Provenance analysis of the Mugrosa Formation (La Fortuna section), Middle Magdalena Valley Basin (MMVB), Colombia

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PREFACE

This study called: Provenance and diagenetic analysis of the Mugrosa Formation (La Fortuna section), Middle Magdalena Valley Basin (MMVB), Colombia, is based on the colecte samples from the stratigraphic column done by Tania Sarith Palmera (PhD candidate). The results are part of the production of the Regional Geology and geochemistry research seedbed, that belongs to the Environmental Geology Research group. Our research is presented as a manuscript to be submitted to the Geology Bulletin – UIS, and it is supported by several Appendix: GIS database; petrographical and heavy mineral description.

The general scientific statement is based on the following question and hypothesis: What is the origin of the sediments of the Mugrosa Formation in the Fortuna sector?. Here, we propose that the source material of the Mugrosa Formation comes from the Central and Eastern Cordillera with a continental affinity related to orogen recycled type, deposited in a meandering channels and floodplains environment. To clarify this hypothesis, we propose as main objective: To determine the sediment provenance of the Mugrosa Formation (La Fortuna Sector) in the MMVB. Through the following specific objectives: (1) To compile a geodatabase for the MMVB. (2) To analyze the heavy minerals of selected samples along the La Fortuna section. (3) To perform the petrographic analysis of sandstones along the La Fortuna section. (4) To integrate the above-mentioned analysis with the available geological information in the MMVB to highlight the sediments source of the Mugrosa Formation in the La Fortuna section.

We want to give an infinite thanks to our advisor professor María Isabel Marín Cerón and our co-advisor Tania Sarith Palmera (PhD candidate), for their attentive guidance and support provided during the realization of this project. We, want also to thank our parents for having always been an unconditional support, not only during the realization of the project, but throughout our entire university life.

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ABSTRACT

The present work integrates petrographic studies (textural and compositional), and analysis of heavy minerals in order to contribute to the origin of the Mugrosa Formation in the Fortuna sector, which is located in the Middle Magdalena Valley basin. The compositional results of eight thin sections show high level of maturity, evidenced by the high percentage of quartz. The textural analysis shows grain sizes predominantly medium to fine-sand, and sub-rounded clasts, confirming the results from compositional analysis. The lithic fragments are predominantly volcanic and sedimentary; most of them are not well preserved. The analysis of heavy minerals showed predominance of ultra-stable mineral species (zircon, tourmaline, and rutile), and rounded zircons; on the other hand, the presence of muscovite and hornblende suggests different possible sources for these rocks. According to our results, we propose a main sediment source from the Eastern Cordillera due to reworking of underlying sedimentary formations, the presence of minerals such as hornblende and muscovite may suggest that the Cordillera Central (in a lesser extent) has also contributed as a source of the Mugrosa Formation.

RESUMEN

El presente estudio integra estudios petrográficos, texturales y análisis de minerales densos con el fin de realizar un aporte a la proveniencia de la Formación Mugrosa en el sector Fortuna, la cual se encuentra ubicada en la cuenca del Valle Medio del Magdalena. Los resultados composicionales de las 8 secciones delgadas analizadas, muestran que en general las rocas de la formación Mugrosa presentan un alto grado de madurez, evidenciado por los altos niveles de cuarzo presentados, lo cual a su vez se confirma con los análisis texturales, que exhiben tamaños predominantes entre arena media-fina y clastos sub-redondeados. Los líticos son predominantemente volcánicos y sedimentarios, y se encuentran bastante deteriorados en su mayoría. El análisis de minerales densos, arrojara una predominancia de especies minerales ultra estables (zircón, turmalina, y rutilo), lo que, junto a la forma

redondeada que presentan gran parte de los zircones evidencia una vez más la madurez de las rocas estudiadas; por otro lado, la presencia de moscovita y hornblenda abre la puerta a múltiples posibles fuentes para estas rocas. Teniendo en cuenta los resultados obtenidos en los análisis realizados y la información recolectada de otros autores, se propone que gran parte de los sedimentos provienen del retrabajamiento de formaciones sedimentarias subyacente y de la Cordillera Oriental; la presencia de minerales como la hornblenda y la moscovita por otro lado, invitan a pensar que la Cordillera Central, aunque en menor medida, también ha sido fuente de los sedimentos que conformaron la Formación Mugrosa.

Keywords:

Heavy minerals, Sandstones petrography, Paragenesis of sandstones, carbonate cements, MMVB

Authorship statement

All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript. Furthermore, each author certifies that this material or similar material has not been and will not be submitted to or published in any other publication before its appearance in the Boletín Geológico- UIS.

1. INTRODUCTION

Provenance analysis incorporating heavy mineral and sandstone petrography is an important technique to understand unroofing histories of individual thrust sheets; extensional fault blocks, estimates of fault displacement; orogen-scale exhumation records; terrane/plate reconstructions, and continent-scale dispersal patterns (Nie et al, 2012 and reference there in).

