Comparison of Reservoir Quality from La Luna, Gacheta and US Shale Formations*

Joel Walls[1] and Elizabeth Diaz[2]

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[1]Ingrain, Inc., Houston, Texas, USA (walls@ingrainrocks.com)
[2]La Agencia Nacional de Hidrocarburos (ANH), Bogota, Colombia

Abstract

A large fraction of all whole core samples recovered today come from shale (mudstone) reservoirs. The primary reason for this is that shale 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. High-quality organic-rich shales usually have permeability 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, Digital Rock Physics (DRP). DRP merges 3 key technologies that have evolved rapidly over the last decade. 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. The third is high-speed, massively parallel computation using powerful graphical processing units (GPU's), originally developed for computer graphics and animation.

This presentation describes an integrated DRP process for analyzing rock properties of shale reservoirs at multiple scales. The process begins with whole core samples, progresses to smaller plug size samples, then ultimately to high-resolution 3D imaging of the pore space. This imaging, combined with unique proprietary fluid flow algorithms allows us to compute shale reservoir properties and provide clear 3D renderings of the pore structure. Core samples were available from 4 wells in the Eagle Ford Formation. Results from these wells are compared to La Luna and Gacheta formation cores from the Litoteca Nacional Bernardo Taborda, Colombia. In summary, a multi-scale rock properties analysis process was applied to the analysis of shale reservoir properties in the La Luna and Gatcheta formations. Key results: Porosity and permeability are comparable to or better than those from the Eagle Ford Formation, permeability in the horizontal plane is 10 to 100 times greater than in the vertical direction, porosity association with organic matter varies from 100% of total to less than 10% of total depending on specific formation and depth, and the transformation ratio for kerogen to porosity ranges from about 20% to 40%.

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Comparison of Reservoir Quality from La Luna, Gacheta, and US Shale Formations

Dr. Joel D Walls, Juliana Anderson, Elizabeth Diaz | Ingrain Inc., Houston*

Maria Rosa Ceron | Agencia Nacional de Hidrocarburos, Bogota

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Presentation Outline

- Scope, goals, focus, and timing of project
- Primary focus of this presentation
  - Middle Magdalena Valley Basin
  - Catatumbo Basin
  - Llanos Basin
- Digital Rock Physics Methodology for Unconventional Resources
- Key results and findings
  - Rock Typing and Analog Formations
  - Rock Quality Measures and Comparisons
  - Example Results
- Summary, Future Analysis

SCOPE, GOAL, FOCUS, AND TIMING

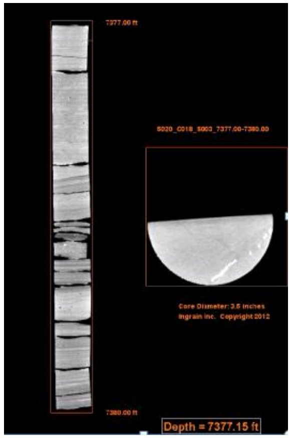
Project Overview: Core Data and Analyses

Project Goal: Identify and characterize shale resource potential in key Colombia basins by analyzing archived core and well log data.

Project Duration: 4 months

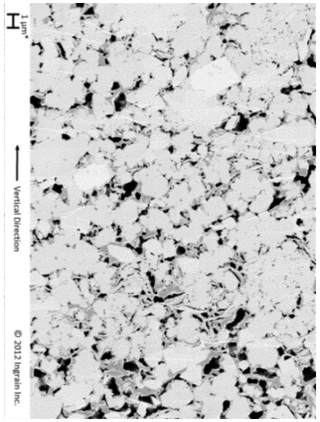
Phase 1: Whole Core X-ray CT Imaging

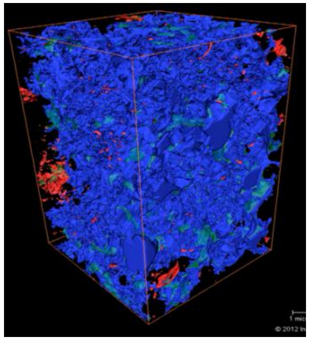
- Total Core Scanned: 31,058 ft
- 139 wells



Phase 2 & 3: Unconventional Rock Quality Workflow

- MicroCT & 2D SEM analysis was performed on 65 wells (4357 plugs, 87000+ 2D SEM images analyzed)
- Top 3 basins analyzed:
    - Catatumbo (1709 plugs)
    - Llanos (842 plugs)
    - Middle Magdalena Valley (803 plugs)
- 3D FIB-SEM analysis was performed on 453 samples.
- Top 3 basins analyzed
    - Catatumbo Basin (141 poro-perm samples)
    - Middle Magdalena Valley (220 poro-perm samples)
    - Llanos Basin (56 poro-perm samples)





*As part of the unconventional workflow, additional analysis of XRF, EDS mineralogy, and Pore Size Distribution on 2D and 3D volumes was performed.

