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PETROFACIES AND DIAGENETIC PROCESSES OF LA VICTORIA FORMATION (EARLY MIOCENE), DINA OIL FIELD, UPPER MAGDALENA VALLEY BASIN, COLOMBIA.

PETROFACIES Y PROCESOS DIAGENÉTICOS DE LA FORMACIÓN LA VICTORIA (MIOCENO TEMPRANO), CAMPO PETROLERO DINA, CUENCA VALLE SUPERIOR DEL MAGDALENA, COLOMBIA

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ABSTRACT

The sandstones at the base of the Honda Group (La Victoria Formation - Early Miocene), in the Dina Field, Upper Magdalena Valley Basin (UMVB) – Colombia, which are present in the analyzed interval of the Dina Norte 27 and Dina Norte 37 wells, are composed of immature clastic rocks classified as Litharenites / Feldspathic Litharenites, due to the presence of volcanic fragments, feldspar / plagioclase and unstable minerals. They are texturally immature due to poor sorting and low roundness of the detritus. The following sequence of diagenetic processes is proposed: minor compaction; grain coating by illite / smectite detritical clay, dissolution of unstable minerals, zeolite (heulandite) precipitation, partial precipitation of non-ferroan calcite cement and finally chloritization of clays prior to hydrocarbon migration.

RESUMEN

Las areniscas de la base del Grupo Honda (Formación La Victoria-Mioceno Temprano), en el Campo Dina, Cuenca del Valle Superior del Magdalena (VSM) - Colombia, presentes en el intervalo analizado de los pozos Dina Norte 27 y Dina Norte 37, composicionalmente corresponden a rocas clásticas inmaduras clasificadas como Litoarenitas / Litoarenitas Feldespáticas, debido a la presencia de fragmentos líticos volcánicos, feldespatos / plagioclasas y minerales inestables. Son inmaduras texturalmente por la baja selección y redondez de los detritos. Se propone la siguiente secuencia de procesos diagenéticos: compactación; recubrimiento de granos con arcillas detríticas Illita/Esmectita, disolución de minerales inestables; precipitación de Caolinita, precipitación de Zeolita (var: Heulandita), precipitación a nivel local de Calcita no ferrosa, formación de pirita y finalmente se da una cloritización de arcillas previo a la migración de hidrocarburos.

KEYWORDS / PALABRAS CLAVE

Diagenesis | XRD | SEM | Petrofacies | Zeolite | Heulandite | Honda Group | La Victoria Formation.
Diagénesis | DRX | SEM | Petrofacies | Zeolita | Heulandita | Grupo Honda | Formación La Victoria.

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1 INTRODUCTION

Knowing the diagenetic history of a hydrocarbon reservoir rock is useful for the exploration of hydrocarbons since diagenesis plays an important role in the post-depositional modification of the porosity and the mineralogy of the rocks, causing a decrease in porosity as result of compaction and cementation or increase in porosity due to dissolution processes [1].

The Honda Group (Miocene) is constituted by La Victoria Formation (Early Miocene) to the base and the overlying Villavieja Formation (Late Miocene) [2]. Until 2016, this group has an accumulated oil production of 95.93 MMbl in Dina, El Espino, La Jagua, Nunda and Río Ceibas fields. The Dina Field, discovered in 1963, is the largest oil producing field in the area, with an accumulated production of 70.08 MMbs to 2016 [3].

The Dina field is located in the central part of the Upper Magdalena Valley Basin (UMVB), within the Neiva Sub-Basin between Central and Eastern Ridges, in the southern part of Colombia. In the Dina field, the base of the Honda Group (La Victoria, Formation) is the main hydrocarbon reservoir due to its sandy character, with porosities between 4.2 and 19.7% and permeabilities that vary between 113.3 and 765 millidarcy (md). This Formation produces oil of 16° API. Between 2011 and 2015, twenty-four (24) wells were drilled, including the Dina Norte 27 and Dina Norte 37 wells, which are the main object of this work [4].

This paper is focused on the integrated mineralogical characterization (Petrography, X-Ray Diffraction – XRD analysis and Scanning Electronic Microscopy - SEM) of core samples from Dina Norte 27 and Dina Norte 37 Wells (Dina Oil Field, Upper Magdalena Valley Basin). This integration allows to establish the main mineralogical characteristics (compositional and textural), which determine the petrofacies and the diagenetic processes that affected the rocks of La Victoria Formation (Honda Group).

The potential of a sandstone reservoir rock to produce hydrocarbons is closely related to its diagenetic history, which in turn depends on many variables, including the initial composition. La Victoria Formation is mainly constituted by volcanic lithic fragments, coming from the Saldaña Formation (Upper Jurassic) and from the intrusive rocks of the Ibague Batolite, exposed in the Miocene in the Central Cordillera [5],[6]. Those of sedimentary and metamorphic origin are associated with a source of sediment from the Eastern Cordillera and the Garzón Massif [7].

Achieving a better understanding of the diagenetic history of the La Victoria Formation allows us to identify mineralogical characteristics that can diminish or enhance the hydrocarbon accumulation / production potential. Additionally, the diagenetic history helps to understand the response of well logs at the Dina oil Field.

In general, the diagenetic studies focus on the analysis of thin sections, where the evidence of compaction, cementation and dissolution are analyzed through a petrographic study. Although petrography remains the mainstay of a classical diagenetic study, in this work the integration with X-Ray Diffraction analysis and Scanning Electron Microscopy (SEM) are excellent complements to further understand the physical and chemical changes that the rocks have undergone since their deposition.

2. THEORICAL FRAMEWORK

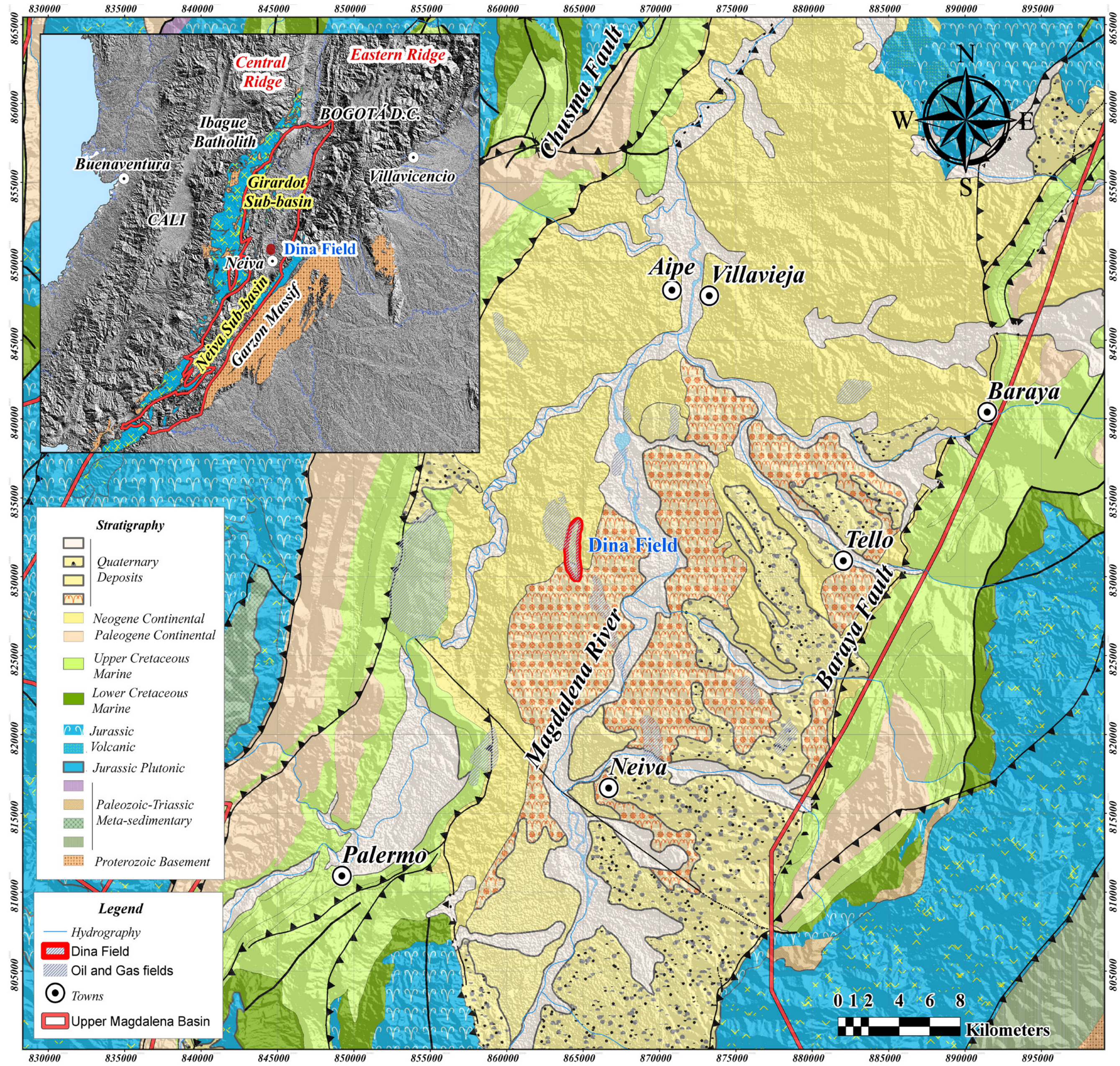
The Upper Magdalena Valley Basin (UMVB **Figure 1**) is one of the most studied Colombian regions, due to its scientific and economic significance. The earlier studies focused on the first oil field, which was discovered in 1951 (Ortega-Tetuán Oil Field) by Texas Petroleum Co. [8],[9]. Since then, several geological studies have been achieved in the area [10]-[14]. The UMVB has two sectors, the Neiva sub-basin located in the south and the Girardot sub-basin located in the north, separated by the Alto de Natagaima [11],[15],[16]. The basin has an area of about 26,200 km^2. It is limited on both sides by the elevations of the Precambrian to the Jurassic basement that defines the flanks of the Eastern and Central Cordillera [17]. **Figure 1** illustrates the location of the UMVB.

