Comparison of Reservoir Quality from La Luna, Gacheta and Eagle Ford Shale Formations Using Digital Rock Physics*

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Abstract

A large fraction of all whole core samples recovered worldwide today come from shale reservoirs. The primary reason for so much shale coring is that petrophysical models require rigorous core calibration to provide reliable data for reservoir quality, hydrocarbon-in-place, and hydraulic fracturing potential. However, the uncertainty in interpreting shale well log data is sometimes matched or exceeded by the uncertainty observed in traditional methods of analyzing core samples. Most commercial core analysis methods in use today were developed for sandstones and carbonates exceeding one mD in permeability. On the other hand, high quality organic-rich shale is usually lower than 0.001 mD. This extreme low permeability creates substantial challenges for existing methods and has contributed to the rapid rise of a new approach to shale reservoir evaluation called Digital Rock Physics (DRP).

DRP merges three key technologies. One is a high-resolution diagnostic imaging method that permits detailed examination of the internal structure of rock samples over a wide range of scales. The second is advanced numerical methods for simulating complex physical phenomenon and the third is high speed, massively parallel computation using powerful graphical processing units (GPU’s).

The DRP process for analyzing rock properties of shale reservoirs at multiple scales begins with whole core samples, progresses to smaller plug size samples, then ultimately to very high-resolution 3D imaging of the pore space. This imaging, combined with unique and proprietary fluid flow algorithms, allows us to compute shale reservoir properties and provide clear 3D renderings of the pore structure.

A comparison between the results of core samples available from four wells in the Eagle Ford formation of southwest Texas, USA, and this study of core samples from La Luna and Gacheta formations from Colombia show that in many important characteristics (porosity, TOC, permeability), the shale samples from Colombia are comparable or better than those from the Eagle Ford shale of Texas.

In summary, multi-scale rock properties analysis brings several advantages to the process of shale reservoir characterization: Accurate porosity determination (connected, isolated, and porosity associated with organic material); permeability in horizontal and vertical directions; ability to determine relative permeability on low perm samples; improved up scaling of results; it works with whole core, core plugs, and cuttings/fragments.

Introduction

As a result of the ANH´s project of digitalization and analysis of cores from the National Core Repository "Bernardo Taborda", using a new technology called Digital Rock Physics (DRP), we can obtain a reliable digital database that preserves an enormous volume of information, gives added value to existing information such as well logs and seismic data, supports research and collaboration, and provides new information for the exploration of conventional and non-conventional plays in some basins of Colombia.

The X-ray CT imaging of the entire core record of a country is a milestone in the history of core analysis. These 3D image volumes by themselves constitute a unique and valuable catalogue. The CT imaging is being performed with a dual-energy process, allowing for a continuous computed log of high resolution Bulk Density (RHOB) and photoelectric factor (PEF) for each piece of core.

During the implementation of this project, approximately 9,500 meters of core were digitized from 140 wells that are mostly located in the Llanos, Catatumbo, and Middle Magdalena Valley areas (Figure 1). From this whole core, 4,500 plug samples were taken for Stage 2 analysis and 450 were selected for Stage 3 analysis of connected porosity and permeability (Figure 2).

Integration of these results together with petrophysical evaluation allowed the high grading of the geological sequences with more potential for unconventional reservoirs. From the data obtained by digital rock physics plus integration of well logs, seismic and other types of data, three Basic Studies were prepared for the Llanos, Catatumbo, and Middle Magdalena Valley areas. These results and reports are now available for downloading from the ANH website. ANH plans to continue with this project in order to implement a digital repository easily accessible to the public.

Method

Digital Rock Physics workflow (Figure 3) starts with a non-invasive, dual-energy X-ray CT scan of the core followed by computation of bulk density and effective atomic number along its length (Stage 1). This data helps geologists identify the natural variations at a scale several times finer than open-hole well logs. This visual data combined with the quantitative information constitutes a powerful database at present and will become a future source of information for the Colombian oil industry for both conventional and unconventional resources exploration and development.

In Stage 2, plug samples are taken at multiple depths based on whole core imaging in Stage 1. Each plug sample is imaged with a high-resolution X-ray method followed by a unique SEM analysis, which provides porosity and organic matter volume fraction and is used as a screening tool to ensure representative samples for the subsequent Stage 3 pore scale analysis of connected porosity and permeability in horizontal and vertical orientation. Fundamental principles and examples of this technology for unconventional resources are discussed in Keehm, et al., 2001, Tölke et al., 2010, and Walls, et al., 2012.

After all digital data are collected and processed, a more advanced analysis is performed to examine the relationships between various rock properties such as organic content, porosity, and directional permeability. These results are then used for up-scaling back to well log and reservoir scale.

Parallel to this process a comprehensive assessment was carried out that included the tectonic and sedimentary evolution of the basin, as well as evaluation of geological, lithostratigraphic, structural, geochemical and petrophysical information available from wells, which added to the results obtained from the different stages DRP process allowed to perform a detailed geological integration, document the petroleum system and the source rock as well as characterize the stratigraphic units under study to determine its quality as a reservoir.

The critical factors for the definition of shaly deposits are organic matter content 2% or greater, thermal maturity that allows the rock to have generated oil or gas, shaly deposits containing less than 40% clay, permeabilities below microdarcies, low permeability and continuous deposits without hydrocarbon migration and thickness greater than 40 feet.