In South America, the North Andean Blocks are in an important orogenic belt to understand the Andean orogenesis along the late Cretaceous to the Cenozoic. In addition, the Andes Cordillera in Colombia is divided into three branches: the Western Cordillera (composed of Late Cretaceous–Cenozoic igneous rocks principally of oceanic affinity); the Central Cordillera (formed by pre-Mesozoic, low- to high-grade metamorphic basement of mixed continental and oceanic origin, intruded by numerous Mesozoic–Cenozoic plutons of the Andean magmatic arcs); and the Eastern Cordillera (built-up by crystalline continental basement of Proterozoic to early Paleozoic age), covered mostly by Paleozoic–Mesozoic strata, related to the sin-rift sedimentation, marine transgression and regression (e.g. Lisama Formation see Mojica and Franco 1990). The Magdalena Valley Basin is between the Eastern and Central Cordilleras, it is one of the best studied areas in Colombia due to its economic importance (e.g. significant accumulations of hydrocarbons see Mojica and Franco 1990; Sarmiento 2009). From South to North, it has been sub-divided into three sub-basins: Lower, Middle and Upper Magdalena Valley.

The focus of this study is the Middle Magdalena Valley basin (MMVB), it is a rift related and/or retroarc (?) sedimentary basin inverted to a foreland basin during the Cenozoic (Daly 1989). Previous studies have established the MMVB as a multi-phase successor basin whose history includes Jurassic–Early Cretaceous rifting (Sarmiento-Rojas 2001), Late Cretaceous thermal subsidence, and latest Cretaceous–Eocene incorporation into a regionally extensive foreland basin that was partitioned during Cenozoic Andean shortening, crustal thickening, and flexural subsidence (Nivia 1987; Gómez 2001). The persistence of Mesozoic–Cenozoic sediment accumulation in the MMVB makes the location a unique sedimentary record of long- term construction of the northern Andes (Sarmiento 2011).

Moreover, the MMVB has a well-known petroleum system that contains important Cretaceous source rocks formations (e.g. Rosablanca, Paja, Tablazo and La Luna formations), deposited in a marine environment (Rangel et al. 2000). The reservoir formations, where deposited during the Cenozoic (e.g. the Lisama, Mugrosa and Real Formations), in a predominant continental environment (e.g. Caballero et al., 2010 and Barrero et al., 2007). Integrated provenance techniques applied to the MMVB such as U–Pb ages, heavy minerals, Nd isotopes, and sandstone compositions (Nie et al., 2012),

stablished that the uppermost Cretaceous to Neogene fill of the MMVB recorded a series of shifts in its source rocks, from (1) exclusively cratonic to (2) magmatic arc, then (3) combined arc and uplifted continental block, and finally (4) retroarc fold–thrust belt. The above-mentioned study and other works (e.g. Caballero et al, 2010) were done in a regional scale, thus more specific studies are needed for each sedimentary formation along the basin, to reduce the uncertainties related to sediment recycling, non-unique source regions, source heterogeneity, and climate conditions. In this report, a provenance analysis of the Mugrosa Formation is performed using heavy minerals, sandstone petrography and analysis of a stratigraphic section of the La Fortuna sector.

The term "Mugrosa Formation" was the first used to refer to a group of sedimentary rocks that are found between the Los Chorros fossil horizon and the Mugrosa fossil horizon, which is located at the top of the formation (Morales, 1958). The lower part of the formation is composed of rarely pebbly fine-to-medium-grained sandstones with dark blue and brown opaque shale interbeds; in the intermediate parts massive and mottled shale increases and is occasionally interrupted by thin layers of fine-grained sandstone; it also contains a fossiliferous horizon at the top (Morales, 1958 and Ward et al., 1973). The Mugrosa Formation has been assigned an Oligocene age and the deposition environment has been related to meandering channels and floodplains (Caballero et al., 2010 and Gómez et al., 2005). The upper part consists of grayish-green sandstones, gray mudstones and layers of conglomerate sandstones, interbedded with shales and mudstones and at its top it has a shale package with abundant bioturbation (Ortiz, 2001; in Acuña and Cuadros, 2015).

Taking into account the above-mentioned facts, our main hypothesis is that the source material of the Mugrosa Formation at La Fortuna Sector comes mainly from the Eastern Cordillera, related to a recycled orogen of continental affinity, deposited in meandering channels and floodplains. In this study we carried out the provenance analysis of the Mugrosa Formation, using a multi-tool approach: (1) Database configuration and analysis (2) Heavy minerals analysis, (3) sandstone petrography and diagenesis (4) Data integration to the light of the provenance analysis and diagenesis.