The basin corresponds geologically to a structurally active area. The deformation towards the area of the north Dina field is associated with four (4) main events: 1) A compressional period that took place at the end of the Cretaceous and at the beginning of the early Paleocene, in which the tectonic strain was reversed and the depositional patterns changed. 2) A period of erosion and no deposition during the Eocene. 3) The sedimentation of the Honda Group during Miocene. 4) An event associated with the reactivation of pre-existing failures occurred during the Neogene [18],[19].

STRATIGRAPHY

Hettner in 1892, was the first author to describe the outcrop located in the San Antonio Creek to the west of Honda city (in the department of Tolima, Colombia) as "Honda Sandstein". Stille (1907, 1938), introduced the name "Series de Honda" and Royo y Gómez in 1942, proposed the name "Formación Honda" for the outcrops located to the north of the village of Villavieja (Huila) and divided the formation into Honda Superior, and Honda Inferior [20].

Stirton [21], elevated the term Honda to the Group category. Wellman [22], included "Grupo Honda" in the Villavieja Formation and La Dorada Formation and makes a good description of the fragments of these formations, which contributes to the definition of the area of origin of the sediments. However, the evolution of diagenetic processes in the rocks studied was not detailed. Finally, Guerrero in [2] established that the Honda Group is comprised of La Victoria Formation to the base and the overlying Villavieja Formation.



Source: Base cartográfica - Servicio Geológico Colombiano SGC - 2015

Figure 1. Upper Magdalena Valley Basin (UMVB), location and boundaries. It is bounded to the east and west mainly by pre-cretaceous rocks of the Eastern Cordillera and Central Cordillera respectively, and by the Chusma and Baraya faults. Dina Oil Field is located 17 km Northwest of Neiva.

The Victoria Formation lies unconformably on the volcanites of the Prado Member of the Saldaña Formation. It is an essentially sandy unit, characterized by the presence of immature clastic rocks due to the volcanic lithics and unstable minerals present, while the overlaying Villavieja Formation consists of white to gray sandstone with some interlayered reddish brown to greenish gray claystones.

The Honda Group was deposited in a meandering fluvial environment, with alluvial channel, floodplains, crevasse splays and swamp lakes facies [23]. Buttler in [24] assigned a thickness of 4000 m to the Honda Formation; 1600 m to the lower part and 2400 m to the upper part. Afterwards, Van Houten [25] outlined a more conservative description with a thickness of approximately 3000m, which decreases towards the sub-basin of Neiva to 1000 - 2000 m [11,25]. Finally, the ANH [26] assigned a thickness of 3000 meters. La Victoria Formation features, complex geometry that gives the reservoir high horizontal and vertical variability. The generalized stratigraphic column of UMVB is shown in Figure 2.

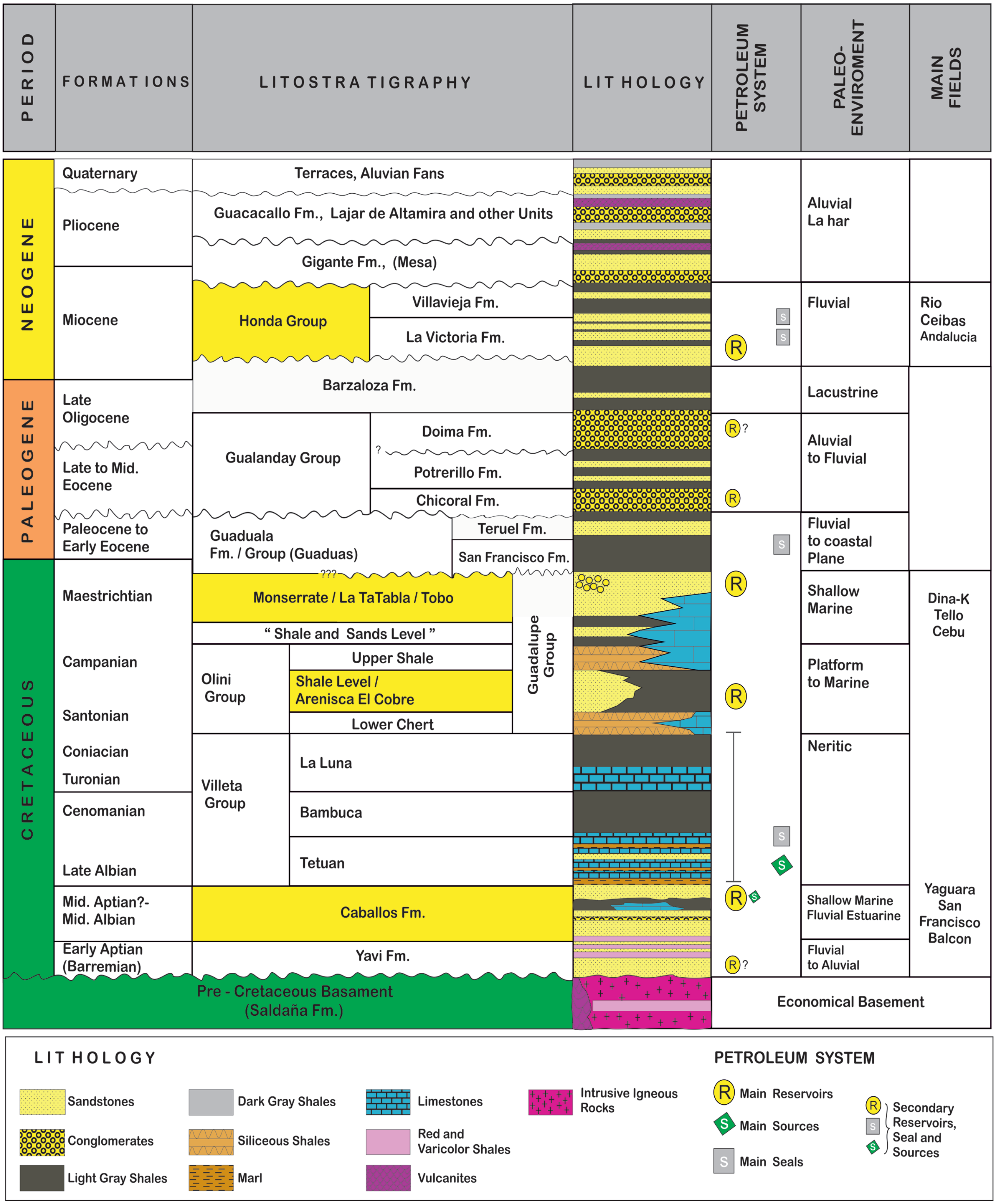


Figure 2. Stratigraphy of the Upper Magdalena Valley Basin. ANH, 2008.