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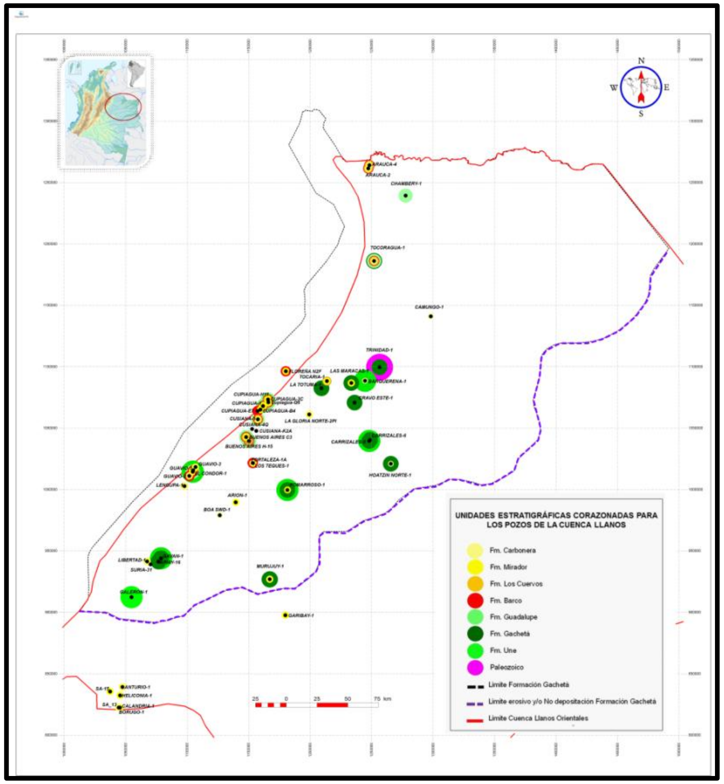
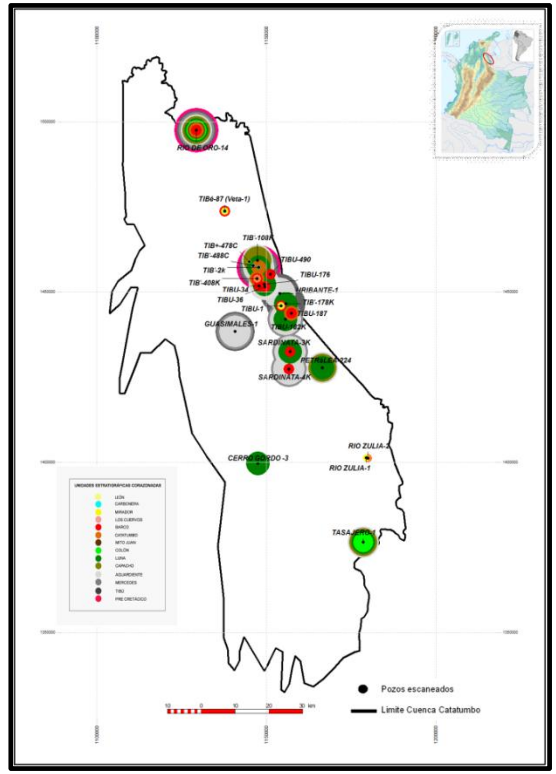
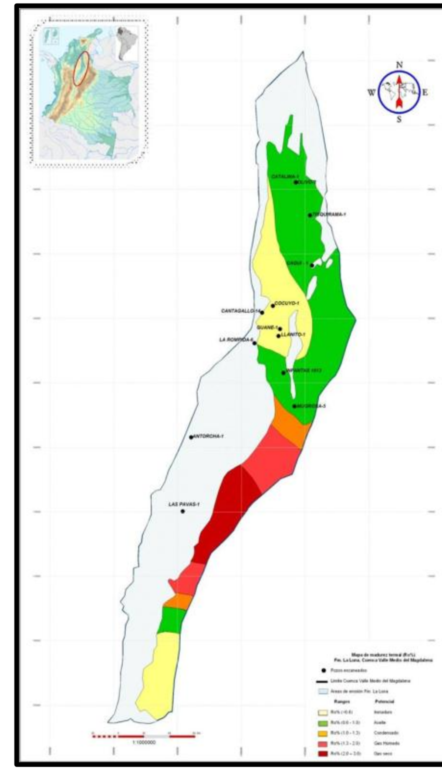
Project Overview: Initial Focus in 3 Basins



Llanos Basin
54 wells
10019 feet of whole core
842 plug samples



Catatumbo Basin
24 wells
7512 feet of whole core
1709 plug samples



Middle Magdalena Valley Basin
13 wells
2012 feet of core
803 plug samples

Approximately 2/3 of total project involves these three basins.

Note: None of the wells in the study were drilled or cored with the intent of unconventional resource analysis.

