. Facies Association 3 (179–455 m; Morales Formation)

In this part of the section, the Mp and Hm–s facies are the most common, but there is an important increase in the frequency of thin sandstone beds. They are interpreted as swamp and distal overbank deposits in a fluvial plain (cf. Miall, 2006). Muds and silts were deposited during floods as suspension deposits in temporary floodplain lakes and ponds marginal to the main channel (Potter et al., 2005). Plant remains, pollen, spores, and coal lenses linked to the type III kerogen confirm the association with continental deposits.

4.4.4. Facies Association 4 (470–563 m; Morales and Galeón Formations)

In this part, the mudstones are in contact with sandstones and conglomerates (Sp, St, Sr, Sm, and Gcm; Figures 3, 6; Table 1). They can be interpreted as fluvial channel and crevasse splay deposits. After a covered interval of 30 m, in the 525–555 m interval, there is an increase in thick beds of volcaniclastic amalgamated sandstones, including mainly lenticular Stv lithofacies (Figure 6, Table 1). This lithofacies, together with Gcm, characterizes the base of the Galeón Formation (Figure 3; Table 2). Stv and Gcm are the most common facies association in the unit, which has a thickness of more than 400 m in the core of the Mercaderes Syncline. Thus, a braided fluvial environment is proposed with a strong supply of volcanic materials.

4.5. Petrography

The studied sandstones are mainly moderately to poorly sorted litharenites, feldspathic litharenites, and sublitharenites (Figure 7a), with medium to very fine grain sizes, subangular to subrounded grains and clay matrix contents between 0 and 18% (Table 3 of the Supplementary Information). They plot mainly in the recycled orogen fields (quartzose and transitional) in the tectonic provenance diagrams (Figure 7b, 7c; Dickinson et al., 1983).

The sandstones are composed mainly of monocrystalline quartz (Qm; 28–12 %) (Figure 8a–8c), and most grains have wavy extinction. The three uppermost samples of the Esmita Formation show an increase in polycrystalline (Qp) mosaic quartz (11–21 %; e.g., Figure 8d). Plagioclase grains are present in most of the slides (0–35 %), some of which are twinned or zoned (Figure 8e). Bone fragments are locally present (Figure 8f, 8g). The lithic fragments are as follows, in order of abundance: sedimentary rocks (mudstones and sandstones; 1–17 %); metamorphic rocks (graphitic schists; 1–10 %) (Figure 8h), which increase in percentage towards the top of the section; intermediate volcanic rocks (1–15 %), which abruptly increase towards the base of the Galeón Formation (40%) (Figure 8h, 8i); and plutonic rocks (0–1 %). Other minerals present in the samples are hornblende (1–8 %), biotite (1–5 %), muscovite (1–5 %), epidote (1–5 %), and chlorite (1–3 %) (Figure 8b). The cement may be calcite, quartz, or chlorite (Figure 8a–8c).

4.6. Heavy Minerals

Figure 9 shows the types and percentages of heavy minerals reported in each stratigraphic unit (see also Table 4 of the Supplementary Information). The minerals identified, in order of abundance, are epidote, zircon, apatite, garnet, hornblende, olivine, and hypersthene with lower proportions of muscovite, biotite, clinozoisite, enstatite, and glaucophane (Figure 9a, 9b). Chlorite and spinel are found only in sample 15 from the Galeón Formation, and glaucophane is found in samples 6 and 13 from the Morales Formation.