Stratigraphy

The relatively high sea level event of the Turonian to Santonian interval in Colombia and Venezuela originated the deposition of large amounts of organic matter of marine origin contained in the offshore deposits of the Gacheta and La Luna Formations, and constitutes a very important interval of source rocks of hydrocarbons.

The Turonian to Santonian interval of the Cretaceous Colombian Basin was deposited during a relatively fast sea level rise (TST) and following high sea level (HST) according to Guerrero (2002). La Luna Formation is included in the interval TST and HST for Middle Magdalena Valley and Catatumbo Basins. In the Llanos Orientales Basin, the lower limit of the Gacheta Formation is a major transgressive surface (TS) placed and the Cenomanian/Turonian boundary meanwhile that the upper limit is a major regressive surface or sequence boundary placed at the Santonian/Campanian boundary.

The La Luna Formation in NE Colombia includes 200 to 300 m (Bouman and Gibson, 1964) of laminated biomicrite of foraminifera, marlstone, bituminous shale, and diagenetic chert with large calcareous concretions and is well dated with ammonites and foraminifera. This unit is subdivided in Salada, Pujamana and Galembo Members.

The Gacheta Formation from the Llanos Orientales is composed of black shale with minor glauconitic sandstone present in parasequences and storm beds (Figure 4). This unit was deposited in the east flank of the Cretaceous Colombian Basin. The Gacheta unit is producing in various fields of the Llanos Orientales area and it is wedged or not present due to erosion towards the east and southeast. Thickness of the Gacheta Formation increases toward the west and the maximum value is found in the southwest, where it is greater than 200 m.

The Eagle Ford Shale from Texas, U.S.A. was also deposited during a Turonian transgressive event (TST) and condensed section (Slatt and Rodriguez, 2012), and includes facies developed in low-energy offshore environments and consists of 75 to 100 m of organic-rich fossiliferous shales, marlstone and biomicrite of foraminifera. This unit can be subdivided into lower, upper, and transitional members that represent three regionally extensive stratigraphic units possessing unique rock properties and characteristic source and reservoir potential according to Harbor (2011).

Gacheta Formation on the Llanos Basin

Based on current analysis of this data, the Gacheta Formation may be prospective but data is still limited. Shales with high values of GR, high resistivities, low clay content and deposited under paleobathymetric shallow conditions, have some evidences that could be related to unconventional reservoirs. The lower part of Gacheta formation fulfilled these parameters.

Hybrid reservoirs of thin sandstones interbedded with organic shales at the base of Gacheta Formation and at the top of Une Fm (Apiay-16, Tocoragua-1, Gavan-1 and La Totuma-1) are another prospective play found in the basin along with the Paleozoic sequence, which seems to have good potential for shaly deposits.

The configuration of the basin corresponds to a structural slope toward the northwest, which borders limit with the foothills, and forms the southeastern edge of the Eastern Cordillera. The source rock in the Llanos basin remained buried by the thrust from the range creating conditions for the generation of hydrocarbons discovered in the foothills. The margin of the Llanos basin, adjacent to the Cordillera Oriental, is seen as an area favorable for the development of unconventional hydrocarbon reservoirs, taking into account the low intensity of structural deformation and the depth of the source rock.
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The average map organic richness (% TOC) today, prepared for the Gacheta Formation, permit to visualize that this parameter increases from east to west and from southeast to northwest, with poor values in the east and southeast (<0.5%) and good values (1-2% TOC) to very good (2-4% TOC) to the northeast (western sector of Arauca). In the central and southern foothills, values are in the range of good. Coal maceral analysis performed in samples of Gacheta Formation show a predominance of organic matter corresponding to kerogen type III, gas and condensate generating potential, with minor contributions of organic matter type II, oil generating potential.

Thermal maturity of Gacheta formation presents maximum temperature values of 435-445°C and vitrinite reflectance (Ro) between 0.6 to 1.0%, based on this results, maps of isovalues for average maximum temperature, pyrolysis and vitrinite reflectance are quite similar in their distribution and increase toward the west where this unit would have entered in oil generation window. The generation area from Gacheta Formation is located in the western part of the basin and runs from the southwest to the northwest of the basin.

Samples analyzed for the Gacheta Formation ranged between 5928 to 10876 feet, and obtained average porosity values around 5.1% and a total porosity of 51% and a volume of solid organic material 4.7%, porosity in organic material of 27%, permeability (k_horizontal) 982 nD, vitrinite reflectance between 0.6 to 1.0% increasing to west, with kerogen type III main condensate and gas generator (Figure 5). The values of porosity and permeability found to the Gacheta Formation in the Llanos Basin could be similar to the North America shale plays like Fayetteville.

La Luna Formation on the Catatumbo and MMV Basins

The Catatumbo Basin is characterized tectonically by large lineations with strike north and north-northeast, which delimit large structural blocks that has preserved stratigraphic units responsible for the generation of hydrocarbons at depths between 5,000 to over 12,000 feet. These lineations may be relay of transpressional systems that have longitudinal and tectonically transported blocks, resulting in flower structures with high deformation, and low deformation on the extended part of these blocks are limited by lineations. These blocks are associated with faults displacement that could be to the order of 3,000-4,000 feet, which has favored the trapped of hydrocarbons in the basin. As result, parameters like deep of source rocks and low intensity of structural deformation on the extend part of blocks delimited by lineations are optimal conditions for the development of unconventional resources.