2. GEOTECTONIC SETTING

The MMVB is the result of the subduction process of the Nazca plate during the Triassic-Jurassic, the rifting process and volcanism associated with it, was responsible for the uplift of the Central Cordillera, with the consequent formation of a back-arc where deposited continental and volcano-clastic rocks (Rángel et al., 2000). Later at the beginning of the Cretaceous a general transgression took place until the beginning of the Cenozoic (Mojica and Franco, 1990), during this period La Luna Formation and its correlative units were deposited (Rangel et al., 2000). Marine regression allowed the deposition of transition sequences marked by the deposition of the Lisama Formation (Fabre, 1983). Finally, during

the Cenozoic, the Eastern Cordillera emerged, which was responsible for the development of a complete continental sequence. (Rangel et al., 2000). Currently the MMVB is an intra-cordilleran basin (Pérez and Valencia, 1977), which borders the Ibagué Fault to the south and, the inferred Espiritu Santo Fault to the north, separating it from the Upper Valley (Sarmiento et al., 2015). The Nuevo Mundo Syncline (NMS) is a north-south oriented structure that is located to the northeast of the MMBV and involves large part of the sedimentary succession in the basin (Figure 2). The evolution of the NMS is closely related to the deformation of the Eastern Cordillera and the La Salina fault propagation by compressional stresses since the Paleocene (Caballero et al., 2010). The NMS shows an excellent exposure of Cretaceous and Cenozoic rocks; hence it is the location of most of the type sections of this basin (Caballero et al., 2010).

The MMVB is located between the Eastern and Central Cordilleras (Figure 1) limited to the southeast by the Bituima and La Salina fault systems (BSFS), to the south by the Piedras-Girardot fold belt, to the north by the Espíritu Santo fault system and to the northeast with the Bucaramanga-Santa Marta fault system (Lozano y Zamora, 2014). The MMVB is itself an asymmetric tectonic depression with two well differentiated margins; In the west, a passive edge is observed, largely deposited on materials from the Central Cordillera (Taborda 1965 in Mojica and Franco, 1990); towards the Eastern Cordillera, the deformation increases due to a compressional margin (Martínez et al., 1988 in Mojica and Franco, 1990).

The Middle Magdalena Valley Basin, has been affected by both distensive and compressive tectonic events, these being generated by the movements and interaction between the Nazca, Caribbean and South American plates. During the basin distensive phase several volcanic events (intermediate and basic intrusions and pyroclastic intercalations of the Jordán formation (Fabre, 1983)) took place. The distensive events have been prolonged, giving rise to interruptions between the Triassic and the Cretaceous according to Mojica and Franco (1990), however, Cooper et al. (1995) indicate that during this period the basin was still in a distensive margin. Thus, at the beginning of the basin a supracontinental graben is formed that allows the deposit of the continental sediments of the Jordán, Girón, Los Santos and Bocas Formations; then, at the beginning of the Cretaceous, caused by this distension margin, a marine transgression occurred the beginning of the Tertiary, where the Lisama Formation is subsequently deposited, which marks the regression event (Fabre, 1983). The compressional phase of the basin begins in the Maastrichtian - Paleocene, in this period the "Eastern Cordillera is defined as a segmented basin filled with synorogenic deposits and with small raised blocks" (Jiménez et al., 2016), later in the Middle Paleocene the inclination of the Central Cordillera favors the reactivation of the western edge of the basin, and then to the Eocene - Miocene, La Paz, Mugrosa, Colorado and Esmeralda Formations were deposited in continental environments (Jiménez et al., 2016).

2.1. Tectonostratigraphic evolution of the northern sector of the MMBV

Few works have been published about the northern MMVB. The igneous activity that occurs in the Mesozoic is the prelude to the opening and formation of the Colombian Cretaceous Basin (which includes the MMVB). The Cretaceous mega-sequence of the MMVB accumulates in the northern sector of a broad graben with a general NNE-SSW orientation (Sarmiento-Rojas et al. 2006). By the end of the Cretaceous the Central Cordillera emerges above sea level, closing the developed sub-basins, related to a barrier islands, coastal lagoons, swamps and finally, in the Paleocene, the development of alluvial plains systems (Sarmiento, 1994).

The final episode of exhumation of the Central Cordillera occurred in the Paleogene (Horton et al. 2010, Nie et al. 2012), with the consequent tilting of the Serranía de San Lucas, leads to the end of the Cretaceous basin and the transformation into a foreland basin. Two episodes have been identified: the first generating micro-basins that fill in as the deformation advances to the east (Sarmiento 1994, Guerrero & Sarmiento, 1996) and the second related to the formation of narrow folds towards the eastern edge associated with the uplift and erosion processes that generated a regional unconformity (Sarmiento et. al. 2015).

The MMVB-unconformity is one of the most important tectonic and stratigraphic limits, where the pre-Eocene rocks are deformed and truncated, extended from the MMVB to the Eastern Cordillera (e.g. Gómez et al. 2003, 2005 a and b, Bayona et al. 2008; Nie et al. 2012). Hereafter, thick assemblages of sedimentary rocks (conglomerates, sandstones and mudstones) are deposited and represented by the La Paz, and Esmeralda, Colorado and Mugrosa Formations in environments ranging from alluvial fans at the base, to river systems, floodplains and meandering rivers (during the late Eocene to early Miocene, Moreno et al. 2011).

The development of Middle Miocene unconformity is related to the Panama Chocó Block knocking (Duque-Caro, 1990). The Bucaramanga Fault generates the exhumation of the Santander massif, generating the erosion of the Cretaceous and Paleogene sequences and the exposure of the basement rocks (Sarmiento et. al. 2015). Then, the north VMM developed between the foothills of the Massif and the volcanic rocks of the Cordillera Central (The Royal Group, Gómez et al. 2005 b; Caballero et al. 2010).