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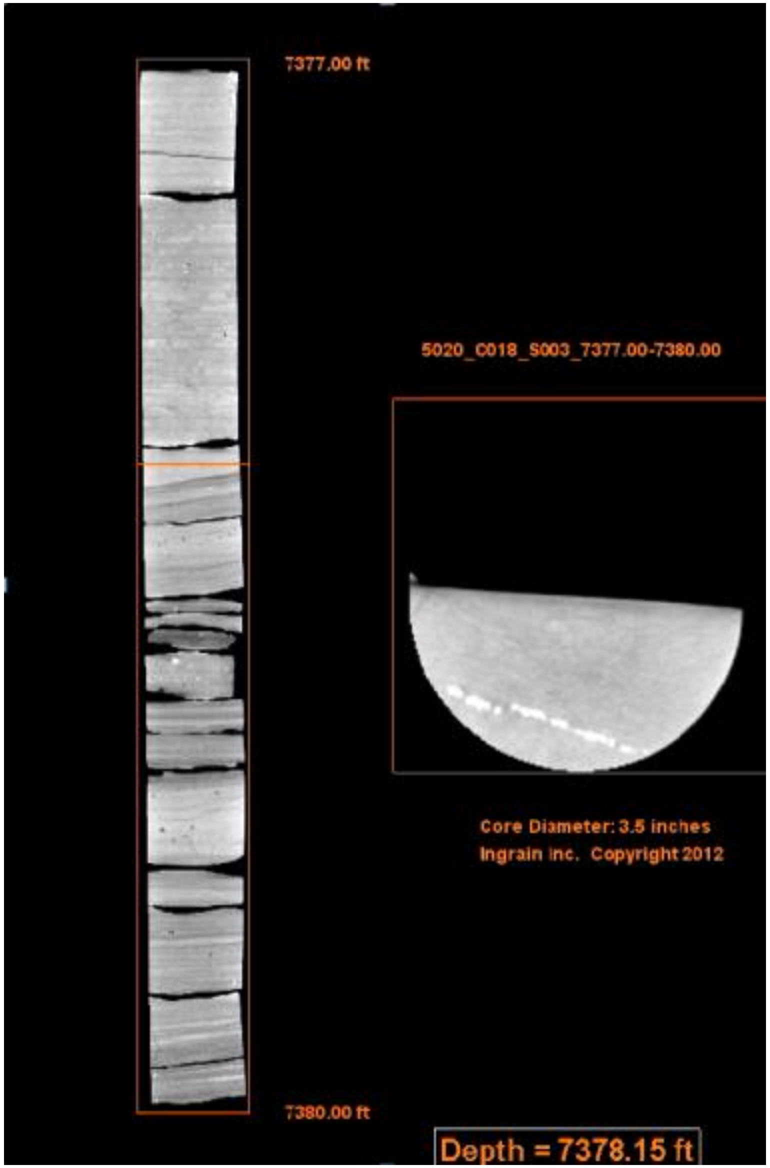
Identify and characterize most productive rock in least amount of time.

DIGITAL ROCK PHYSICS METHODOLOGY FOR UNCONVENTIONAL RESOURCES

Examples: Whole Core CT Imaging



- Half millimeter resolution over entire whole core (500 CT slices/ft)
- Provides the visual information for a detailed geologic description.
- Dual energy CT imaging shows layering, healed and open fractures, and other geologic features.