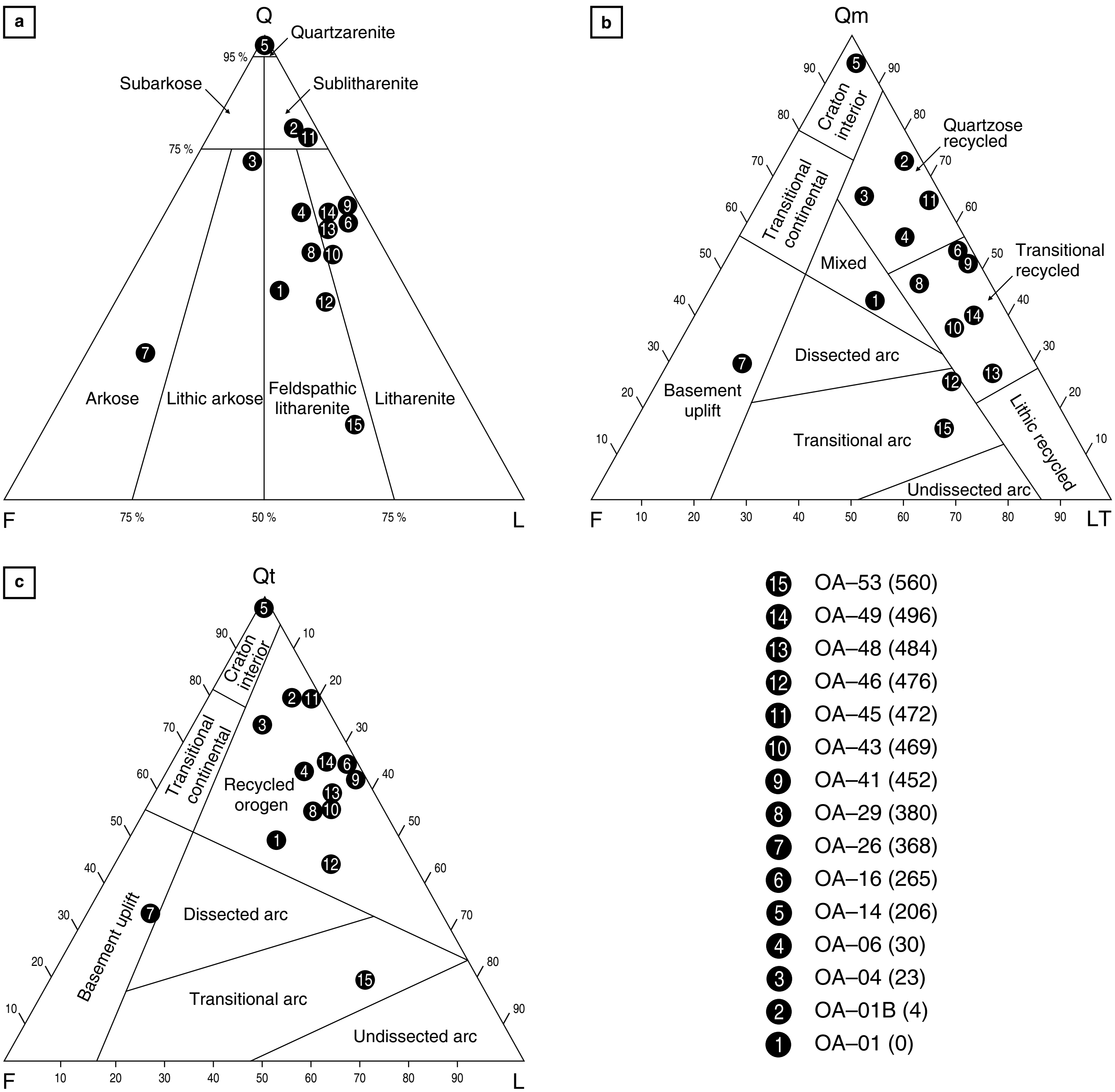

Figure 7. (a) QFL modal classification diagram of the studied sandstones (Folk, 1974); **(b)**, **(c)** Tectonic provenance diagrams (Dickinson et al., 1983): (Q) total quartz (no chert); (F) potassium feldspar + plagioclase; (L) lithic fragments (no chert); (Qm) monocrystalline quartz; (LT) total lithics (including chert); (Qt) total quartz (including chert). The values to the left in circles correspond to the numbers of the samples represented in the stratigraphic log (Figure 3), and the OA codes show the numbers of field samples. The numbers in parentheses show the thickness in meters above the section.