3. CONCEPTUAL FRAMEWORK AND METHODS

Provenance analysis, "includes all the research that may help to reconstruct the lithospheric history of the earth" (Basu, 2003). Regarding sedimentary petrology, this term has been used to identify the related-factors for sediment production, with specific reference to the composition of the source rocks and climatic conditions (Weltje, 2004). However, inferring the origin of the sediment from the final product is not easy because the detrital spectrum evolves as the sediment is transported from the source rock to the basin (Weltje, 2004). Thus, provenance studies are summarized into two fundamental ideas: the concept of sediment-petrological province or petrofacies and the relationship between the composition of the sandstones and the tectonic environment.

Sedimentary provenance studies began in the 19th century with the microscopic investigation of accessory (dense) minerals in recent sands. Thurach (1884) was the first to accomplish this type of study and later Retgers (1895) was the first to make explicit suggestions on the use of characteristic minerals to determine paleogeographic characteristics. Fleet (1926) introduces the method of counting grains to improve the estimation of relative mineral frequencies. The petrographic analysis of the main minerals that make up sandstone would not have been possible without the invention of thin section petrography by Sorby (1880), who also carried out a detailed investigation of the different varieties of quartz. On the other hand, Judd (1886) recognized, for the first time, the influence that climate had on the preservation of feldspars and these two studies, together with Mackie (1899) that delves further into these two issues, were the which laid the basis for the descriptive petrography in thin section. Later, Krynine (1940) inspired by the ideas of his professor M.S Shvesov in 1920, strongly defended the importance of tectonic control over the compositional and structural properties of sandstones. Already Chayes (1949) with the introduction of the first device to count points, opens the way to the measurement of the modal composition from thin sections. Finally, Dickinson and Valloni (1980), pointed out that the modal composition of sandstones is largely controlled by plate tectonics.

Thoulet (1913) was one of the first to highlight that the complexity of the heavy mineral assemblages found in different rocks seemed to decrease with the increase in their geological age; later Pettijhon (1941) considers that the absence of many heavy minerals in the oldest sedimentary sequences is due to the elimination of unstable minerals by dissolution and later, this same author in 1973 proposed the following classification: Very unstable minerals (olivine); unstable minerals (hornblende, actinolite, diopside, augite, hypersthene and andalusite); moderately stable minerals (Epidote, kyatine, garnet (rich in iron), sillimanite, sphene and zoisite); stable minerals (apatite, garnet (poor in iron), staurolite, monazite; and ultra-stable minerals (rutile, zircon and tourmaline)

This work integrates geo-database conformation of the MMVB with sandstones petrography and heavy minerals analysis, along the La Fortuna stratigraphic column (from Tania Palmera, a PhD student at EAFIT University). Preparation and analysis were done at the Thermochronology Laboratory (EAFIT University).

3.1. Database conformation and reference stratigraphic sections

The ArcMap 10.3 program was used to create the geological database (Annex 1); the cartography base (1:500.000) was taken from the Agustín Codazzi Geographic Institute (IGAC, geoportal.igac.gov.co) and hydrocarbon sedimentary basins of Colombia map from the National Agency of Hydrocarbons (ANH, anh.gov.co) (Figure 3). Then polygons of each study were geolocated (including outcrops, stratigraphic columns, seismic lines, wells, among others). Several attributes were added to each polygon (e.g. title, author, year, abstract, keywords and figures). Finally, using the "Create Attachments" tool, the corresponding main picture were attached to each paper and can be accessed by using the "Identify" tool and clicking on the clip icon ("Open Attachment Manager") that appears above the list of attributes. The final database, permitted us to understand the state of the art at the study area, as will be summarized on the results.

3.2. Heavy minerals analysis

To prepare the six selected samples (TPH 1-3, TPH 1-4, TPH 1-5, TPH 1-7, TPH 1-9), the rock was fragmented to get 300 g of 400 μm grain size, followed by sieving up to 200 mesh to get 100 gr for mineral separation. Finally, the grains were mounted using epoxy coating solution (Melmount® refractive index $\eta x = 1.539$). The assembly of heavy minerals was counted (350 grains) using a Zeiss petrographic microscope (Primostar model), to identify the stable and ultra-stable heavy mineral species following the Mange and Maurer (1992) method.

3.3. Sandstone petrography

For sandstone petrography, 8 thin sections extracted from the La Fortuna section were used. For each section a count of 300 points was made using a Zeiss petrographic microscope, Primostar model, in order to perform a modal, textural and compositional analysis (Ingersoll et al., 1984; Folk and Ward, 1957). The compositional analysis of each thin section consists mainly of: quartz (monocrystalline and polycrystalline); feldspar (potassium and plagioclase); Volcanic, metamorphic or sedimentary lithic fragments, characteristics such as porosity, cement and matrix were also taken into account, as well as accessory minerals. On the other hand, a textural count was also made in which the rocks were classified texturally according to Folk (1974), in addition the phi factor is calculated

using the diameter in mm of the clasts (-log2 * Particle diameter in mm) and with the phi factor is obtained from the granulometric mean and the selection or classification (standard deviation) (Folk y Ward, 1957).