Continuous whole core scan from Sardinata Norte - 2 well, Catatumbo Basin

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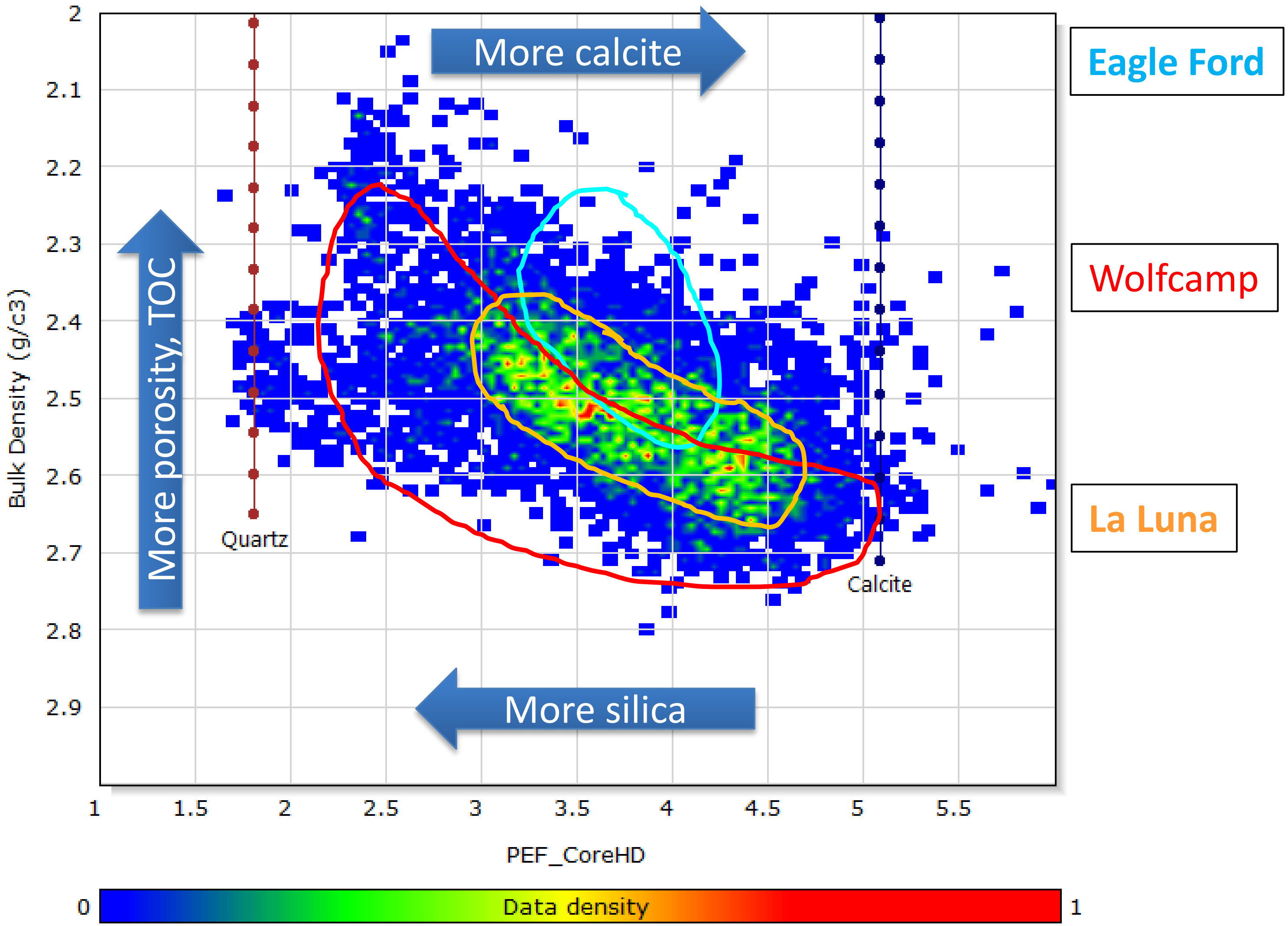
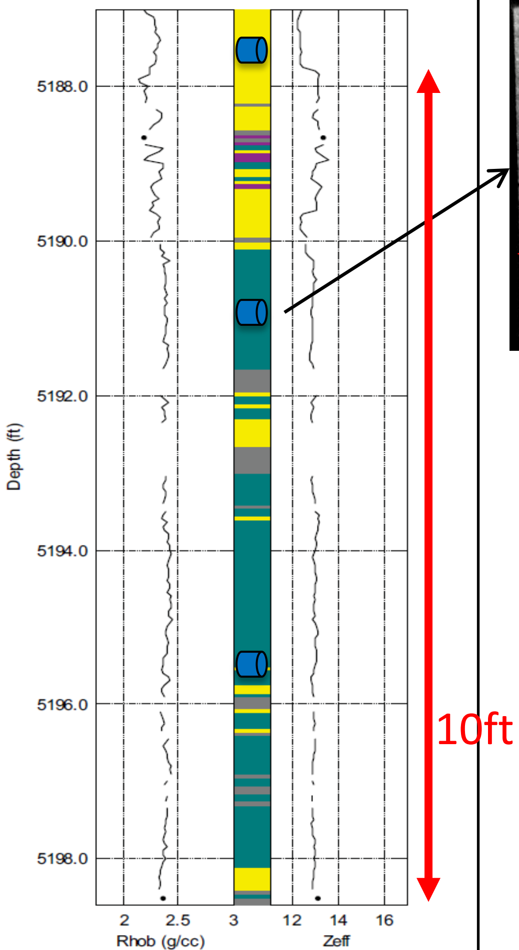
CoreHD Litho-density Analogs: Catatumbo - La Luna