A dominance of anhedral and subhedral subrounded to subangular grains is observed (Figure 9). Hornblende (46%), apatite (25%), and epidote (18%) are abundant in the Esmita Formation (Figure 9a). In the Morales Formation, the most abundant minerals are zircon (11 to 30 %), epidote (22 to 27 %), apatite (9 to 24 %), and garnet (2 to 22 %), followed by hornblende (1 to 13 %), tourmaline (5%), rutile (2%), hypersthene (0.3 to 6 %), olivine (3%), muscovite (3%), glaucophane (1%), clinozoisite (3%), biotite (2%), and enstatite (1%). The Galeón Formation contains garnet (39%), zircon (20%), epidote (14%), and apatite (12%) as the most abundant minerals, followed by olivine (7%), tour-

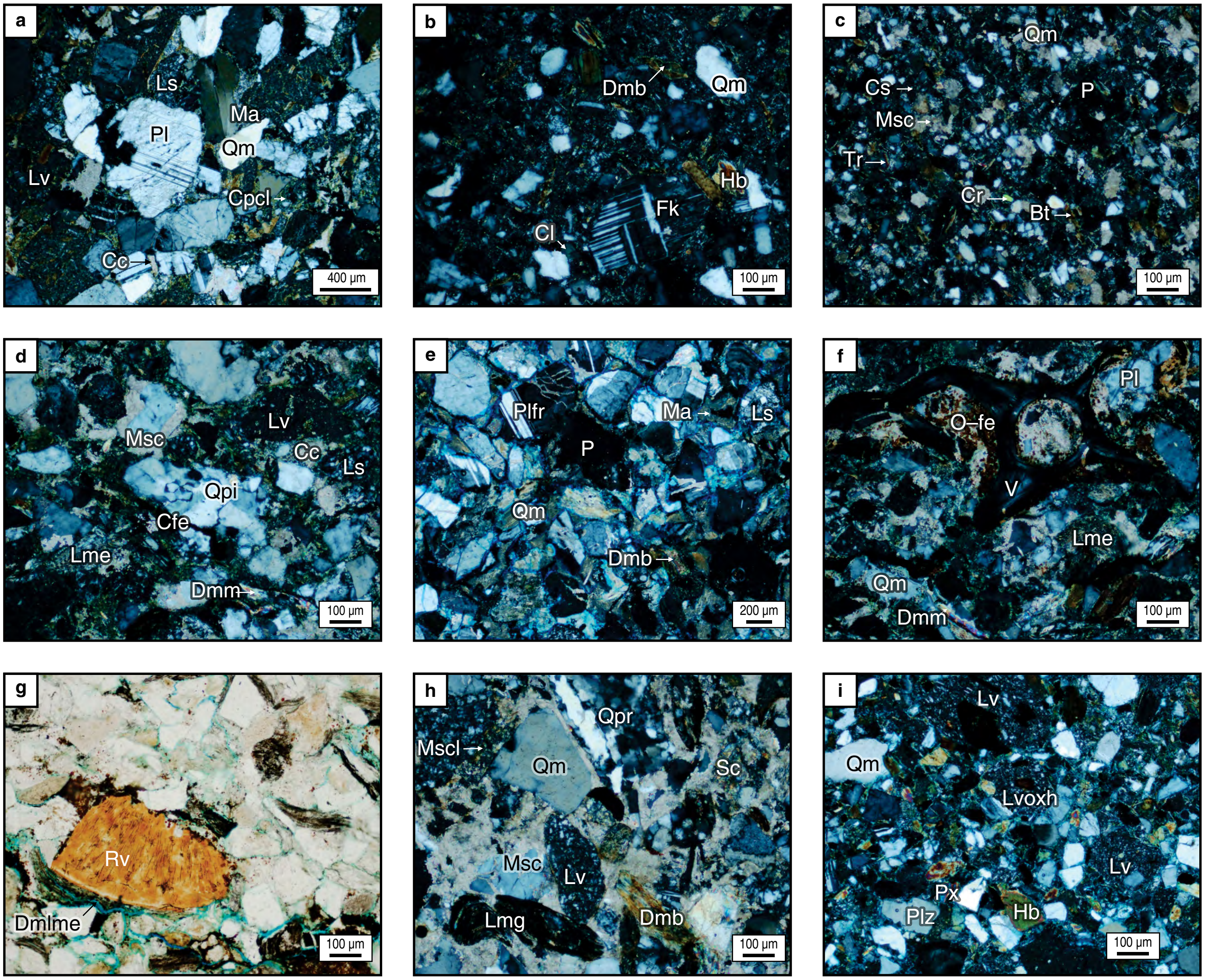

Figure 8. Photomicrographs of the studied sandstones. **(a)** Feldspathic litharenite (sample 1; Esmita Formation) with monocrystalline quartz (Qm), plagioclase (Pl), intermediate volcanic rocks (Lv), siliceous siltstone (Ls), chlorite cement (Cpcl), clay matrix (Ma), and calcareous cement (Cc); crossed nicols. **(b)** Lithic arkose (sample 3; Esmita Formation) with monocrystalline quartz (Qm), potassium feldspar (Fk), hornblende (Hb), chlorite (Cl), and deformed biotite (Dmb); crossed nicols. **(c)** Quartz arenite (sample 5; Morales Formation) composed of monocrystalline quartz (Qm), biotite (Bt), zircon (Cr), tourmaline (Tr), siliceous metasomatism by carbonates (Msc), siliceous cement (Cs), and pores (P); crossed nicols. **(d)** Litharenite (sample 6; Morales Formation) with polycrystalline quartz of igneous origin (Qpi), metamorphic schist (Lme), volcanic rocks (Lv), sedimentary rocks (Ls), mechanical deformation of muscovite (Dmm), siliceous metasomatism by carbonates (Msc), carbonate cement (Cc), and ferruginous cement (Cfe); crossed nicols. **(e)** Arkose (sample 7; Morales Formation) with monocrystalline quartz (Qm), fractured plagioclase (Plfr), sedimentary lithic fragments (Ls), deformed biotite (Dmb), clay matrix (Ma), and pores (P); crossed nicols. **(f)** Sublitharenite (sample 11; Morales Formation) with monocrystalline quartz (Qm), plagioclase (Pl), schist (Lme), mechanical deformation of muscovite (Dmm), cross sections of vertebrae (V), and iron oxides (O–fe); crossed nicols. **(g)** Immature sublitharenite (sample 11; Morales Formation) with phosphatic remains (Rv) and schists (Dmlme); parallel nicols. **(h)** Feldspathic litharenite (sample 12; Morales Formation) with monocrystalline quartz (Qm), recrystallized polycrystalline quartz (Qpr), intermediate volcanic (Lv), graphitic schists (Lmg), sericite (Sc), deformed biotite (Dmb), metasomatic silica and carbonate (Msc), and metasomatic chlorite and silica (Mscl); crossed nicols. **(i)** Feldspathic litharenite (sample 15; Galeón Formation) with monocrystalline quartz (Qm), zoned plagioclase (Plz), hornblende (Hb), volcanic lithic fragments (Lv) with oxyhornblende (Lvoxh) and pyroxene (Px); crossed nicols.

maline (4%), rutile (2%), spinel (1%), muscovite (1%), and chlorite (1%) with lower proportions of hypersthene (0.3%), enstatite (0.3%), biotite (0.30%), and hornblende (0.3%) (Figure 9a).