4. RESULTS

4.1. Database conformation

The database was exported in ArcGIS Map Package (.mpk) format and is presented as a file attached to this text (Annex 1 and 2; Figure 3). A total of 17 studies are shown in the database. The spatial distribution of the studies varies largely along the MMVB, to the north (88%) and to the south (12%). In a close up, 53% of the studies have been focused along the NMS. In general, most of the papers in the database are related to the stratigraphy and petrography. The Figure 3, show a distribution of petrography-related papers (23 %); lithostratigraphic (5 %); geochemistry (11 %); paleocurrent (11 %), geophysical and thermochronological studies (11 %) and structural geology (5 %); multiple methods (34 %). Using the available dataset, indicate a variation of the sedimentary facies from the bottom to the top of the Mugrosa Formation, dividing the Formation into the lower and upper member.

4.1.1 Lower Mugrosa Formation

The general deposition environment for the Mugrosa formation is meandering fluvial channels and floodplains (Caballero et al., 2010). The Lower Mugrosa formation facies vary from bottom to top starting with scouring of channels followed by migration of lower-flow regime sand dunes along the bottom. Flood basin deposits and Lower-flow regime sedimentation in fluvial cannels and crevasse splays at the top of the sequence (Gómez et al., 2005; Quintero et al., 2010).

Paleocurrents are directed to the east and southeast and sandstone petrography petrofacies are classified as sublitoarenite (Caballero et al., 2010; Sánchez et al., 2012). The available thermochronological data (AFT: apatite fission tracks and ApHe: (U-Th) / He in Apatite, Sánchez et al 2012), indicates burial ages of 27.8 +/- 4.1 Ma (AFT) and 4.9 to 9.9 Ma for ApHe. Zircon detrital ages (U/Pb) are consistent with 200 and 400 Ma peaks (Nie et al., 2012; Caballero et al., 2013a; Caballero et al., 2013b).

4.1.2 Upper Mugrosa Formation

Sedimentary facies of the Upper Mugrosa formation vary from bottom to top starting with con Scouring of channels followed by migration of lower-flow regime sand dunes ; Fluvial point-bar deposits; over bank deposits; bioturbated crevasse splay deposits; Lower-flow

regime sedimentation in fluvial channels and Flood basin deposits at the top of the sequence (Gomez et al., 2005; Quintero et al., 2010).

The Mugrosa Formation has been related to a meandering and braided river with facies of bar deposits, crevasse splay, channels and floodplain (Gomez et al., 2005). Madero et al. (2010) in the Llanito field, identify sedimentary facies related to floodplains, channel sandstones and crevasse splay. Likewise, in the Casabe field similar facies associations were found (Caballero et al., 2010) assigning an environment of meandering fluvial channels and flood plains to the Mugrosa formation (Figure 3).

Gomez et al., 2005 classify the sandstones of the Mugrosa Formation as sub-arkose to arcosa-lithic (). Caballero et al. (2010) classify the sandstones of the Mugrosa formation as sublitoarenite and because in the underlying formation (Esmeralda formation) the classification is arkose to arkose-lithic and also supported by the change in the direction of paleocurrent, establish a change of provenance for the rocks of the Mugrosa Formation, the Eastern Cordillera. In general, a low proportion of lithic fragments and a strong presence of quartz have been found in the sandstones of the Mugrosa Formation, the lithic fragments that appear are mostly sedimentary (Nie et al., 2012; Caballero et al., 2013a).

Paleocurrents are directed to the west, and northwest (Gómez et al., 2005); and the AFT ages (13.4 + -5.6 Ma) and peaks of 185 Ma to 440 Ma (U/Pb) (Sánchez et al., 2012; Nie et al., 2012., Caballero et al., 2013a; Caballero et al., 2013b). Variations in the records of Paleocurrents, has been pointed out by Rubiano (1998) and Gómez et al. (1999); they mention that the paleocurrents flow with an easterly direction in the Oligocene , related to a source area from the west (e.g. Central Cordillera). Gómez et al. (2005) stated that the paleocurrents are mainly south-east, this is consistent with a strong erosion of the Central Cordillera and the sinking generated by the Eastern Cordillera in the Oligocene. Caballero et al. (2010) find an important change in the direction of paleocurrents since in the formations of the Eocene (Esmeraldas and La Paz Formations) the direction of the flow of paleocurrents is mainly towards the east, while in the Mugrosa Formation (Oligocene) the direction of the paleocurrent flow is to the west. Other more recent authors establish the direction of Paleocurrents in the Mugrosa Formation to the west (Moreno et al., 2012; Caballero et al., 2013a).

Therefore, from the database analysis we proposed La Fortuna, as an important sector to be analyzed, to understand the Lower member of the Mugrosa Formation, as a complementary analysis to current PhD study: E*ffects of the hydrocarbons interaction on the diagenesis in reservoirs of silicyclastic sands. Example Mugrosa Formation, VMM Basin, Colombia (Palmera, Tania, EAFIT).*

4.2. Heavy minerals analysis

The heavy minerals are all those with a density greater than 2.89 g / cm3 and are common accessory minerals in sedimentary rocks, which are useful to identify the origin and source of sediments (Mange and Maurer, 1992). For the Mugrosa Formation along the La Fortuna section, the relative amount of heavy minerals was normalized and presented in percentages to facilitate the visualization of the proportions as shown at Figure 4 (Annex 3), in addition, the proportions of these minerals are shown in the stratigraphic column (Figure 6a).