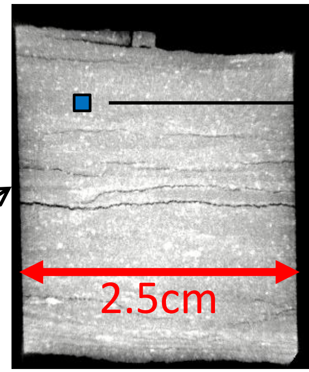


Examples: Sample selection, Micro CT & 2D SEM Imaging

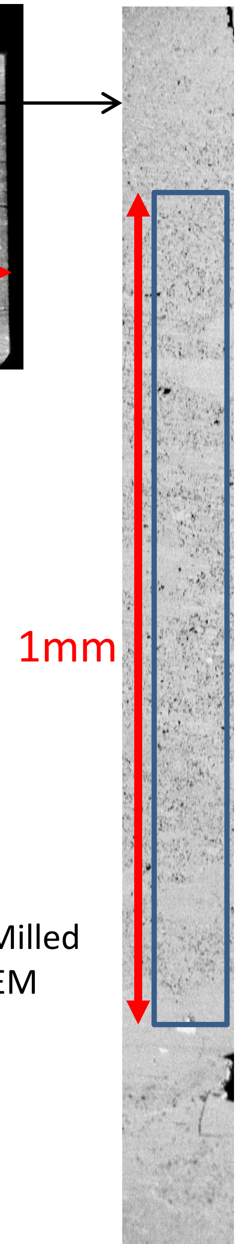


Log by CoreHD™ Facies

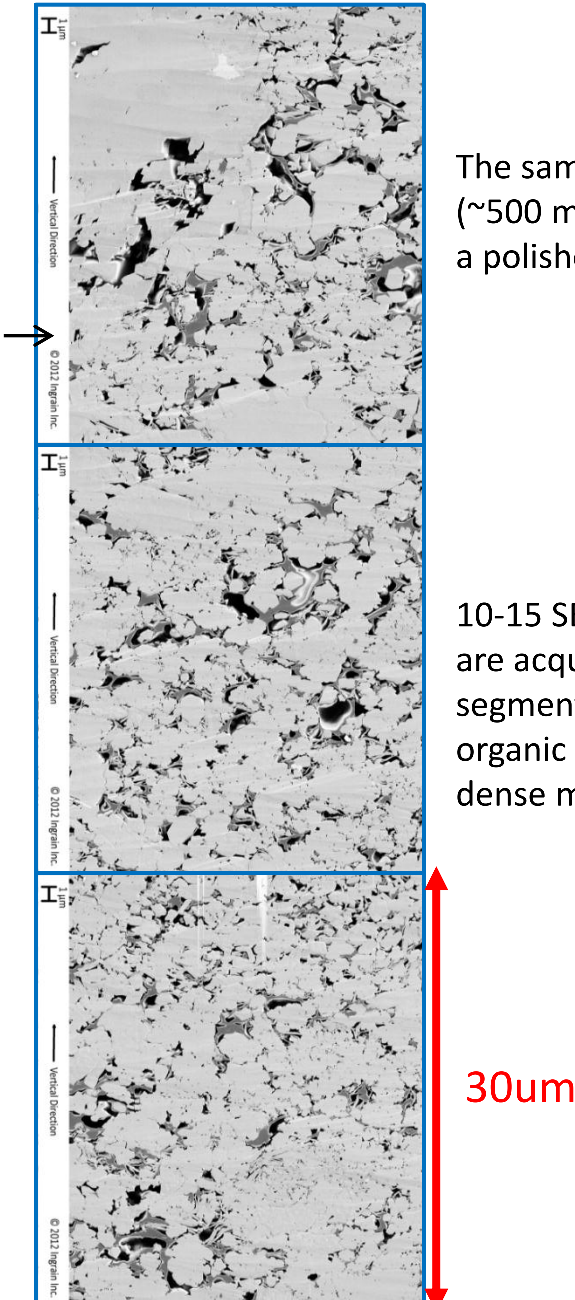
Multiple 1” plugs are taken from each whole core



MicroCT scan



Ion Milled SEM

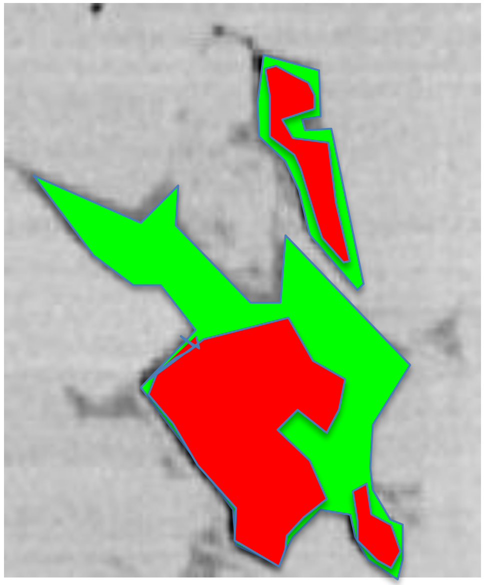


The sample is ion milled (~500 microns) to create a polished surface.

10-15 SE and ESB images are acquired and segmented for porosity, organic matter, and high dense minerals.