3. EXPERIMENTAL DEVELOPMENT

The diagenetic processes of the Victoria Formation in the two wells (Dina Norte 27 and Dina Norte 37) are chronologically ordered following the stages set out by Worden and Burley, in [27]: Eogenesis, Mesogenesis and Telogenesis.

The integrated mineralogical characterization includes conventional petrography, XRD and SEM. The petrographic analysis was performed with a Carl Zeiss™ triocular microscope Axioskop-40 / Axioplan-2 model.

In order to observe the compositional and textural features, forty-two (42) thin sections were analyzed (22 for Dina Norte 37 and 20 for Dina Norte 27). They were impregnated with epoxy to augment sample cohesion and to prevent loss of material during the grinding procedure. A blue dye is added to the epoxy to highlight the pore spaces. The thin sections are stained for carbonates (Alizarin Red-S and potassium ferricyanide) and potassium feldspar (sodium cobaltinitrite), according to the methodology and technical procedure defined by Dikson [28] and Chayes [29]. The rock classification is established according to Folk [30]. For the petrographic analyses, the point counting method was used (300 points for composition and 200 for texture). Wentworth's scale [31] was used for grain size. In order to estimate the roundness of sedimentary particles, the comparatives images from Powers [32] were used; the sorting is calculated with the formula of approximate standard deviation of the distribution of grain size established by Folk) [30] in [1].

X-Ray Diffraction was performed with an Olympus™ XRD Portable Analyzer Terra-441 model, which uses CuKα1 radiation and a detector D8 Bruker™ CCD (Charge Coupled Device) with DaVinci geometry which also uses CuKα1 radiation and a linear detector Lynxeye. This technique was used to identify the minerals that have an organized internal structure such as clay minerals (philosilicates) and non-clay minerals, and made it possible to establish the mineralogical profile and mineral content in the evaluated intervals. The analysis was performed under two modes: clay fraction (particles with an effective diameter less than 2 µm) and Bulk rock. The final results were obtained using Diffrac Plus EVA software © version 13, 2007, Bruker AXS and the PDF-2 © crystallographic database (Dust Diffraction File) of the International Diffraction Data Center [33]. The SEM analysis was performed using a LEO1450VP™ microscope, which has two detectors, one for primary electrons and the other for secondary electrons. In addition to this, the microscope has an Oxford – Prime™ X-Ray detector in an energy dispersive system, which enables chemical elements relative concentration measurement in the rock. Based on these analyses a series of micrographs were obtained using different magnification in various sample areas in order to determined morphology, distribution, elemental composition of the minerals present and textural and microstructural features in the rocks. SEM Petrology Atlas [34] was used as a reference in SEM image interpretation.

The mineralogical integration followed the workflow described below. (Figure 3)

- Petrography Analysis: enables identification and quantification of minerals greater than 4 µm.
- XRD Analysis: identifies and semi-quantifies minerals including philosilicates (clay minerals) with an organized internal structure.
- SEM Analysis: describes morphology in the minerals and identifies elemental composition.

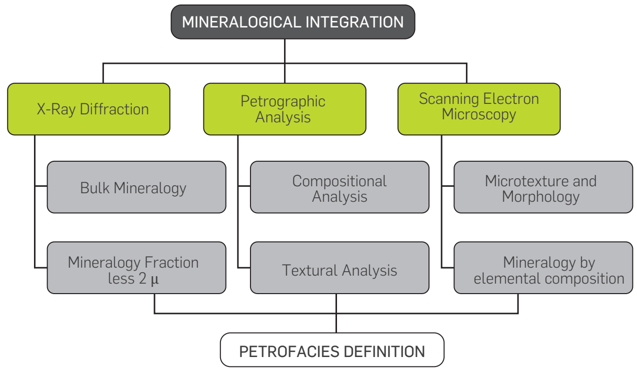


Figure 3. Workflow to perform mineralogical integration studies.

4. RESULTS

Knowing the generation, destruction and distribution of minerals in the rocks of La Victoria Formation, is of great importance to understand the impact on the storage capacity and mobility of fluids (porosity and permeability) in the different groups of rocks called petrofacies, a term used as posed by De Ros and Goldberg (2007) [35] as a concept for oil reservoir characterization.

Reservoir petrofacies are defined by the combination of specific structures, textures and primary composition, with dominant diagenetic processes. The concept of reservoir petrofacies is a tool for the systematic recognition of these main petrographic attributes that control the petrophysical behavior of rock units, resulting in significant implications for petroleum exploration and production. [35].

The position of the samples analyzed in the Folk triangle (1974), is shown in Figure 4.

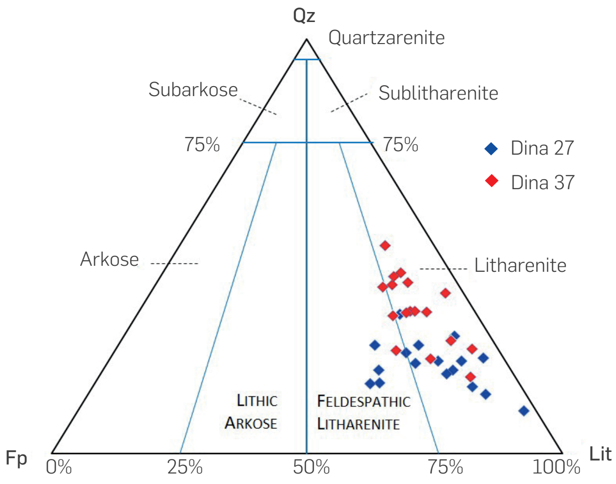


Figure 4. Position of the samples from the Dina 27 and Dina 37 wells, in the Folk classification triangle (1974). Slight increase in lithic fragments in the Dina 37 well.

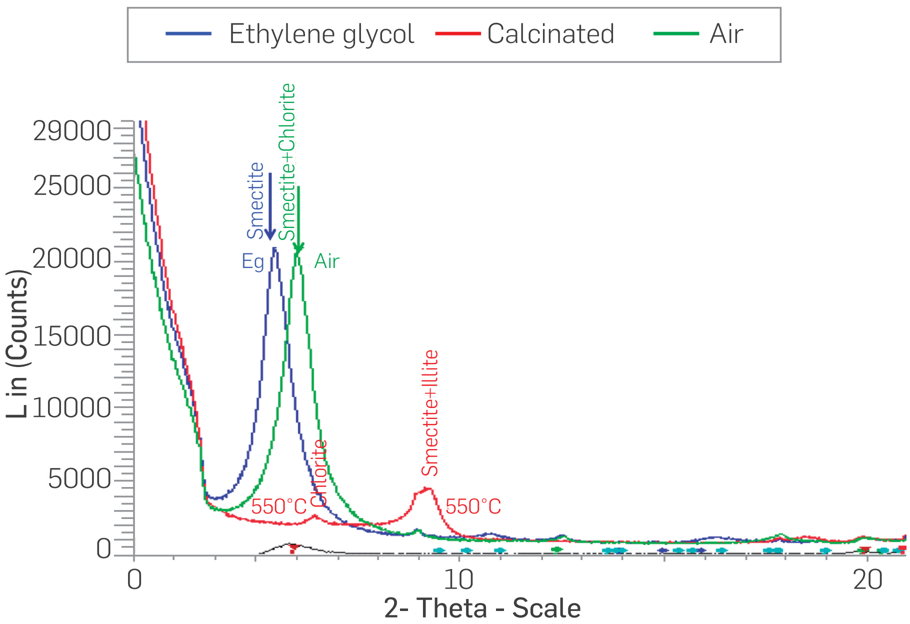


Figure 5. XRD profile that illustrates the predominance of smectite clay in the Dina field. The green arrow points to the smectite and the blue arrow indicates the smectite treated with Ethylene glycol.