Stratigraphically, the deepest sample (TPH 1-5) has six different species of heavy minerals: zircon (61%), opaque minerals (21%), calcite (12%), tourmaline and garnet, opaque, calcite, rutile and tourmaline yield 5% of the sample. The zircons are subhedral, in some cases they retain their original shape, but most have slightly rounded edges; they are generally colorless to yellowish or brown colors. Opaque minerals and calcite are amorphous; rutile occurs in elongated forms and with a yellowish-brown color; tourmaline has green colors and a square shape while garnet is amorphous and colorless (Figure 15).

Sample TPH 1-4 is higher in the sequence and has the same minerals except for calcite. Zircon remains by far the most abundant mineral at 70%, followed by opaque minerals at 27%; the percentage of tourmaline, rutile and garnet decreased considerably, occupying only the remaining 3%. The shape of the minerals is quite similar to the TPH 1-5 sample, the only difference is that the zircons retain their shape a little better (Figure 16).

The TPH 1-3 sample is the one that continues in the sequence, it presents 16% hornblende, being the only sample in the sequence to contain this mineral; in this case, opaque minerals are the most abundant (48%), followed by zircon (23%); calcite (9%) appears again in this sample and tourmaline increases compared to the previous samples, occupying 3%. Opaque minerals are amorphous; zircons are colorless, subhedral, and elongated in shape; Hornblende is brown in color, elongated in shape and has a stringy habit; tourmaline is dark green and square in shape (Figure 17).

The sample TPH 1-7 is quite similar to the sample TPH 1-5, it has zircon (61%), opaque (28%), calcite (5%); tourmaline (4%) is more frequent than in the other samples; rutile and garnet appear again with 1% and 0.6% respectively. The shape and color of the minerals is quite similar to that of the TPH 1-4 and TPH 1-5 samples; tourmaline appears in dark green colors and also in green-brown tones (Figure 18).

Compared to the other samples, TPH 1-9 is the one with the lowest amount of zircon (19%); the most abundant mineral is calcite (54%) followed by opaque (21%), tourmaline and rutile also appear (Adding 2% between the two minerals); and the high garnet content

present in this sample (4%) is noteworthy. Zircon crystals are colorless and subhedrals but in some cases they preserve quite well their shape (Figure 19).

Using the ZTR index, there is a relation of the percentages of zircon, tourmaline and rutile with the total translucent heavy minerals at each sample, allowing the mineralogical maturity to be calculated, according to the following equation: 100 * (zircon + tourmaline + rutile) / total transparent heavy minerals) (Zhu et al., 2017). Thus, the closer values to 100 indicates a greater maturity (Hubert, 1962; Zhu et al., 2017). Here the samples from the bottom of the sequence (TPH 1-4, TPH 1-5, TPH 1-7) presented high ZTR values (99, 82 and 92 respectively); while the samples TPH 1-9 and TPH 1-3 show lower values (27 and 50 respectively) (Figure 6a).

4.3. Sandstone petrography

4.3.1 Size and grain shapes

Grain size variation have been found from the bottom to the top of the La Fortuna section (Annex 4). From very coarse to coarse sandstone (TPH 1-6) to medium to fine sandstone (TPH 1-4); an increase of size grain is shown at the middle of the section (TPH 1-3, fig. 5a, similar to that reported at the bottom of the sequence; TPH 1-6), a noticeable grain size reduction to fine sand (TPH 1-9), followed by grain size increases to coarse and medium sandstones (TPH-13) have been seen at the top of the sequence.

Medium selection, sub-rounded grains with high sphericity, predominantly concave or point contacts and predominantly secondary porosity (20%) (TPH 1-6). High selection with rounded to sub-rounded grains and high sphericity that present predominantly concave or point contacts and porosity (15%) (TPH 1-4); medium-low selection and sub-angular clasts with medium-low sphericity and mainly secondary porosity (11%). A reduction in porosity (5% and 1%) have been seen due to the higher percentage of matrix (TPH 1-7 and TPH 1-8-2) and the presence of Ms at TPH 1-8-2; same porosity pattern (5% and 2%) is also shown at TPH 1-9 to TPH 1-10 with and increment to 16% (TPH 1-13).

4.3.2 Composition

Following the above-mentioned description from bottom to the top, there is Quartz = Qz (43.3%, with 3.3% polycrystalline and 2.2% metamorphic); Feldspar = Fd (14%); lithic fragments: Sedimentary = Ls (6%) + Volcanic = Lv (2%). Two types of cement: kaolinite (5%) and undifferentiated clays (2%) (TPH 1-6; Figure 8).