Example is from Infantas-1613 well, Sample 315, VMM

Quantifying Porosity Associated with Organic Material (PA_OM) and "Apparent Conversion Ratio"

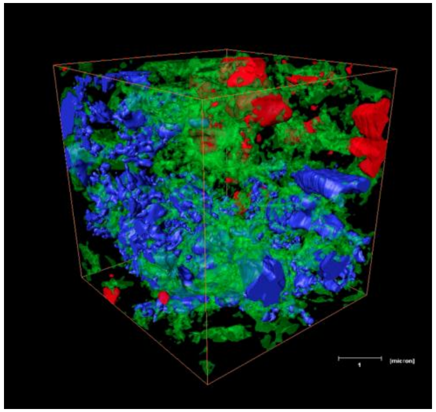


Enlarged image from FIB-SEM

Red = Porosity associated with organic material (PA_OM)
Green = Solid OM

Apparent Conversion Ratio **= Red Area / (Red + Green Area)**
(or Porosity of OM) = PA_OM / (PA_OM + Solid OM)

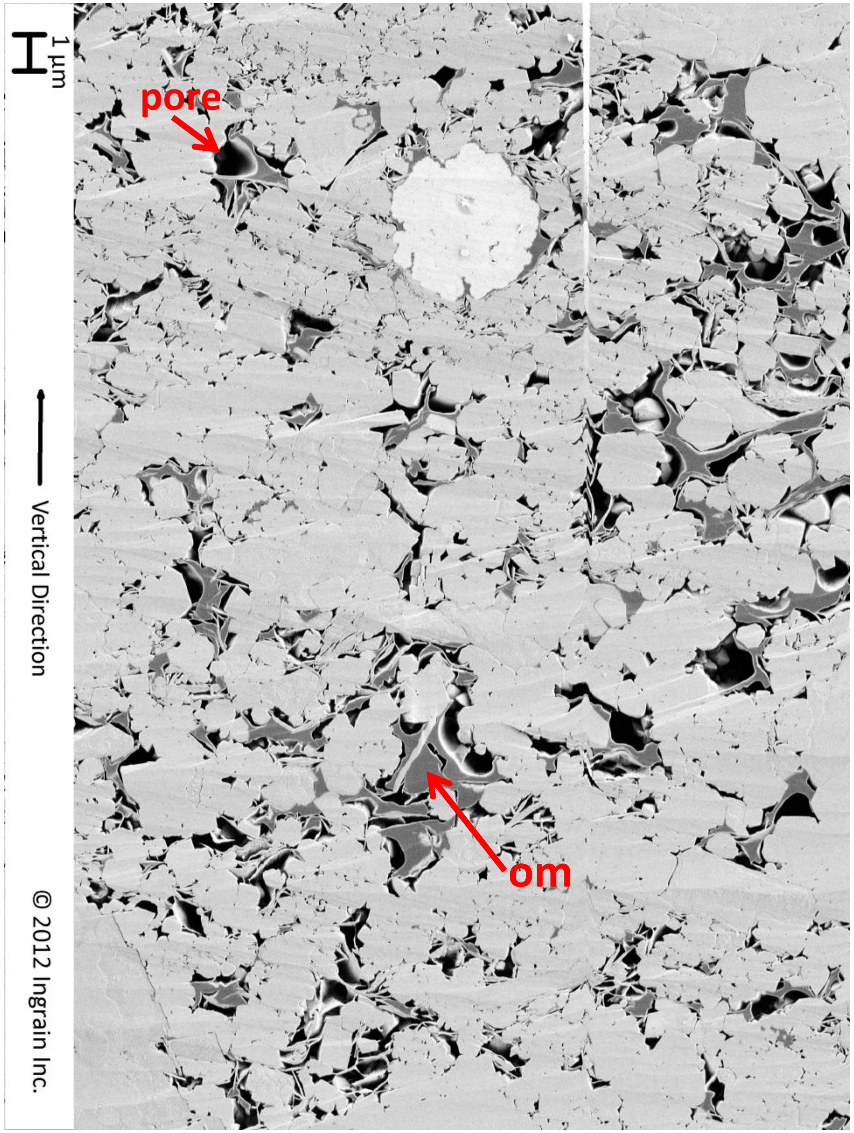
Conversion ratio can only be directly quantified by Digital Rock Physics analysis.

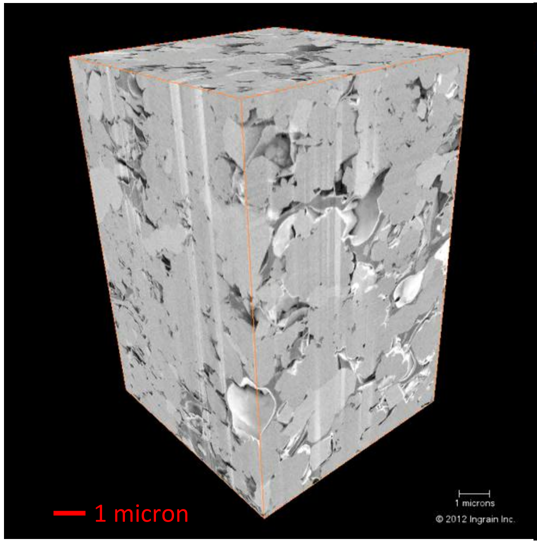


Example: Sample SE2 has PA_OM = 11% and solid OM = 7.7%
Conversion ratio = 11 / (11 + 7.7)
Conversion ratio, Sample SE2 = 59%