PETROFACIES

The integrated mineralogical characterization performed on the Dina Norte 27 and Dina Norte 37 oil wells, which were drilled in La Victoria Formation (Honda Group), made it possible to establish that this unit is dominated by compositionally immature sandstones (presence of unstable minerals and lithic fragments in a relatively high abundance) and immature to sub-mature texturally sandstones (poor to moderate sorting). The XRD analysis indicates that the predominant clay mineral in the rocks of La Victoria Formation of the Dina Field corresponds to smectite. (Figures 5 and 6).

Three (3) rock types were identified, and these have been termed as petrofacies in this article. The composition of grains in each analyzed thin section (Dina Norte 27 and Dina Norte 37 wells) is shown Table 1. Figure 6 presents the defined petrofacies and XRD detailed results from every sample analyzed; Figure 7 shows photomicrographs and SEM images of the identified petrofacies at La Victoria Formation.

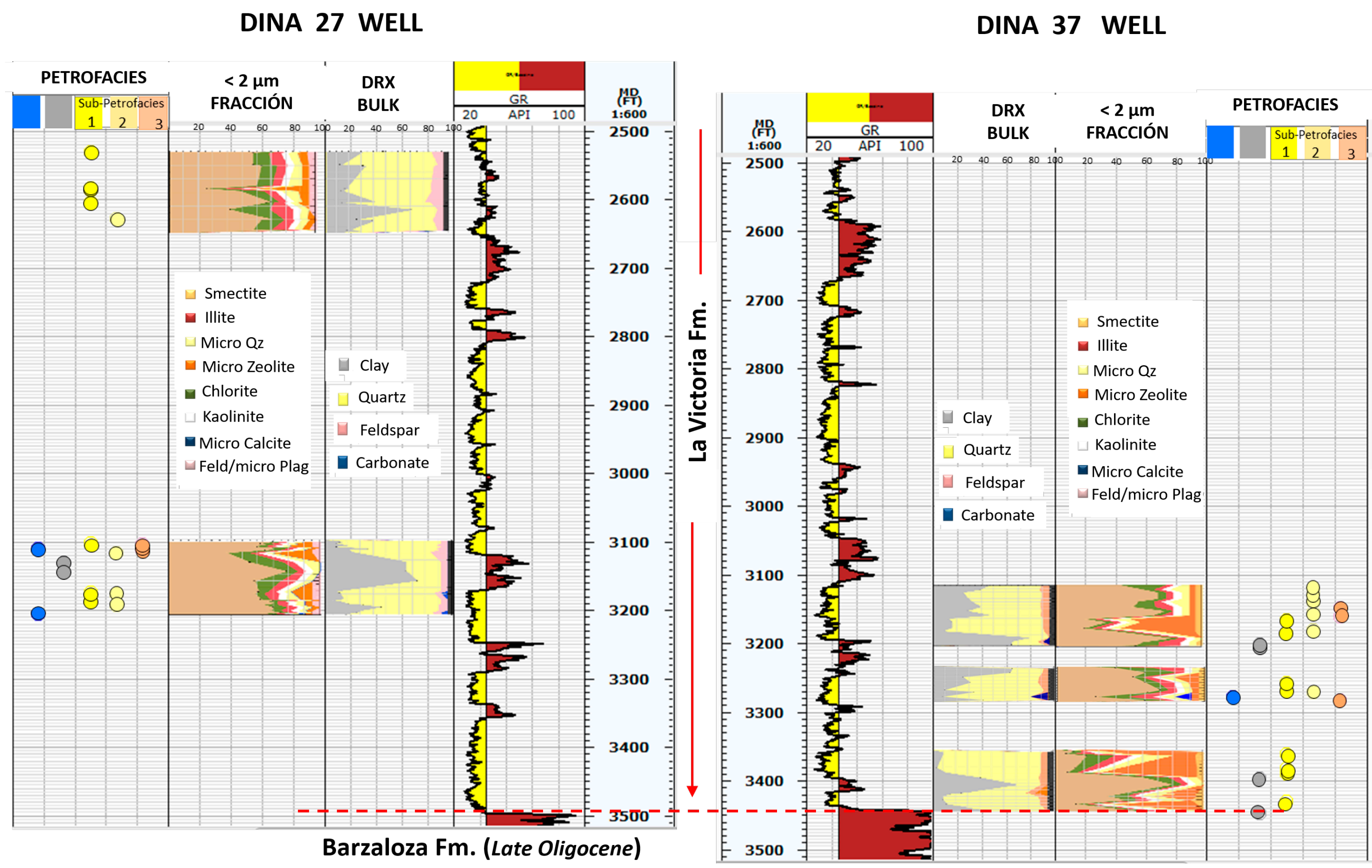


Figure 6. Sample Depth, petrofacies and XRD detailed results (Bulk and Fraction minor than 2µm) from Dina Norte 27 and Dina Norte 37 Oil Wellsat La Victoria Fm. at the base of the Honda Group.

Table 1. Percentage of Constituent Minerals and petrofacies description. Wells Dina 37 and Dina 27. La Victoria Formation (Dina Oil Field-UMVB)