The La Luna Formation is the principal Cretaceous source rock in the Catatumbo and MMV basins, wherein the composition, thickness and distribution were determined by the interplay between advances in sea level and sediment supply. Petrophysical evaluation on Salada Member of the La Luna Formation shows 150 feet of net pay (range 5,920-6,151 feet) with a high potential for unconventional resources presenting very good isovalues averages of 2-4% TOC (Figure 6).

The results of samples analyzed for La Luna Formation at Catatumbo Basin ranged between 4,057 and 8,310 feet (Figure 7). Average porosity values around 4.8%, total porosity of 71%, volume of solid organic material 8.1%, porosity in organic material of 20%, permeability (k_horizontal) 733 nD, vitrinite reflectance between 0.6 to 2.0% increasing to the south, with kerogen type II mostly condensate. For MMV Basin this unit ranged between and 2,742 to 12,405 feet, and obtained average porosity values around 6.3%, total porosity of 47%, volume of solid organic material 7.7%, porosity in organic material of 29%, permeability (k_horizontal) 920 nD, vitrinite reflectance between 0.6 to 1.0% increasing to the south and east, with kerogen type II mostly oil (Figure 8).

Conclusions

The La Luna Formation from a stratigraphic point of view is the sequence with the highest potential for unconventional resources in MMV and Catatumbo basins. The expected hydrocarbon present in this unit is predominantly condensate in the central and northern part of the basin, gas in the southern part, and in less proportion, liquid HC in sectors (west and east) of the central part. The Gacheta Formation is the sequence with highest potential for unconventional resources in Llanos Basin although data is limited, because present shales with high values of GR, high resistivities, low clay content and was deposited under paleobathymetric shallow conditions, parameters related to unconventional reservoirs. Comparisons are shown in Table 1.

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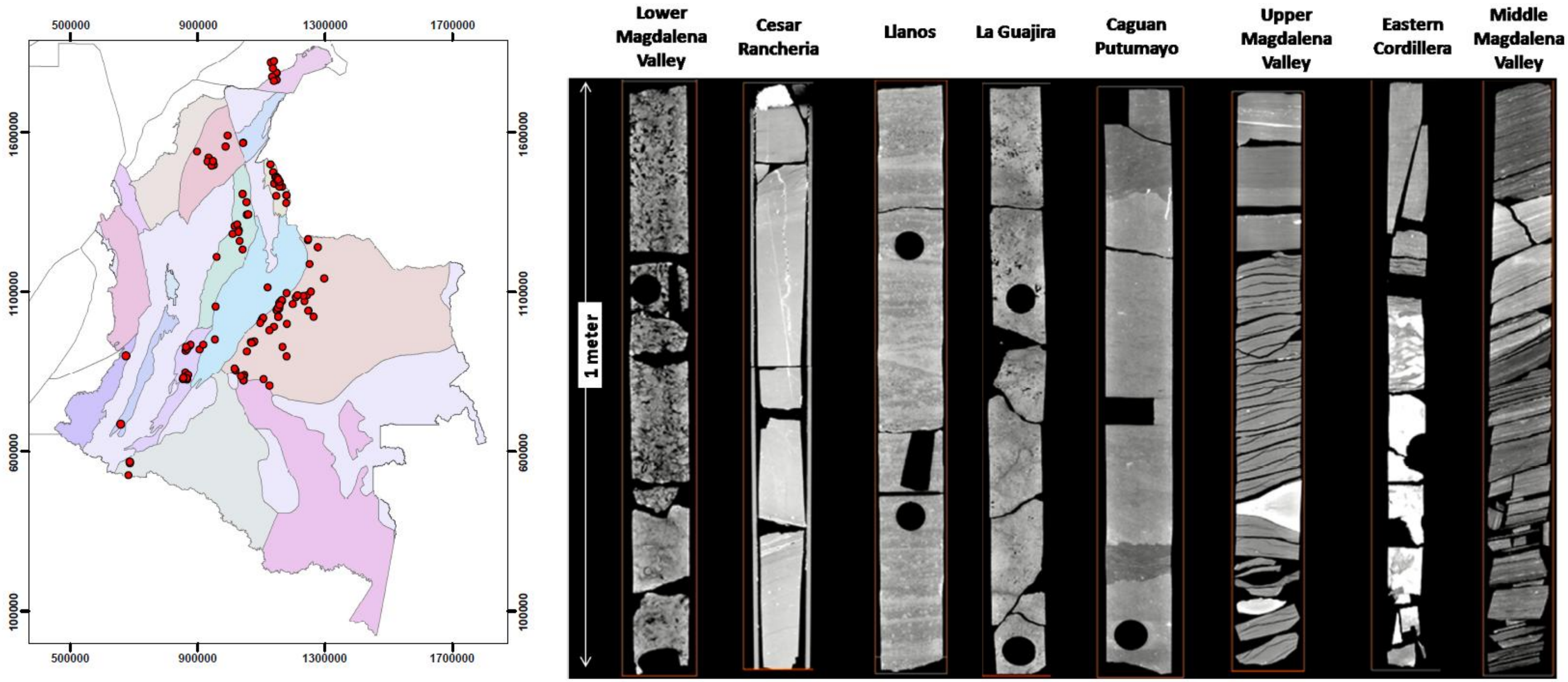

Figure 1. Location of digitized wells and examples of vertical X-ray CT (Computerized Axial Tomography) slices of whole core samples extracted from 3D volumes of different wells and basins.