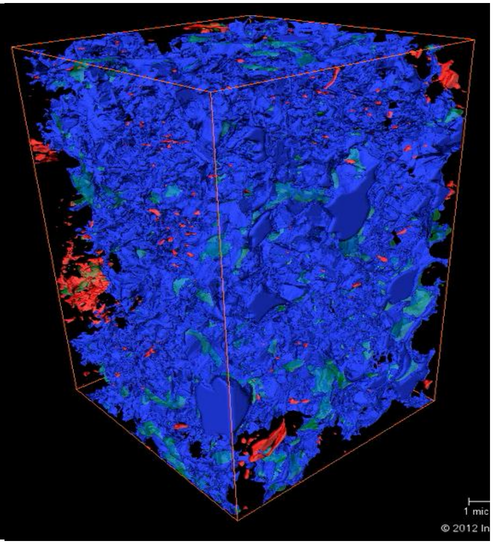
Average for formation = 39%

3D SEM Imaging: VMM Basin





Surface of 3D FIB-SEM Volume



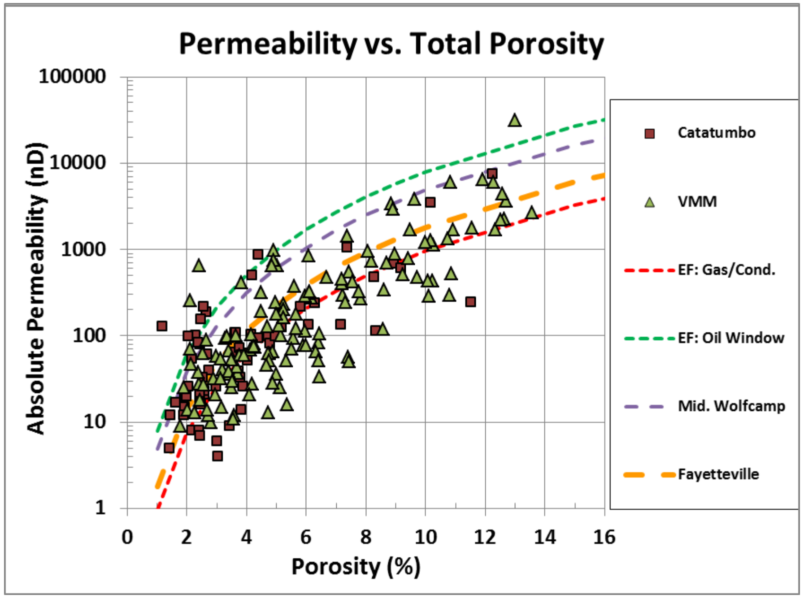
Pore Volume

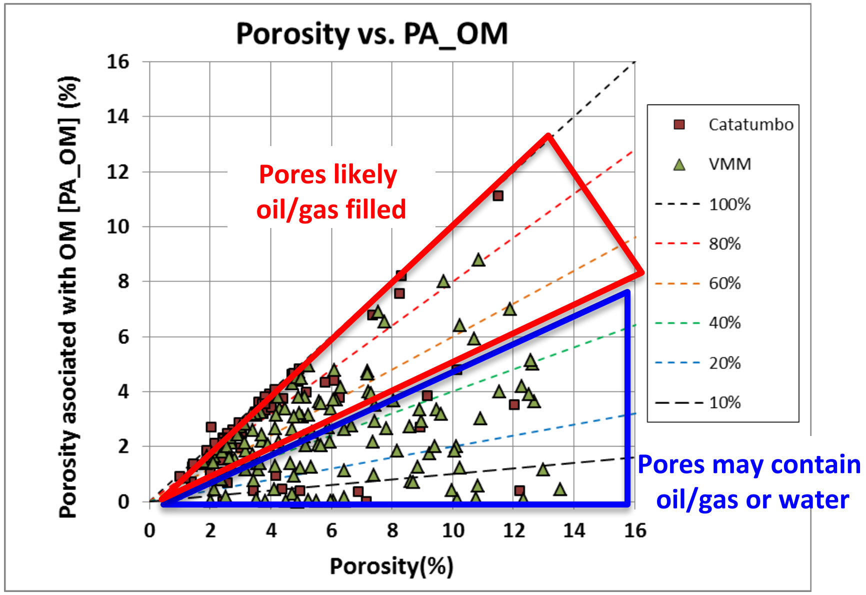
Red: isolated pores Blue: connected pores
Green: organic material