WELL	DEPTH (Ft)	QUARTZ			FELDSPAR			ROCK FRAGMENTS				ACCESORIES			DUCTIL				AGGLUTINANTS			POROSITY			COMPOSITIONAL CLASSIFICATION	PETROFACIES
		MONORYSTALLINE	POLICRYSTALLINE	TOTAL	K- FELDSPAR	PLAGIOCLASE	TOTAL	SEDIMENTARY	IGNEOUS	METAMORPHIC	TOTAL	OPAQUE	TRANSLUCENT	TOTAL	MICAS	ORGANIC MAT	INTRACLAST	TOTAL	MATRIX	CEMENTS	TOTAL	PRIMARY	SECUNDARY	TOTAL		
DINA 37	3122.5	8.8	2.8	11.5	1.4	17.1	18.4	1.4	32.3	4.1	37.8	0.5	7.4	7.8	2.8	0	0	2.8	0	11.1	11.1	10.1	0.5	10.6	Litharenite / Feldspathic Litharenite	
	3126.5	11.1	6.9	18.0	1.8	8.8	10.6	7.4	34.1	10.6	52.1	0	2.3	2.3	0.0	0	0	0.0	0	6.9	6.9	6.9	3.2	10.1	Litharenite	
	3140.5	11.4	5.2	16.6	2.0	11.7	13.7	2.3	35.8	8.1	46.3	0	4.2	4.2	0.3	0	0	0.3	0	10.1	10.1	6.5	2.3	8.8	Litharenite	
	3148.5	10.8	1.4	12.2	3.1	18.1	21.2	1.7	26.4	11.1	39.2	1.4	11.8	13.2	0.3	0	0	0.3	0	11.1	11.1	1.7	1.0	2.8	Litharenite / Feldspathic Litharenite	
	3154.5	17.4	7.2	24.6	1.5	9.6	11.1	0.6	35.7	1.5	37.8	0.6	4.8	5.4	0.0	0	0	0.0	0	11.4	11.4	7.8	1.8	9.6	Litharenite	
	3161.5	12.2	1.9	14.1	2.9	15.4	18.3	5.5	24.1	8.7	38.3	0	8.0	8.0	0.6	0	0	0.6	0	18.0	18.0	0	2.6	2.6	Litharenite / Feldspathic Litharenite	
	3166.5	14.8	6.0	20.8	2.1	3.0	5.1	9.7	27.8	10.3	47.7	0	3.0	3.0	0	0	0	0	0	12.7	12.7	7.9	2.7	10.6	Litharenite	
	3180.54	7.7	7.7	15.5	3.1	5.7	8.8	15.5	26.3	10.8	52.6	0	3.1	3.1	0	0	0	0	0	11.9	11.9	6.2	2.1	8.2	Litharenite	
	3185.5	8.4	10.4	18.8	1.2	2.1	3.3	23.0	19.7	17.3	60.0	0	0.9	0.9	0	0	0	0	0	6.9	6.9	9.0	1.2	10.1	Litharenite	
	3201.5	21.5	0	21.5	0	0	0	0	0	0	0	0	1.9	1.9	0	0	0	0	76.6	0	76.6	0	0	0	Claystone Slightly Silty	
	3206.5	8.3	0	8.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	91.7	0	91.7	0	0	0	Claystone Slightly Silty	
	3258.17	14.5	4.8	19.4	4.0	13.7	17.6	3.1	27.3	7.0	37.4	0	1.3	1.3	1.8	0	0	1.8	0.0	6.6	6.6	14.1	1.8	15.9	Litharenite / Feldspathic Litharenite	
	3268.5	12.6	4.1	16.7	1.7	4.8	6.5	5.8	28.7	17.7	52.2	0	1.4	1.4	0	0	0	0	0.0	7.5	7.5	14.3	1.4	15.7	Litharenite	
	3271.5	14.6	6.3	20.8	3.6	8.3	12.0	7.3	30.7	8.9	46.9	0	0.5	0.5	0	0	0	0	0.0	10.4	10.4	7.3	2.1	9.4	Litharenite	
	3277.67	0.5	6.5	6.9	0	1.0	1.0	24.6	2.2	18.1	44.9	0	0	0	0	0	0	0	47.1	0	47.1	0	0	0	Litharenite With Calcareous Matrix	
	3282.5	14.2	4.4	18.7	1.8	12.4	14.2	1.8	32.0	10.2	44.0	0	2.7	2.7	0	0	0	0	0	15.6	15.6	2.7	2.2	4.9	Litharenite	
	3361.5	10.2	3.1	13.3	1.2	6.7	7.8	23.5	27.1	11.0	61.6	1.2	2.4	3.5	0	0	0	0	0	8.6	8.6	3.1	2.0	5.1	Litharenite	
	3382.5	10.5	1.8	12.3	1.8	5.0	6.8	38.6	17.7	10.5	66.8	0	0	0	0	0	0	0	0	3.2	3.2	7.7	3.2	10.9	Litharenite	
	3389.88	6.2	2.3	8.5	0.7	1.3	2.0	13.1	49.0	10.1	72.2	0	1.6	1.6	0	0	0	0	0	6.5	6.5	8.2	1.0	9.2	Litharenite	
	3397.00	21.7	1.4	23.1	0.0	4.7	4.7	0.0	9.2	0	9.2	4.1	1.4	5.4	0	0	0	0	57.6	0	57.6	0	0	0	Claystone Slightly Silty	
	3430.63	12.6	2.0	14.6	2.3	7.6	9.9	5.6	38.3	7.6	51.5	0	0.3	0.3	0	0	0	0	0	12.3	12.3	8.8	2.6	11.4	Litharenite	
	3447.5	9.3	0	9.3	0	0	0	0	1.1	0	1.1	0	0	0.0	0	0	0	0	89.6	0	89.6	0	0	0	Claystone Slightly Silty	
DINA 27	2530.50	12.4	4.5	17.0	3.0	7.9	10.9	0	41.5	4.2	45.8	0.6	3.0	3.6	2.1	0	4.5	6.7	0	3.3	3.3	10.3	2.4	12.7	Litharenite	
	2583.58	21.5	7.4	28.8	5.5	5.5	11.0	0.6	25.8	5.5	31.9	0.6	3.7	4.3	1.2	0	0	1.2	0	2.5	2.5	19.6	0.6	20.2	Litharenite / Feldspathic Litharenite	
	2587.50	25.0	4.9	29.9	4.4	5.4	9.8	1.5	26.0	6.4	33.8	0.5	3.4	3.9	0.5	0.5	0	1.0	0	3.4	3.4	16.7	1.5	18.1	Litharenite	
	2604.50	7.5	7.2	14.8	1.3	5.9	7.2	1.6	48.2	6.9	56.7	1.0	2.0	3.0	0	0	3.6	3.6	0	4.6	4.6	9.2	1.0	10.2	Litharenite	
	2628.58	25.8	6.7	32.5	4.1	5.2	9.3	6.2	23.2	5.2	34.5	2.1	1.5	3.6	0	0	0	0	0	10.8	10.8	9.3	0.0	9.3	Litharenite	
	3101.71	10.8	8.6	19.4	0.4	4.0	4.3	2.5	46.4	4.0	52.9	0	1.4	1.4	0	0	2.2	2.2	0	4.7	4.7	11.9	3.2	15.1	Litharenite	
	3102.50	32.1	8.2	40.3	3.6	4.6	8.2	4.1	24.5	3.6	32.1	0.5	3.1	3.6	0	0	0	0	0	5.1	5.1	10.2	0.5	10.7	Litharenite	
	3104.50	15.9	6.8	22.7	3.9	3.4	7.2	10.1	36.7	6.3	53.1	0.5	1.4	1.9	0	0	0	0	0	8.2	8.2	4.8	1.9	6.8	Litharenite	
	3107.50	20.2	3.4	23.6	3.1	8.9	12.0	1.4	29.5	4.5	35.3	1.0	1.7	2.7	0.3	0	0	0.3	0	22.6	22.6	0	3.4	3.4	Litharenite	
	3109.50	20.1	7.0	27.1	2.3	7.9	10.3	2.8	29.9	8.9	41.6	0.9	0.9	1.9	0	0	0	0	0	16.4	16.4	2.8	0	2.8	Litharenite	
	3111.50	26.4	4.9	31.3	3.1	4.3	7.4	2.5	25.2	5.5	33.1	1.2	9.2	10.4	0	0	0.6	0.6	0	10.4	10.4	6.7	0	6.7	Litharenite	
	3116.33	14.4	4.2	18.6	2.8	12.3	15.1	0.4	33.3	6.7	40.4	1.1	1.8	2.8	0.4	0	0	0.4	0	8.8	8.8	10.5	3.5	14.0	Litharenite Feldespática	
	3130.50	12.2	0	12.2	0	0	0	0	0	0	0	2.0	0	2.0	0	6.1	0	6.1	79.6	0	79.6	0	0	0	Claystone Slightly Silty	
	3143.83	23.5	0.0	23.5	0	0	0	0	0	0	0	1.2	0	1.2	0	30.9	0	30.9	44.4	0	44.4	0	0	0	Claystone Slightly Silty	
	3174.25	23.8	7.0	30.8	1.6	1.6	3.3	1.6	39.4	4.5	45.6	1.2	2.1	3.3	0	0	1.0	1.0	0	3.7	3.7	12.3	0	12.3	Litharenite	
	3176.58	15.1	11.9	27.0	3.2	6.3	9.5	7.1	28.2	6.7	42.1	0.4	1.6	2.0	0	0	0	0	0	7.5	7.5	11.9	0	11.9	Litharenite	
	3187.25	12.9	10.3	23.3	0.9	6.0	6.9	1.7	31.0	16.4	49.1	0	0	0	0	0	0	0	0	9.5	9.5	10.3	0.9	11.2	Litharenite	
	3192.79	18.9	14.8	33.7	2.1	6.2	8.2	4.1	29.6	6.2	39.9	0.8	0	0.8	0	0	0	0	0	7.8	7.8	9.5	0	9.5	Litharenite	
	3205.50	17.0	8.8	25.9	2.7	4.8	7.5	9.5	28.6	4.1	42.2	1.4	4.8	6.1	0	0	1.4	1.4	0	11.6	11.6	5.4	0	5.4	Litharenite	
	3206.20	20.1	5.2	25.4	3.7	6.7	10.4	3.7	32.8	2.2	38.8	0.0	3.0	3.0	0	0	0	0	0	21.6	21.6	0.7	0	0.7	Litharenite / Feldspathic Litharenite	

Petrofacies:	L / LF-cal	Cly / Slt	L/LF-poros	L/LF-poros-cly	L-comp
Lithology	Litharenite to Feldespathic Litharenite with calcareous cement	Claystone with scarce silty grains quartz	High Porosity Litharenite to Feldespathic Litharenite	Slightly Clayey with good porosity Litharenite to Feldespathic Litharenite	Slightly compact with low porosity Litharenite to Feldespathic Litharenite
Mineralogical and morphological characteristics by SEM and DRX	Predominant clay Smectite. Obstruction by calcareous cementations between grains is observed	Clay mineral predominant is Smectite.	Predominant clay is Smectite. The clays cover the grains and the walls of the pores. Occasionally the clay completely fills the pore. Zeolite is often observed.	Predominant clay is Smectite. The clays cover the grains and the walls of the pores. Occasionally the clay completely fills the pore. Zeolite is often observed.	Often, clay (smectite) fills pores completely. In some pores zeolite is observed.