5. Discussion

The Morales Formation accumulated in swamps, lakes, and overbank fluvial environments, under anoxic–dysoxic condi-

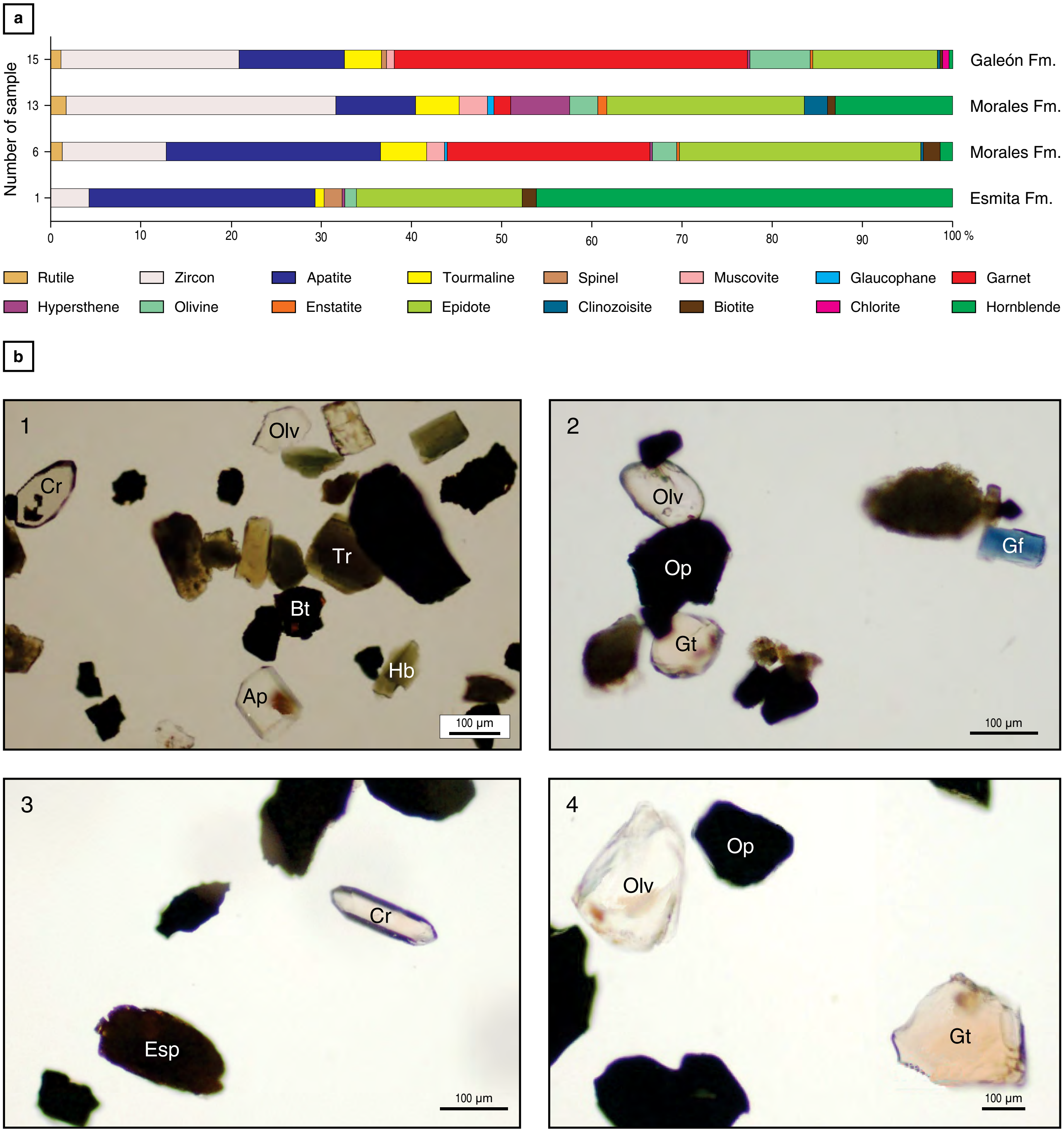

Figure 9. (a) Heavy mineral bar diagrams for the analyzed sandstones from the Morales Creek stratigraphic section. The numbers in the ordinate represent the sample codes in Figure 3. **(b)** Photomicrographs of the heavy mineral assemblage. (1) Sample 1 (Esmita Formation); (2) Sample 6 (Morales Formation); (3) Sample 15 (Galeón Formation); (4) Sample 15 (Galeón Formation). Abbreviations: hornblende (Hb), olivine (Olv), biotite (Bt), garnet (Gt), spinel (Esp), tourmaline (Tr), apatite (Ap), zircon (Cr), glaucophane (Gf), and opaque minerals (Op).