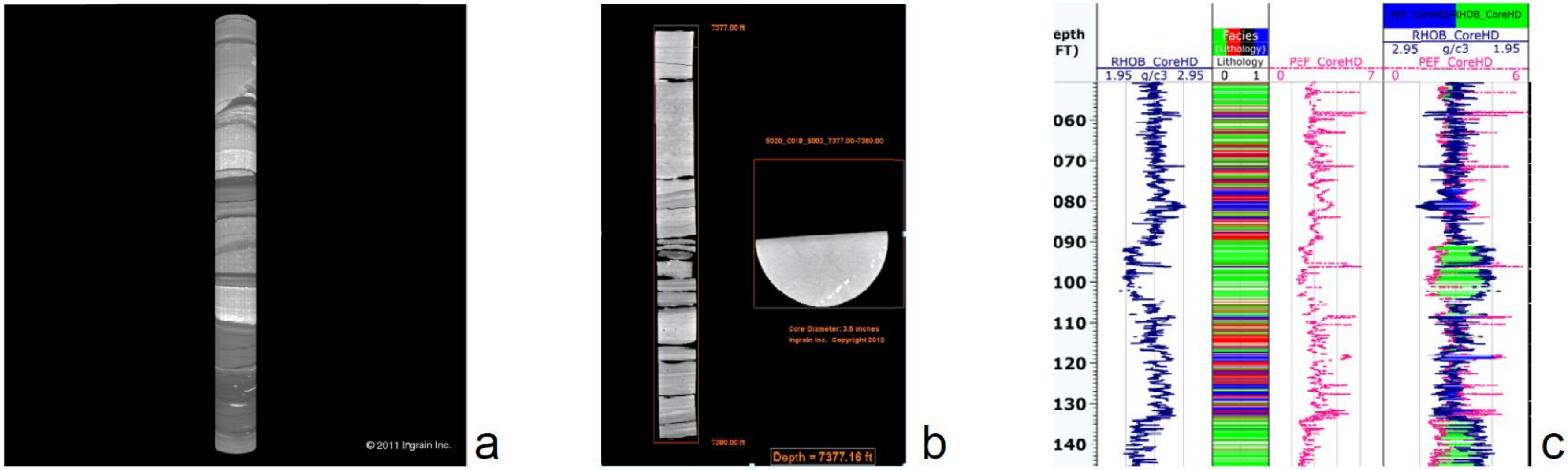

Figure 2 a. Example of a section of core fully imaged in 3D at a resolution of 625 microns per vertical slice. b. Image results from scanning of one meter of slabbed core. c. Computation of bulk density and effective atomic number along length of core.