PETROFACIES: LITHARENITE TO FELDSPATHIC LITHARENITE WITH CALCAREOUS CEMENT (L/LF-cal)

The rocks of this petrofacies are grain-supported sandstones, with poor to moderate sorting and grain shapes that vary from sub-rounded to angular. The most abundant grain sizes are medium to coarse sand. Composition: $Q_{30}\ F_{10}\ L_{60}$.

Petrologically, the sandstone can be classificated as litharenite to feldspathic litharenite. The lithic fragments are principally of volcanic origin. Quartz is mostly undulosed monocrystalline and some are non-undulosed. Feldspars (K-feldspar and plagioclase) usually shows partial dissolution. This petrofacies is characterized by the presence of poikilitic calcite (non-ferroan calcite) varying from 11.6% to 21.6% which is blocking nearly all the porous space. The pore space proportion in these rocks varies from 0.7% to 5.4%. XRD analysis that shows the most abundant clay mineral is smectite.

PETROFACIES: CLAYSTONE WITH SCARCE SILT GRAINS OF QUARTZ (Cly / Slt)

Claystone with traces of quartz siltstone. These rocks do not show any porosity at petrographic scale. XRD analysis resulted in defining a clay-like mineralogy in which smectite is the dominant mineral together with small amounts of chlorite and illite.

PETROFACIES: LITHARENITE TO FELDSPATHIC LITHARENITE (L/LF)

These are grain supported sandstone with poor to good sorting, and moderate packing of the grains. Composition: ($Q_{26.5}\ F_{13}\ L_{60.5}$); predominant in this petrofacies lithic fragments of volcanic origin that are frequently chloritized; the sedimentary and metamorphic lithics are found in a smaller proportion. Quarz, mainly monocrystalline, plagioclase (Average: 7.7 % Pgc) and potassium feldspar (Average: 2.4 % Fk).

The main clay-like minerals are smectite and, to a lesser proportion, chlorite and illite, which are found as a coatings of some porous walls, and in some cases these minerals are partially filling up the porous space. Another agglutinat mineral is heulandite (variety of zeolite) organized in small crystals on the framework grains surface. (Traces to 6.6%).

In most of the samples, porosity is relatively good (total petrographic porosity = 2.6 - 20.2%). Primary porosity dominates with average values of 8.6%. Secondary porosity traces are associated with unstable minerals dissolution (Average 1.6%). This petrofacies is sub-divided into three (3) groups (sub-petrofacies) with the intention of further characterizing slight textural and compositional changes

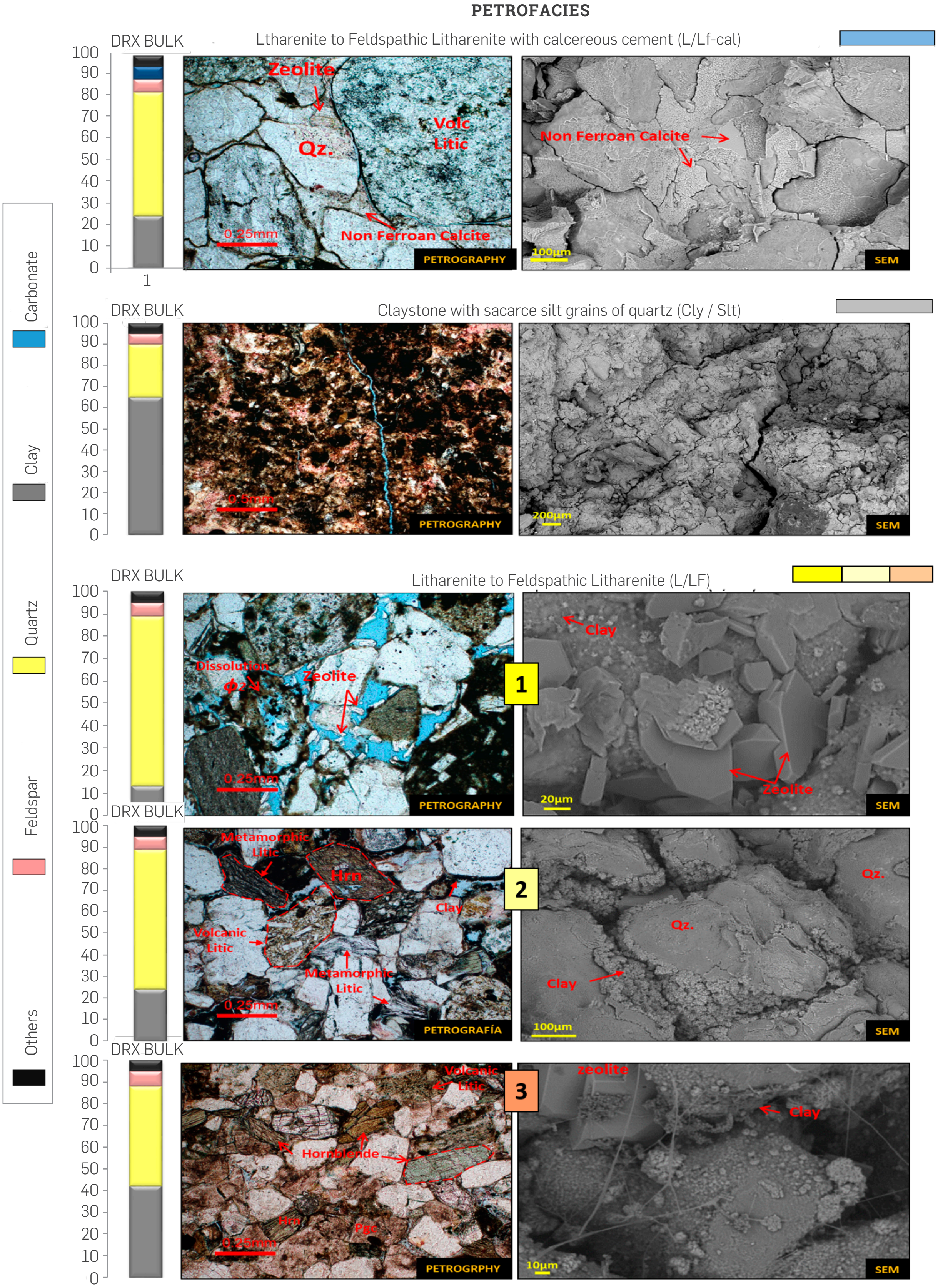


Figure 7. Petrofacies micrograph and SEM images from Dina Norte 27 and Dina Norte 37 Oil Wells at La Victoria Fm.

in the rocks: (1) Porous Litharenite to Feldspathic Litharenite **(L/LF-porous)** (Average Porosity: 12.5%); (2)Porous Litharenite to Feldspathic Litharenite **(L/LF-porous-cly)** (Average Porosity: 10.1%); (3) Litharenite to Feldspathic Litharenite, slightly compacted, and with low porosity **(L-comp)** (Average Porosity: 4.5%).

The Litharenite to Feldspathic Litharenite petrofacies is defined as the main oil reservoir rock in the petroleum system. In general, it has very good petrophysical properties, with exception of the slightly compacted, low porosity Litharenite to Feldspathic Litharenite sub-petrofacies **(L-comp)**, which has poor petrophysical properties and porosities that on average, have a range of 2-3% eventually reaching values of 7 %.

DIAGENETIC PROCESSES

Eight (8) diagenetic processes that affected the rocks are defined in relative terms as early, medium and late stages according to the Worden and Burley (2003) [36] criteria. These diagenetic processes describe the following sequence: (1) Mechanic compaction, bioturbation (?); (2), illite-smectite grain coatings; (3) Unstable minerals dilution (mainly potassium feldspar, plagioclases and volcanic lithic fragments); (4) zeolite precipitation. (Var. heulandite); (5) non-ferroan calcite local precipitation; (6) Pyrite Precipitation; (7) Partial clay chloritization; (8) hydrocarbon migration.