tions. The exclusive presence of plant debris, pollen, and spores suggests continental environments. This interpretation is further supported by the type III kerogen obtained from the pyrolysis analysis (Figure 5). The sandstones and conglomerates of the Galeón Formation can be interpreted as fluvial braided deposits dominated by gravel and sand bars. Although the Esmita and Morales Formations have low percentages of volcanic porphyritic fragments, the Galeón Formation shows an abrupt increase in volcanic rock fragments, glass, and crystals (Figure 3). Based on the occurrence of mainly ca. 15 Ma subhedral to euhedral zircons identified, we favor an increase in magmatic arc activity during the middle Miocene. This detrital magmatic record can be associated with the exhumation of the Neogene porphyritic subvolcanic bodies exposed along the Patía valley, which originated from the subduction of the Nazca Plate in the Colombian Pacific (Echeverri et al., 2015). Neogene magmatic rocks extend from the Western Cordillera to the Central Cordillera (Barbosa, 2003). In the lower Miocene deposits of the Upper Magdalena Valley (Honda Formation), the volcanic deposits are thinner and finer–grained than those identified in the Patía Sub–basin. This difference is probably explained by the proximity of the volcanic centers to our study area.

The sandstone petrography (conventional and heavy minerals) reveals that the sedimentites of the Esmita and Morales Formations came from multiple sources and can be related to a recycled orogen (Figure 7). The presence of glaucophane in the Morales Formation suggests a high–pressure metamorphic source, such as the Arquía Complex (Jambaló, western border of the Central Cordillera), where a $^{40}Ar/^{39}Ar$ Late Cretaceous metamorphic age was obtained for blueschists (Bustamante et al., 2011). Other minerals that can be related to metamorphic sources are epidote, clinozoisite, chlorite, muscovite, tourmaline, and eventually rutile (Figure 9). Additionally, deformed metamorphic and recrystallized metamorphic quartz grains associated with foliated rock fragments (e.g., graphitic schist) are identified (Figure 8). It is important to mention that towards the top of the studied section, the percentage of garnets increases significantly (Galeón Formation; Figure 9, sample 15). Weber et al. (2002) reported, within the Pliocene – Pleistocene volcanic deposits of the area (Mayo River), tuffs with mafic and felsic fragments (granulites, amphibolites, gneisses, hornblendites, pyribolites, and pyroxenites) rich in garnets associated with a mantle wedge. Our data show that garnet–rich tuffs are present in this area at least from the middle Miocene.

The sedimentary and volcanic fragments can be related to the Diabásico and Dagua Groups, or alternatively to the Quebradagrande Complex (Maya & González, 1995), which crop out in the Western and Central Cordilleras, respectively (Figure 1; Gómez et al., 2015a). Pardo–Trujillo et al. (2020) mentioned that some parts of the Western Cordillera emerged during the early – middle Miocene based on petrographic and detrital zircon evidence in the neighboring Tumaco Basin (Figure 1). This result is consistent with a sedimentary and volcanic source located to the west of the basin. Nevertheless, the petrography of the volcanic and sedimentary lithic fragments of the Quebradagrande rocks are similar to these units. The potassium feldspar, biotite, zircon, tourmaline, and hornblende probably came from the Paleogene – Neogene granitoids that crop out in the Western Cordillera (Figure 9); however, the Central Cordillera basement has Triassic, Jurassic, and Cretaceous plutonic rocks, which makes interpretation difficult. It is also possible that some rounded grains of the ultrastable heavy mineral phases, such as apatite and zircon, were reworked from Paleogene or Cretaceous sedimentary units. A geochemical study of detrital zircons in sandstones (e.g., Hf isotopes) can help to discriminate some igneous and metamorphic sources.