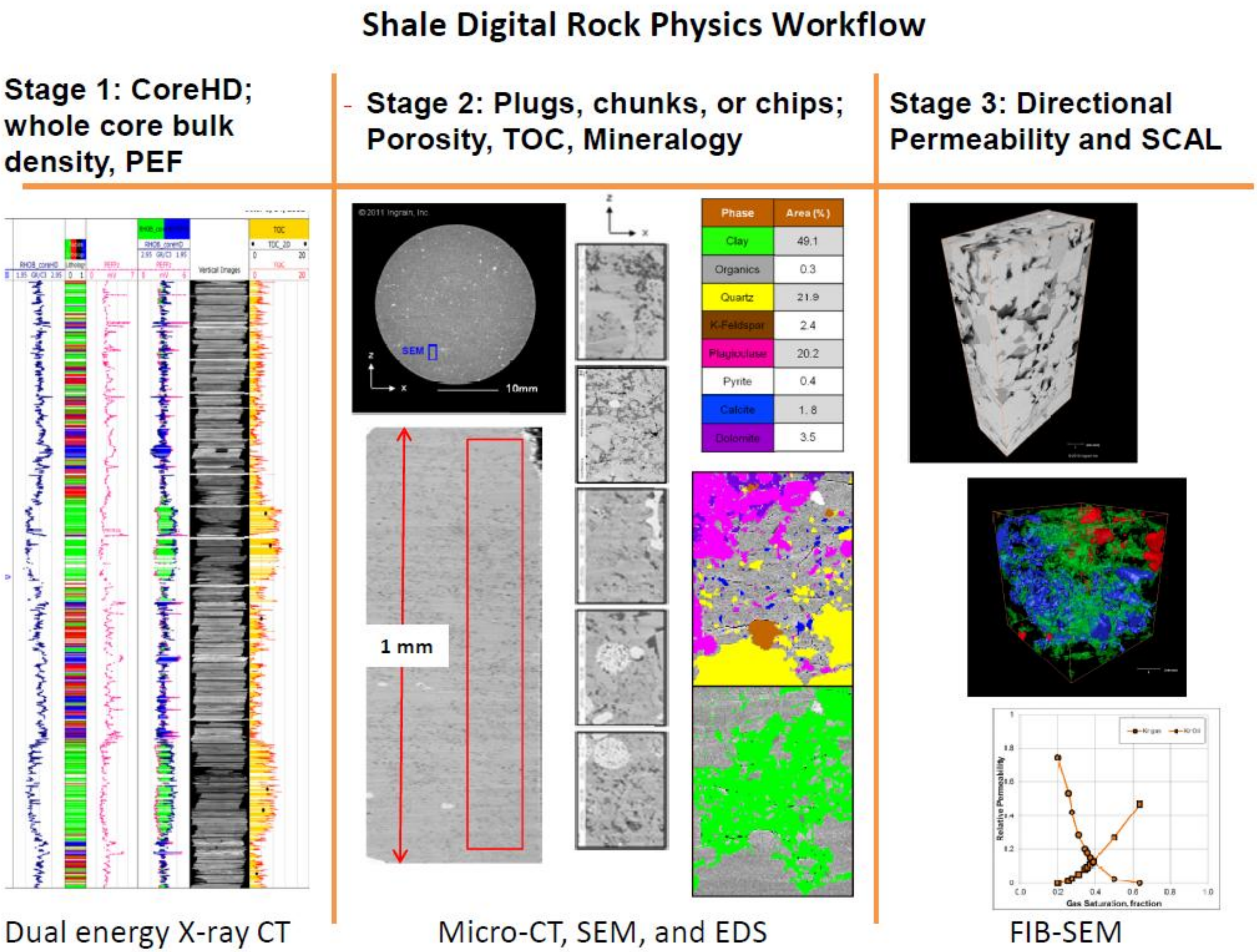

Figure 3. Digital rock physics workflow for shales and other unconventional resources. Dual energy X-ray CT imaging is used for lithology, facies, and parasequences discrimination, and to aid in up scaling.

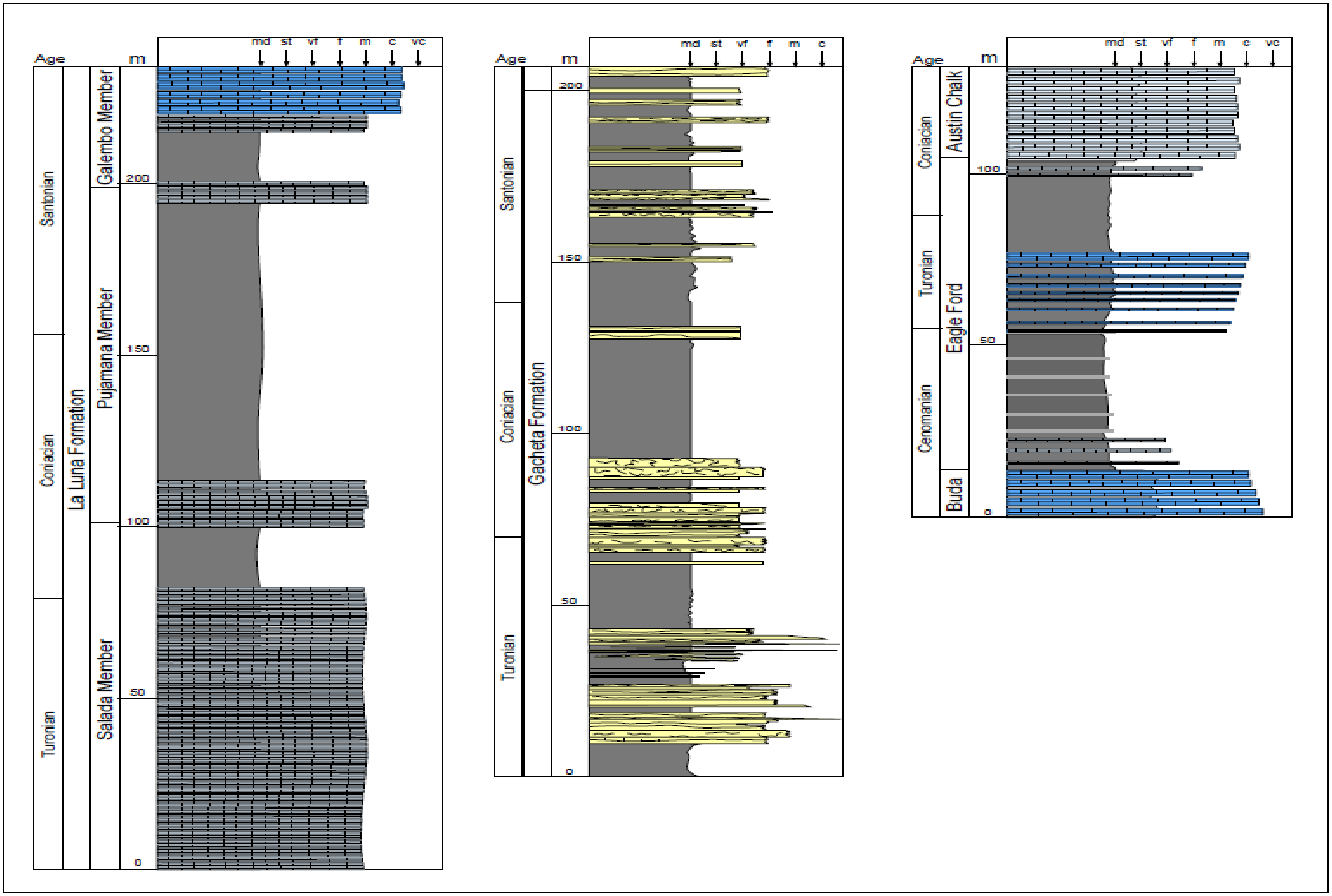

Figure 4. Comparative stratigraphic generalized columns of La Luna (Modified from Ballesteros & Parra, 2012), Gacheta (Modified from Guerrero, 1996) and Eagle Ford (Modified from Harbor, 2011) Formations.