A progressive increase of Qz (52.3-55) with variation in metamorphic-related quartz from 4.35 to 3.3%, Fd (3.3 to 5.7%) and lithics from 5.3-3-3% (Ls) and 7.3%-0% (Lv) and 0-2%

(Metamorphic = Lm) were noticed (from TPH 1-3 to TPH 1-4) Two types of cement are observed, undifferentiated clays (9.7%) and calcareous (5.7%), siderite (17%) appear only at TPH 1-4. Mo (organic material) filling fractures (1% at TPH 1-4, Figure 7);

The TPH 1-7 and TPH 1-8-2 samples are very similar to each other. Qz content varies from 39-40% (4% -6% metamorphic), Fd (7%) and lithics (11% - 9%) respectively. There is Lm 2% (TPH 1-7) and total absence at TPH 1-8-2. There is calcareous cement (25%), kaolinite and undifferentiated clays (3% at TPH 1-8-2 which are absent in the TPH 1-7). The Ms is clearly deformed (TPH 1-8; Figure 11) compared to TPH 1-7. The Mo (2% to 6%), although there is a particularity highly concentrated in specific areas of the sample (TPH 1-7; Figure 9 and 10).

The fine sand sample (TPH 1-9; Figure 12) has a sub-rounded shape with high sphericity and the concave contacts. Compositionally the Qz increase (45%) with 4% of metamorphic- Qz; Fd (4%) decreases with respect to the previous samples while the percentage of lithics remains constant with 11% (Ls = 4.7 % and Lv = 7%). The predominance of calcareous cement continues (14%), undifferentiated clays (4%) and kaolinite (2%) are also observed in a smaller quantity. The presence of Ms (Muscovite) (7%) and Mo filling fractures continues to increase up to 7%.

The most particular sample (TPH 1-10) plots on the border of sandstone to mudstone rock (Figure 13). The Ms decreases sharply, while the percentage of Mo increase up to (8%). The Fd (7%) and the proportion of lithics is higher (12%) with a clear predominance of Ls (8%). Compositionally, there is a Qz (47%) related to Lv and Ls origin (8% and 4.7%), the absence of Lm continues. The percentage of Fd (4.7%) is the lowest in the section; Mo decrease up to 4% and Ms reappears (2.7%). Finally, although calcareous cement continues to dominate (7.3%), its proportion decreases with respect to undifferentiated clays (5%).

4.3.3 Petrofacies

Two petrofacies (sublitoarenite and feldspathic litho-arenites) were observed, according to the QFL Folk (1974) and Dott (1964) diagrams and in the QFL diagram of Dickinson (1979) (Figure 4). The most abundant clast is quartz (43%), followed by lithic fragments (%) and feldspars (%) respectively (Figure 5 and 6). The sublithoarenite petrofacies at the bottom of the La Fortuna section (TPH-3 and TPH-4) and the felsepatic lithoarenite petrofacies (rest of the samples, plotted in the recycled-orogen field of the Dickinson's diagram (1979), which agrees with the quartzose recycled field (Dickinson, 1985).

In general, the analyzed samples present different variety of cements (e.g. undifferentiated clay, calcite, siderite and kaolinite). The dominant porosity is secondary, either due to dissolution or fractures. The dominant clast-size is sand, rarely gravel or mud. Texturally,

all the samples fall into the classification of arenite (medium) (Folk, 1974) and they are moderately well classified, with sub-rounded grains and with low to high sphericity with mostly concave or point contacts.

5. DISCUSSION

Source area during the deposition of the Mugrosa Fm. may be inferred according to the above-mentioned petrographic characteristics and heavy minerals analysis (e.g. Weltje, 2004). Two petrofacies were found at the La Fortuna section from bottom to the top (Figures 5a and 6). The feldspathic litho-arenites, with a mean modal composition of Qz (68.59%), Fd (12.68%) and FR (18.73%); sub-angular clasts, low sphericity which increases as the grain size decreases. The sub-lithoarenite petrofacies, with an average modal composition of Qz (78%), Fd (6.5%) and FR (15.5%) and sub-rounded to rounded clasts with a medium sphericity.

In general, the Eocene Esmeraldas Formation, which underlies the Mugrosa Formation up to the most recent formations, have been associated with Eastern Cordillera sources. Paleocurrent studies indicate that flow directions since the Miocene have trends towards the west relate to an east-source (Gómez et al 2005, Caballero et al 2010, Moreno et al., 2010); however, other studies show variations in paleocurrent towards the north and even towards the east (Rubiano, 1998, Caballero et al., 2016). The Zircon U / Pb sediments dating, show mixed ages at the Mugrosa Formation (e.g. Precambrian (1800-900 Ma); Paleozoic (300-250 Ma), Jurassic (200-150 Ma)); the oldest ages associated with cratons or reworked sediments of the Guyana shield and the Jurassic magmatic arcs from the Central Cordillera (e.g. Nie et al., 2012, Moreno et al., 2010, Sanchez et al., 2012; Caballero et al., 2011; Caballero et al. al., 2013a; Caballero et al., 2013b; Horton et al., 2015) and the Santander Massif (REF).