Lower – middle Miocene fluvial and marine fine–grained units in NW South America have been described in several regions of Colombia (e.g., de la Parra et al., 2019; Hoorn et al., 2010; Jaramillo et al., 2017). In the Upper Magdalena Valley sector, van der Wiel & van den Bergh (1992) mentioned a fine–grained unit of 700 m–thick lacustrine–fluvial deposits in the lower part of the Honda Formation (Neiva Sub–basin). The radiometric dating of thin volcanic layers in this unit reveals K/Ar ages of 15.8 ± 0.6 Ma and 14.3 ± 0.5 Ma, which can be partially correlated with the top of the Morales Formation and the base of the Galeón Formation. Similarly, de la Parra et al. (2019), based on palynological evidence, suggested the occurrence of extensive lacustrine systems in the Middle and Upper Magdalena Valley Basins (e.g., Colorado and Barzalosa Formations). The age of these lakes can be associated with the "Pebas phase" of the Pebas system (ca. 16–11.3 Ma) in the Amazonian Basin, in which a mega wetland expanded, reaching its maximum extent (Hoorn et al., 2010).

As mentioned, the Galeón Formation concordantly overlies the Morales Formation on the axial axis of the Mercaderes Syncline. Nevertheless, the sudden change in composition of the Galeón Formation could also be related to a disconformity (Figure 2). The ca. 15.4 Ma U/Pb age obtained for the base of the Galeón Formation, which is not Pliocene as proposed by León et al. (1973) and Ruiz (2002), constrains the age of the angular unconformity that exists between the volcaniclastic Galeón and Pleistocene Mercaderes Formations (Figure 1). We suggest that this unconformity was produced during the late Miocene? – Pliocene interval (Figure 2). This unconformity can thus be compared to the angular unconformity reported between the volcaniclastic La Paila and Zarzal Formations in the northern segment of the Cauca Sub–basin, where a late Miocene – Pliocene age has been estimated (Alfonso et al., 1994; Barrero et al., 2006; López et al., 2009). However, more geochronological information is needed to solve this problem.

There is no detailed structural research in the study area. Surface geologic mapping and seismic information show that the Cauca–Patía sedimentary rocks compose part of a thick–skinned thrust and related fold system with a west vergence (Alfonso et al., 1994; Barrero & Laverde, 1998; Barrero et al., 2006). According to regional information, during the Cenozoic, the western region of Colombia experienced compression and wrench tectonics due to the ENE oblique subduction of the Farallón and Nazca Plates below the South American margin (Pardo–Casas & Molnar, 1987; Somoza & Ghidella, 2012). In this scenario, we speculate that the subsidence that allowed the accumulation of hundreds of meters of mud–dominated sediments in the Morales Formation could have been formed in pull–apart basins associated with wrench faults.

6. Conclusions

In the Neogene deposits of the Patía Sub–basin (SW Colombia), a new unit, named the Morales Formation, is defined. It consists of a sedimentary succession with a thickness of 470 m, composed mainly of gray–black mudstones with some intercalations of thin sandstone beds, interpreted as lake, swamp, and overbank deposits accumulated in fluvial systems. The data presented in this work linked to the regional geology of the Llanos and the Middle and Upper Magdalena Valley Basins suggest the occurrence of extensive lacustrine systems in the Colombian intramontane basins during the early Miocene.

The ca. 15 Ma (zircon U/Pb) age obtained for the basal strata of the Galeón Formation is interpreted as the onset of intense volcanic activity in the Patía Sub–basin. Thus, the Galeón Formation is older than had been considered in the geological literature. These data and the new palynologic information indicate a Burdigalian – early Langhian (ca. 19–15 Ma) age for the Morales Formation.