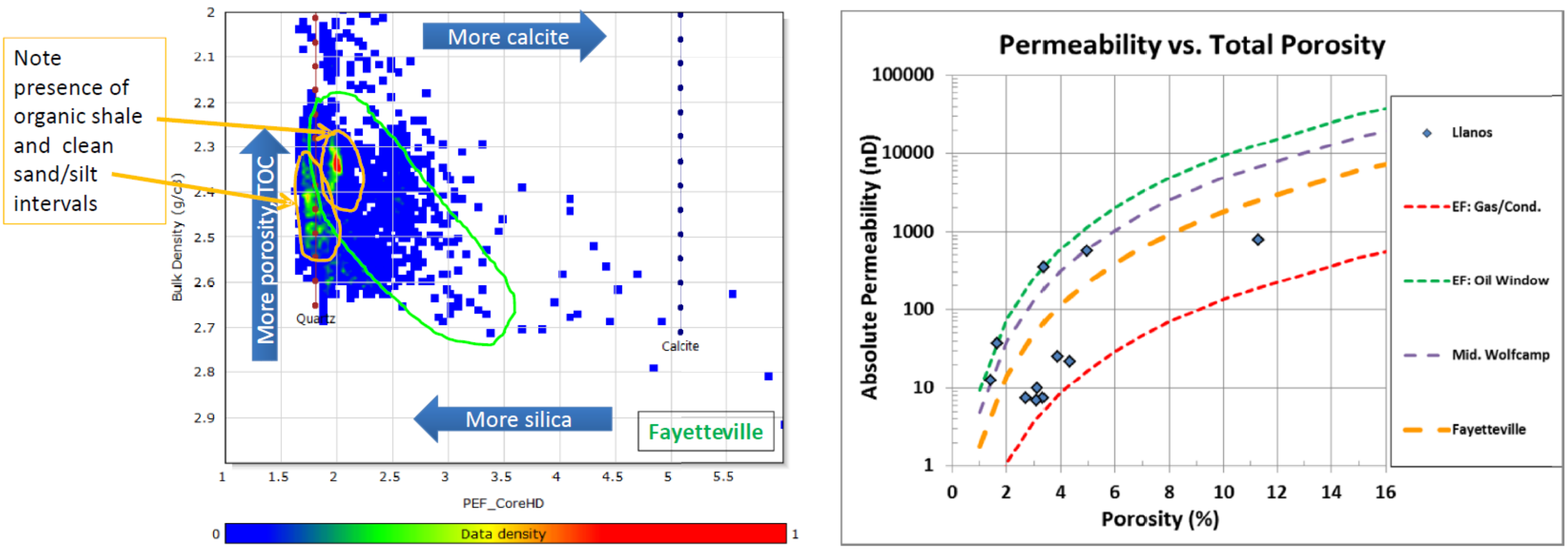

Figure 5. CoreHD Litho-density Analogs Gacheta Formation in Llanos Basin.