The diagenetic processes occurring to La Victoria Formation deposits are described in terms of relative time. The first process presented is compaction, which was not very intense since the framework grains display mainly point and long contacts (**Figure 8**). Moderate to low compaction causes a loose grain packing that allows the preservation of a high proportion of intergranular space **(petrofacies L / LF, primary porosity average: 8.6%)**

The dissolution of unstable minerals (**Figure 9**) occurred along all stages of the diagenetic history. It is confirmed by the presence of

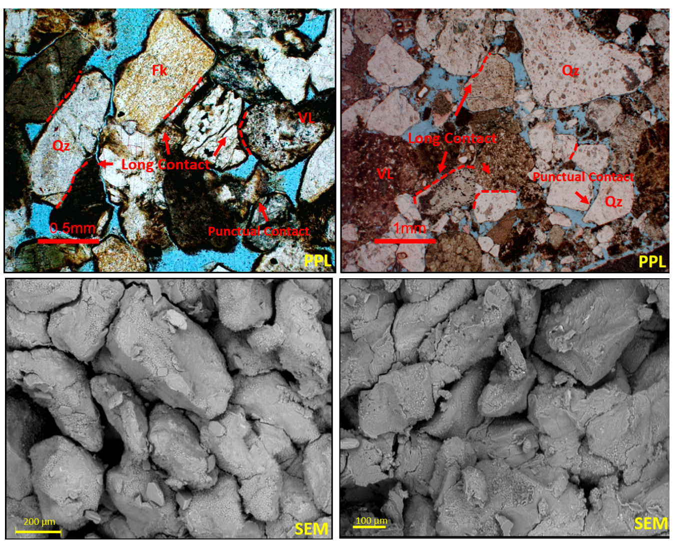


Figure 8. Long and point contacts between grains. Most of the samples seem to have moderate compaction. Fk: Potassic Feldspar – VL: Volcanic Lithic – Qz: Quartz. PPL: Plane –Polarized light.

andesine crystals in different stages of dissolution, from scarce to almost completely dissolved. Many minerals that show partial dissolution due to their instability probably arrived to the deposit with a slight degradation process. Cementation is a process that occurs in several diagenetic events including precipitation of pyrite clays, zeolite and non-ferroan calcite. Some pyrite crystal are formed association with claystone and siltstone levels (Petrofacies Cly / Slt). Pyrite precipitation is encouraged by the content of organic matter present in the deposits originating from flood plains associated with fluvial channels [37].

A high proportion of framework grains are coated by authigenic clay minerals, which were identified by XRD and SEM analysis as a mixture of chlorite-illite-smectite (**Figure 10**).

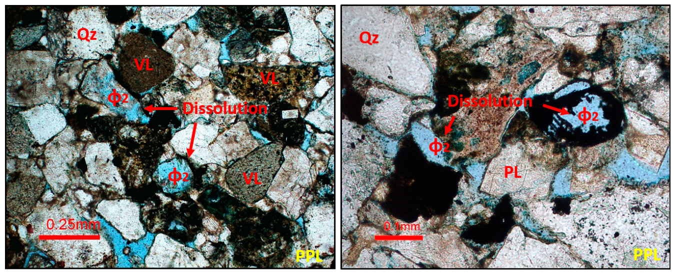


Figure 9. Secondary Porosity (ϕ2) as a result of unstable minerals dissolution.PL: Plagioclase– VL: Volcanic Lithic – Qz: Quartz. PPL: Plane –Polarized light.

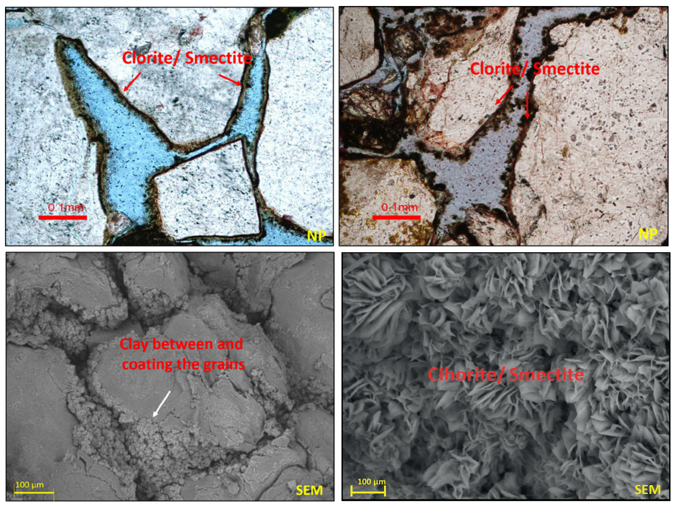


Figure 10. Chlorite-smectite grain coatings PPL: Plane –Polarized light.

The next agglutinant mineral that appears in the diagenetic history is the zeolite. It is formed in the early stages of diagenetic history as a result of the transformation of volcanic glass [38]. This mineral was identified in previous studies as a possible variety of discolored muscovite [22]. The XRD results made it possible to define the zeolite as a variety of heulandite, which is a rare mineral in detrital rocks. Zeolite is shown in small crystals (20 to 110 Mμ) rimming the grains (**Figure 11**), and there it is possible to observe that authigenic clays are produced before and after the zeolite precipitation. Zeolite rarely fills the entire pore space, but usually is isolated and in low proportion values (petrographic data: maximum 6.7%, present in Dina Norte 37 at 3180.54 feet) and consequently, it has a low impact on the reservoir porosity.

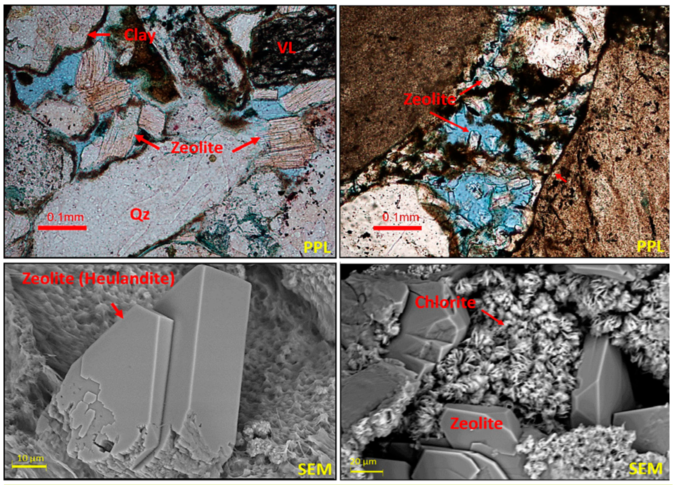


Figure 11. Zeolite precipitation in tabular crystals. VL: Volcanic Lithic – Qz: Quartz. PPL: Plane –Polarized light. SEM: Scanning Electron Microscope

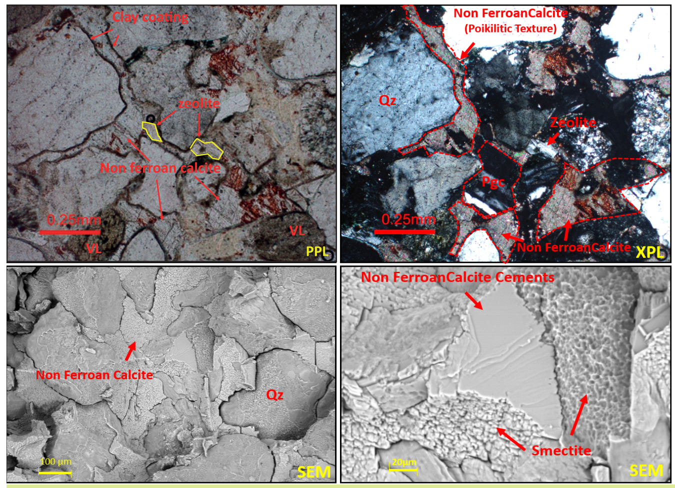


Figure 12. Non ferroan calcite cement precipitation with a poikilitic texture. PPL: Plane –polarized light. XPL: Crossed polarized light.

Petrographic evidence establishes that after zeolite precipitation, there is an episode of calcareous cementation. During the meso-diagenetic stage, the calcite precipitation process post-dates the authigenic clay and zeolite (Figure 12). This cement appears locally at some levels of La Victoria Formation in patches with a poikilitic texture (petrofacies L/LF-cal. Figure 7). When present, it occludes most of the porosity. The origin of this carbonate might be from caliches [39]; levels of caliche (calcrete) in the Honda Formation are reported by Van Der Wiel [40].