The studied sandstones are litharenites, feldspathic litharenites, sublitharenites, arkoses, and lithic arkoses. Their components were derived from sedimentary, metamorphic, plutonic, and volcanic rocks associated with the Western and Central Cordilleras. With the current state of knowledge, it is difficult to discriminate the provenances of the sediments. Some of them (e.g., glaucophane and probably garnet) can be associated with the basement of the Central Cordillera.

Acknowledgments

We thank the Universidad de Caldas and the Agencia Nacional de Hidrocarburos for their financial support (contract 092 of 2009). Thanks to geologists Juan Sebastián ROSERO and Diana OCHOA for their advice. Professor Agustín CARDONA (Universidad Nacional de Colombia Sede Medellín) helped us in the preparation and identification of heavy minerals. Special thanks to the staff of the Instituto de Investigaciones en Estratigrafía (Universidad de Caldas) for their technical and logistical support, especially to Edward OSORIO and Juan Pablo BETANCUR. We give special thanks to Jorge GÓMEZ TAPIAS (Servicio Geológico Colombiano) for his help during the translation and editing of this chapter. We thank the reviewers and editor for the comments that improved this manuscript. The Fundación Carolina supported Andrés PARDO–TRUJILLO with a postdoctoral stay in Salamanca (Spain, 2018) for the finalization of this document. Andrés PARDO–TRUJILLO especially thanks the scientific and technical staff of the Universidad de Salamanca for their hospitality and support, especially professor and friend José Abel FLORES.

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Explanation of Acronyms, Abbreviations, and Symbols:

ANH	Agencia Nacional de Hidrocarburos
HI	Hydrogen index
IIES	Instituto de Investigaciones en Estratigrafía
LA–ICP–MS	Laser ablation inductively coupled plasma mass spectrometry
TAI	Thermal alteration index
TOC	Total organic carbon

Authors' Biographical Notes

Andrés F. GALLEGO–RÍOS is geologist of the Departamento de Ciencias Geológicas at Universidad de Caldas (Manizales, 2012). He has worked as geologist in different geological consulting companies, executing local and regional stratigraphic and tectonic projects. He has also worked as a geologist describing well cores from several basins in Colombia.

Andrés PARDO–TRUJILLO is a geologist in the Departamento de Ciencias Geológicas at the Universidad de Caldas (Manizales, 1998). Andrés obtained his MS in vegetal micropaleontology in 1997 and his PhD in Science from Liège University (Belgium, 2004). He has worked since 1989 as a professor in the Departamento de Ciencias Geológicas at Universidad de Caldas, Colombia, in sedimentology, regional geology, palynology, and field geology. From 2006–2009, he worked as an advisor at the Agencia Nacional de Hidrocarburos (ANH), where he participated in the geological study of several Colombian sedimentary basins. Andrés is currently the director of the Instituto de Investigaciones en Estratigrafía (IIES) and of the Grupo de Investigación en Estratigrafía y Vulcanología (GIEV) at the Universidad de Caldas. His main interest is the study of the geological and biological evolution of the NW corner of South America during the Cretaceous – Cenozoic.

Guillermo A. LÓPEZ–PLAZAS is geologist of the Departamento de Ciencias Geológicas at Universidad de Caldas (Manizales, 2012). He has worked as a geologist for different geological consulting companies. He has also worked as a well logger and geologist in several basins of Colombia.

Sebastián ECHEVERRI is a geologist from the Universidad de Caldas, with an MS in Earth sciences from the same university and PhD in science and geotectonics from the Universidade de São Paulo, Brasil. Sebastián works as a researcher in the Grupo de Investigación en Estratigrafía y Vulcanología (GIEV) Cumanday–Instituto de Investigaciones en Estratigrafía (IIES) at the Universidad de Caldas and is part of the EGEO research group at the Universidad Nacional Sede Medellín. His main research area is the regional geology and tectonostratigraphic evolution of convergent margins.