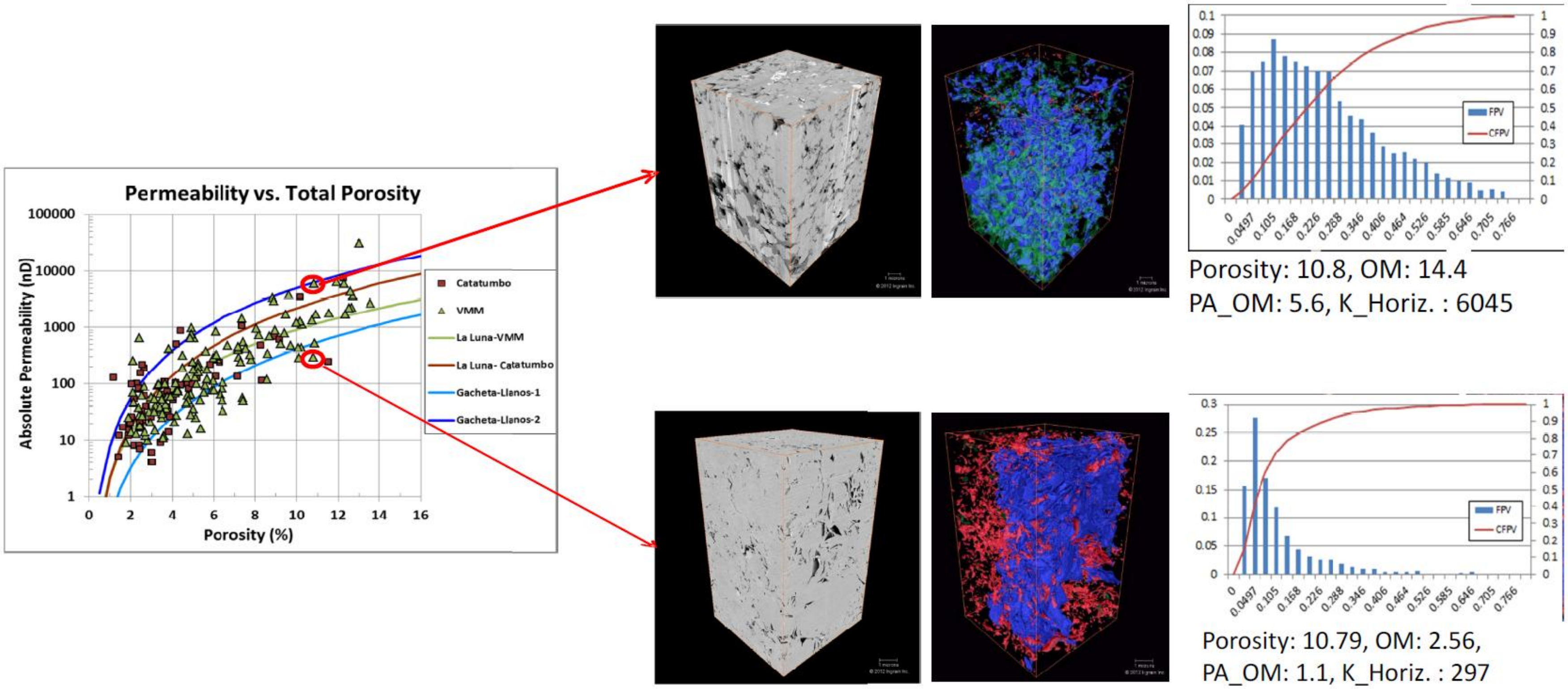

Figure 6. Samples 1 and 2 of Infantas-1613 well, have similar porosities but their horizontal permeability values differ. Sample 1 contains more organic porosity and is connected through the organic matter, this sample has the higher permeability. Sample 2 contains mostly inter-granular porosity and has much lower permeability. Images on right show 3D view of connected porosity (blue), isolated porosity (red), and solid organic material (green).

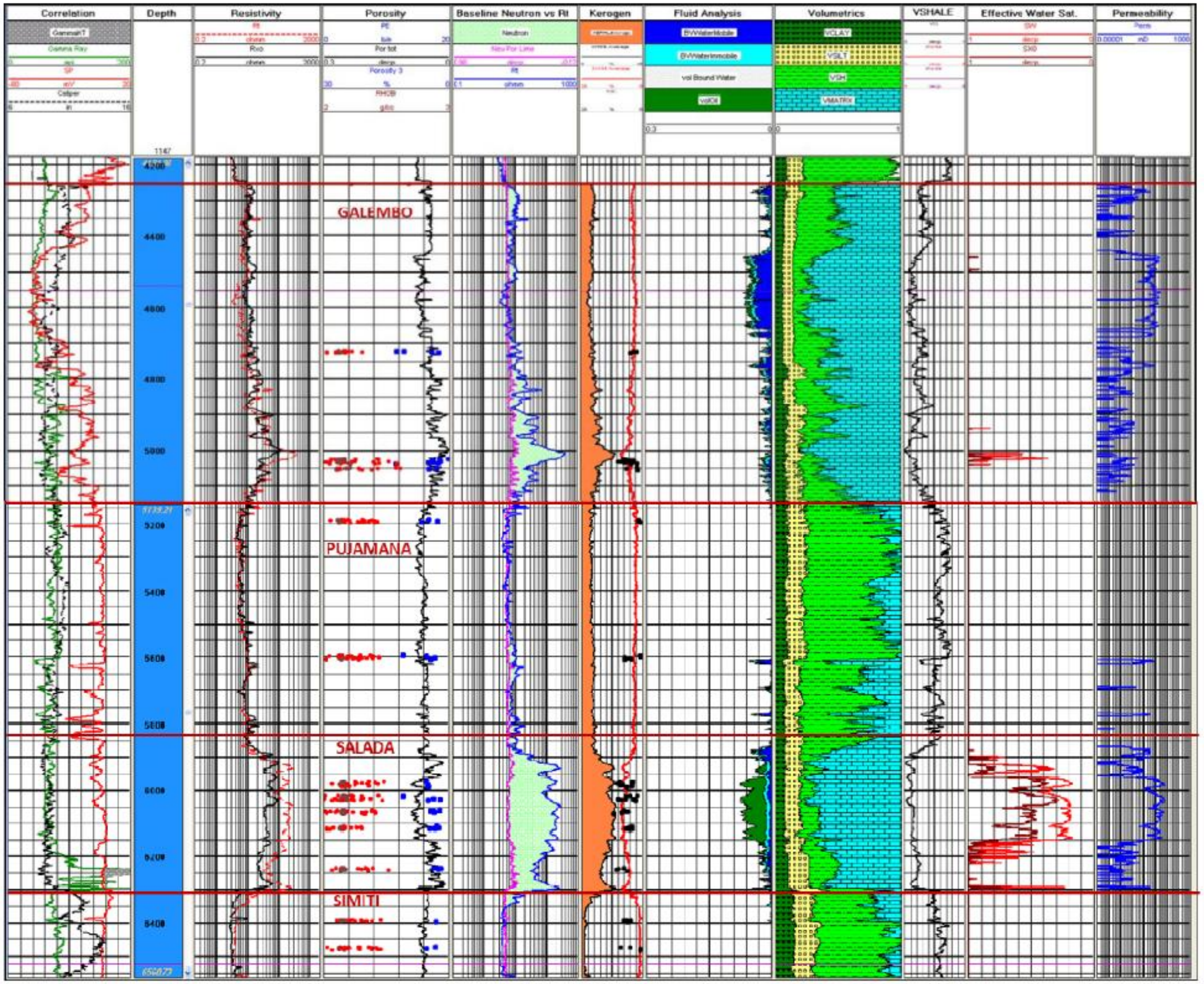

Figure 7. Petrophysical Interpretation of La Luna Formation (MMV Basin) at Infantas-1613 well.