According to Soriano [38], the volcanoclastic sandstones as well as the silicate dissolution (plagioclase and zeolite) represent an important source of calcium (Ca^{2+}) and carbonate for the precipitation of carbonate cements in sandstones [41], therefore a possible genesis of the calcite cement observed in the L / LF-cal petrofacies is the dissolution of volcanic lithic fragments coming from Saldaña Formation [40] and the dissolution of plagioclase present in La Victoria Formation. (Figure 12)

Partial chloritization of clays originating from smectite present in all petrofacies, is associated with alteration of volcanic detritus coming from the Saldaña Formation and accessory minerals such as hornblende, diopsium and augite that provide iron, magnesium and calcium for the formation of chlorite, according to the following equation (Larese et al., 1984; Wilson & Stanton, 1994 in [42]).

$$KNaCa_2Mg_4Fe_4Al_{14}Si_38O_{100}(OH)_{20}10H_2O = +(Fe^{2+},Fe^{3+}) \rightarrow$$

(smectite)

$$(Mg, Al, Fe)_6\,(Si, Al)_4O_{10}](OH)_8 + SiO_2 + K^+ + Na^+ + Ca^{2+} + H_2O$$

(chlorite)

Finally, hydrocarbon migration occurred during late diagenesis. Oil traces have been seen impregnating some authigenic clays, but not in fluid inclusions that are observed in the carbonate cement. Therefore this event is proposed to be the last one to occur in the paragenesis of La Victoria Formation, (Honda Group base).

DISCUSSION OF FACTORS CONTROLLING RESERVOIR QUALITY

Based on the analysis of the diagenetic processes that affected the rocks of La Victoria Formation, several factors are considered that control the quality of the reservoir. One of them is the presence of illite / smectite thin coatings on the framework grains (Figure 10), which contributed to the preservation of the primary porosity

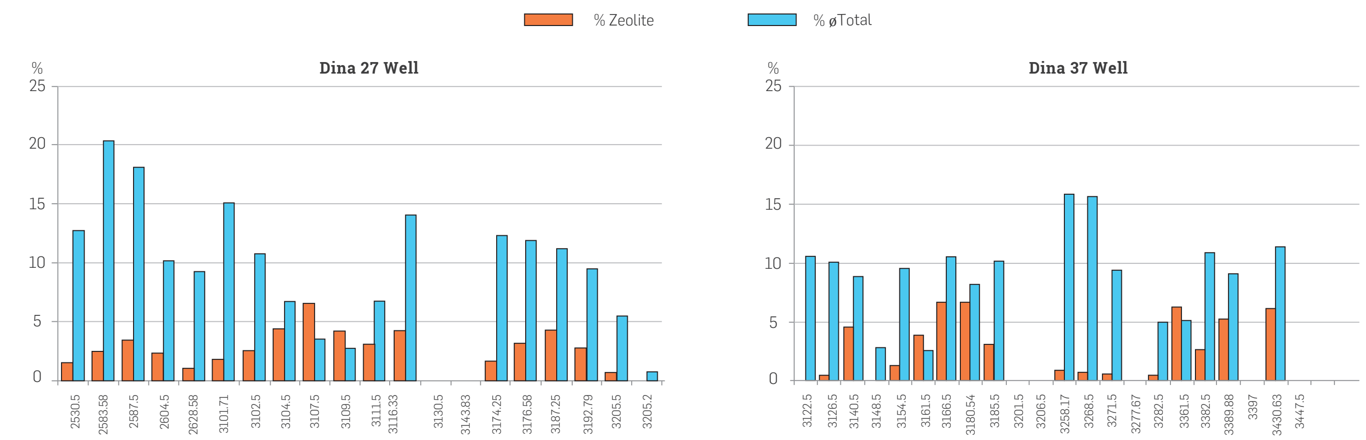


Figure 13. Relationship between the proportion of total petrographic porosity and the proportion of zeolite (var: heulandite). Relatively high zeolite proportions result in a noticeable decrease of porosity.

of the rock due to the fact that it avoided the precipitation of other minerals that could eventually saturate the remaining porous space. Similarly, it encouraged the conservation of a loose / moderate packaging of the framework grains [36].

Smectite has a high cation exchange capacity, which affects the magnitude of the readings for the resistivity logs [4], therefore, it is important to know its presence and distribution so that it can be considered in the reservoir fluid saturation model. Another mineral which affects the resistivity measurements in the reservoir is carbonate cement; the local presence of calcite patches partially or totally saturates the porosity, decreasing the storage capacity of the reservoir rocks [4].

The precipitation of zeolite is generally present in low proportions (Traces – 7.5 %). However, at the depths where its proportion is higher than 5% the primary porosity decreases (Figure 13).

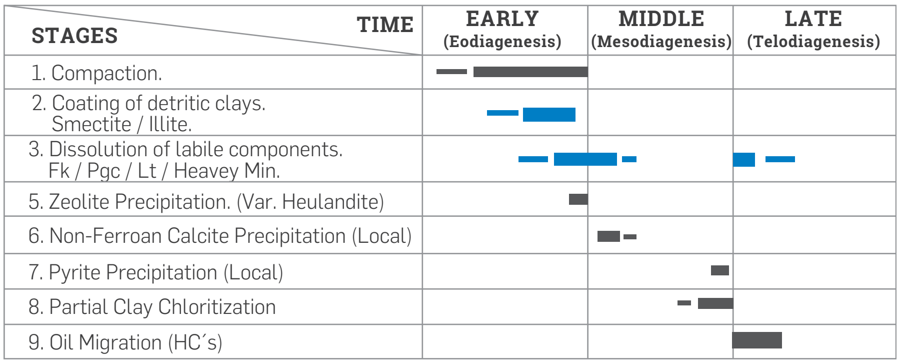


Figure 14. Proposed succession of the main diagenetic processes that occurred at La Victoria Formation deposits (Honda Group), Dina Oil Field.

Another diagenetic event that promotes reservoir quality is the partial dissolution of unstable compounds such as calcium plagioclase (labradorite, bitownite), volcanic lithic fragments and ferromagnesian minerals (hornblende principally). The dissolution of these compounds originates secondary porosity that can reach up to 3.5% of the total porosity.

A summary of the succession of the main diagenetic processes and their relative position in time, is shown in Figure 14.

CONCLUSIONS

Integrated mineralogical characterization was used to establish that samples from La Victoria Formation correspond to Litharenite to Feldspathic Litharenite with a major amount of volcanic lithics. XRD reveals that main cementing minerals are a mixture of clays including smectite and a minor proportion including chlorite and illite. Other agglutinant minerals are zeolite (var. heulandite) and non ferroan calcite.

The major petrographic porosity is intergranular primary porosity, varying from traces to 19.2%. Volcanic lithics and unstable mineral dissolution generates secondary porosity up to 3.7 %. The total petrographic porosity varies from 0.7 to 20.2%.

Several diagenetic processes affected the rocks of La Victoria Formation in the Dina oil field (UMVB, Colombia). Initially, moderate to low compaction causes loose grain packing that allows the preservation of a high proportion of primary porosity. At the end of the eodiagenetic stage and after initial compaction, a film of smectite-illite covers the grains, contributing to the preservation of primary porosity because it prevented precipitation of other minerals. Then, at the beginning of mesodiagenesis, unstable minerals dissolve and this event generates secondary porosity of up to 3.7%. Subsequently, the walls of some pores are partially covered in low proportions by heulandite crystals, however, when the amount is greater than 5%, the primary porosity decreases. Then, part of the clays is chloritized and locally patches of calcite and traces of pyrite are precipitated. Finally, hydrocarbon migration occurs at the beginning of telodiagenesis stage.

The quality of reservoir is essentially controlled by three diagenetic processes; one is one is illite-smectite grain coatings, promoting the preservation of original porosity; another is labile minerals dissolution, which causes secondary porosity, improving the quality of the reservoir; and local presence of calcite patches, which partially saturates the porosity decreasing the storage capacity potential of the reservoir rocks.

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