The high quartz content is reflecting a high compositional maturity, this may be due to a distant sediment source or a reworking of pre-existing sedimentary rocks, where quartz, as the most resistant abundant component, is preserved much better than feldspar or lithic fragments (Prothero and Schwab, 2014); additionally, the sporadic presence of chert clast, together with the size of the clasts and their sub-angular to sub-rounded shape, indicates that this clast could come from the reworking of chert and quartz from previous formations (La Paz Formation or granitic and rhyolitic rocks of the Eastern Cordillera as indicated by Caballero et al., 2010) as shown by the figures 5b and 5c. The lithic fragments are mostly volcanic and sedimentary with few occurrences of metamorphic fragments. The volcanic lithic fragments in the MMVB have been associated mainly with a Central Cordillera related source. The metamorphic lithic fragments from the Guyana shield, the Santander Massif or the Central Cordillera, while the sedimentary lithics are constantly associated

with reworking of sediments that were deposited in the basin since the Mesozoic and that, due to upon the uplift of the Eastern Cordillera (Eocene-Oligocene formations), they suffered weathering, erosion and were redeposited in the current intra-cordilleran basin (Moreno et al., 2010; Nie et al., 2012; Caballero et al., 2010).

Additionally, the presence of volcanic, sedimentary and metamorphic lithics observed in the studied samples indicates that the most appropriate source for the sediments of the Mugrosa Formation is the Eastern Cordillera, where the Mesozoic and Paleogene formations (e.g. Jordán, Girón and Lisama) could be the source of the sedimentary fragments, as previously stated by Caballero et al. (2010). The volcanic fragments could also come from reworking of underlying formations also reported at the Lisama and La Paz Formations (Nie et al. 2012). However, it cannot be ruled out the Central Cordillera as source area. Thus, complementary studies (e.g. zircon and apatite chemistry and thermochronogy; detailed paleocurrent studies and Anisotropy of magnetic susceptibility) may help in the future a higher resolution to the source area. Metamorphic lithics have many possible source areas such as the rocks of the Santander massif; the Guyana shield and/or the Central Cordillera basement.

The clasts good-selection, as well as a medium roundness and sphericity are consistent with a distant source and/or sediment reworking (Prothero and Schwab, 2014). The presence of muscovite is strongly related to the presence of organic matter and its deformation could be related to hydrocarbons migration through the pores and fissures, although a metamorphic origin cannot be totally discarded. Muscovite is a common mineral in low grade metamorphic rocks and its presence could be an indicator of a metapelite source in the Santander Massif (e.g. the Silgará Formation).

Heavy minerals, according to the classification by Pettijohn et al. (1973), were mostly composed of ultra-stable species (zircon, tourmaline and rutile), so the ZTR index was quite high (TPH 1-4, TPH 1-5, TPH 1-7). Higher ZTR values (TPH 1-9) may relate to the higher presence of carbonates and/or high compositional maturity. The strong presence of carbonates is closely related to the calcareous cements as have been described at the petrography. The presence of hornblende (a very common mineral in high-medium grade metamorphic, sample TPH 1-3) could be related to a Central or Eastern Cordilleras basement source. Finally, the rounded-shape zircons related to a remarkable dominance of ultra-stable minerals supports the distant source and/or reworking hypothesis.

6. CONCLUSIONS

With the data obtained and the bibliography studied, we consider that the most appropriate source for the samples studied is mainly the Eastern Cordillera. This is proposed based on:

- The most recent papers that study the Mugrosa Formation and the northern zone of the MMVB, indicate that the provenance of the Mugrosa Formation sediments is the Eastern Cordillera. The predominance of ultra-stable species in the heavy minerals (Zircon, Tourmaline and Rutile) indicates a high compositional maturity, which, together with the predominance of rounded crystals, is associated with a reworking of sedimentary formations such as those present in the Eastern Cordillera. The appearance of hornblende, although it does not contradict what was previously stated about the Eastern Cordillera, expands the possibilities of provenance since it can come from multiple sources (e.g. Guyana shield, the Eastern Cordillera or the Central Cordillera).

- The high quartz content (70% approximately), low percentage of matrix (generally less than 3%), the size of the crystals (medium to fine sand) and their shape (sub-angular to sub-rounded shape) are evidence of a high maturity, which is associated with a reworking of the underlying sedimentary formations. The sedimentary lithics are associated with the Eastern Cordillera, while the volcanic can have a multiple origin, since they can originate both by reworking of underlying formations from the Eastern Cordillera or directly from the Central Cordillera.

- Available low-temperature ApHe thermochronology data published by Sanchez et al. (2012), shows fully reset cooling ages, centered on 4.8 Ma. These ages possibly mark the initial event of exhumation in the MMVB, which caused important fracturing that allowed hydrocarbon seepage.

- Accumulation of hydrocarbons occurred in the MMVB within structural traps, generated by 36-25 Ma burial event (AFT) (Sanchez et al. 2012; Caballero et al. 2013b). However, they migrated along the (20-10 Ma) and escaped through the latest and most intense fracture porosity system recorded in the samples (10-4Ma) (Sanchez et al. 2012) (Figure 20). These factors promote hydrocarbon biodegradation and transformation. Their occurrence is a clear indicator of temperatures higher than 110°C in the basin.

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