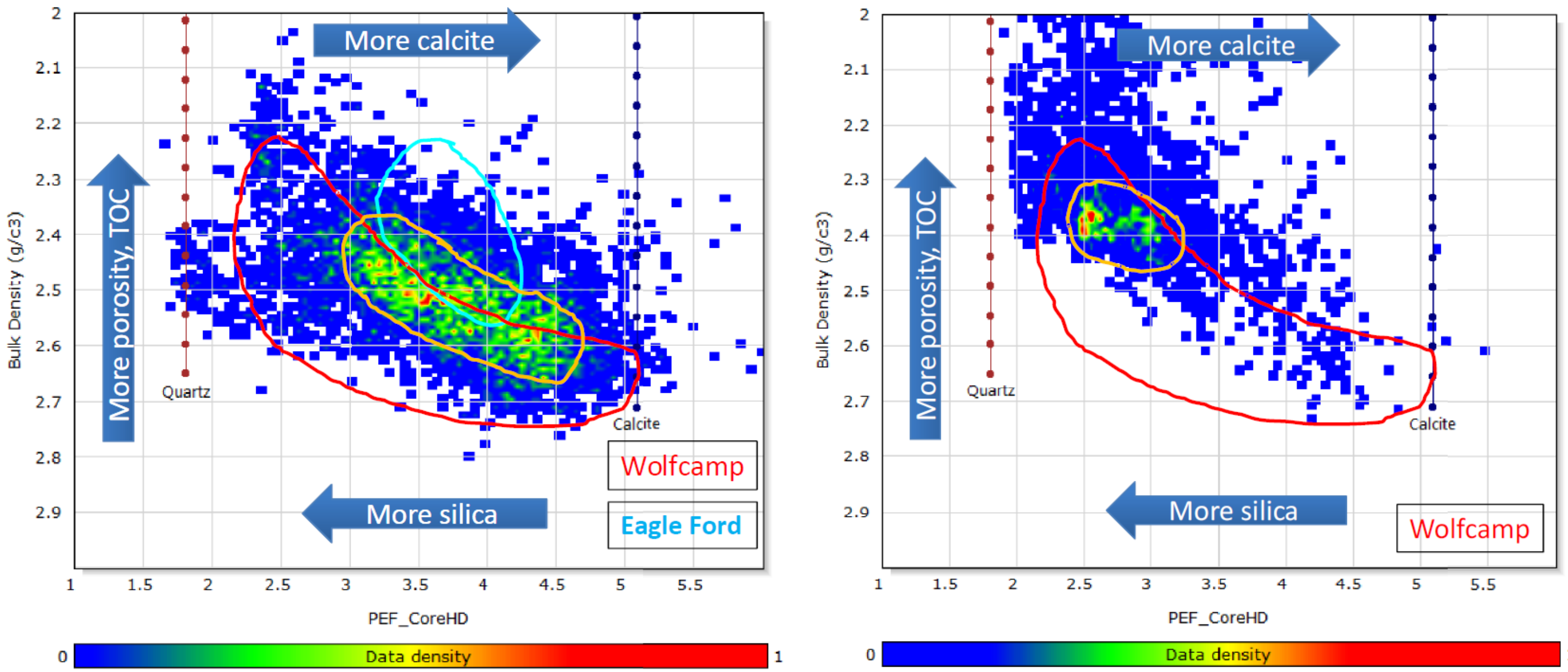

Figure 8. Rock quality compared to analogs of La Luna (MMV and Catatumbo) is similar to or better than many North America shale plays. A. La Luna, Catatumbo: TOC higher, porosity slightly lower, perm higher than Wolfcamp or Lower Eagle Ford. B. La Luna, VMM: Porosity similar and permeability higher than middle Wolfcamp.

Averages	La Luna VMM	La Luna Fm Catatumbo	Llanos Gacheta	Middle Wolfcamp	Lower Eagle Ford	Fayette-ville
Depth Range (ft) Core Samples	2742- 12405	4057- 8310	5928-10876	5600-11000	3800-13000	2100-7700
Porosity (%)	6.3	4.8	5.1	6.4	7.3	4.3
Organic porosity (% of Total Porosity)	47%	71%	51%	60%	67%	80%
Solid Organic Material (vol %)	7.7	8.1	4.7	7.0	5.2	9.6
Porosity of Organic Material	29%	20%	27%	22%	39%	23%
Permeability (K_horizontal)	920	733	982	200	730	120
Maturity (Ro), Kerogen Type	0.6 – 1.0 (Increasing to south & east) Type II	0.6 – 2.0 (Increasing to south) Type II	0.5 –0 .8 (Increasing to west) Type III	0.7-1.0	0.8 to 1.6	1.2-1.5
Likely Hydrocarbon Type	Mostly Oil	Mostly condensate	Conden-sate to gas	Oil to conden-sate	Oil to dry gas	Dry gas

Table 1. A comparison between the data obtained for the Gacheta Formation in the Llanos basin and the La Luna Formation in MMV and Catatumbo basins of Colombia and an important North America shale plays.