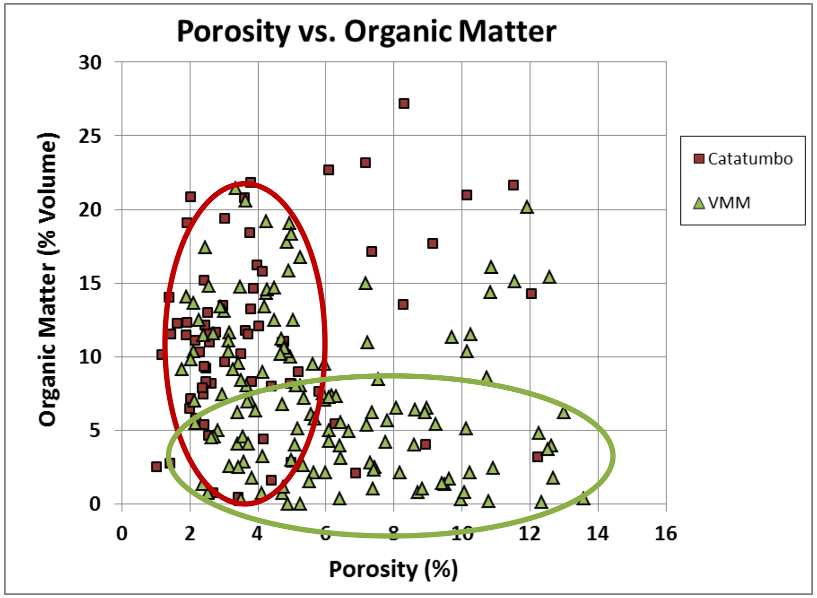
Infantas-1613 Sample 315	Volume %
Total Porosity	10.7
Non-Connected Porosity	0.4
Organic Matter Content	8.6
Porosity Associated with Organic Matter	5.9
Porosity of Organic Material	41
Absolute Permeability (k_Horiz.)	1350 nD

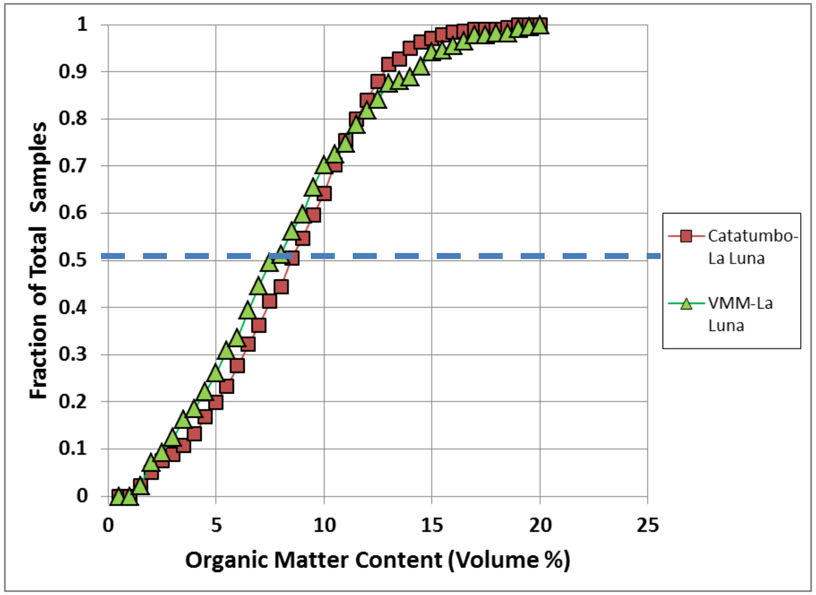
KEY RESULTS AND FINDINGS

Rock Quality Analysis – La Luna Fm

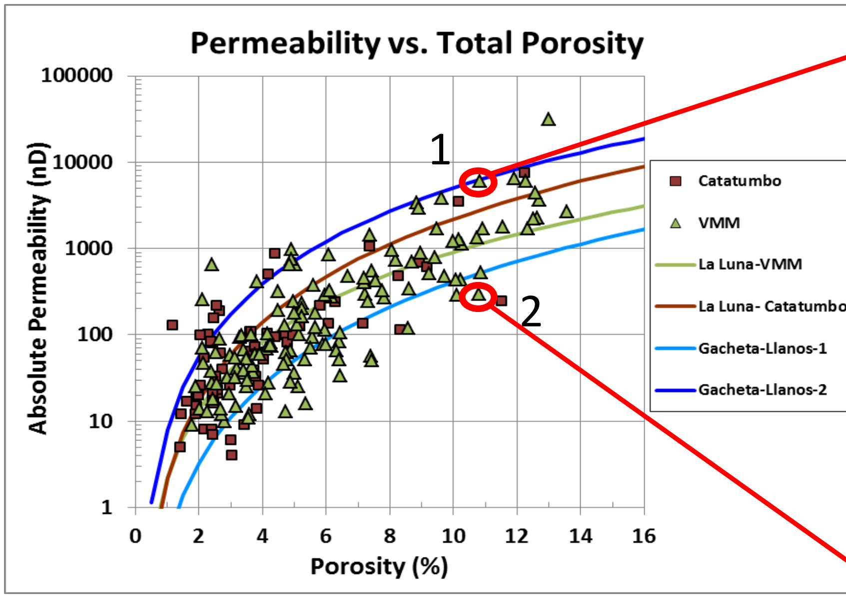




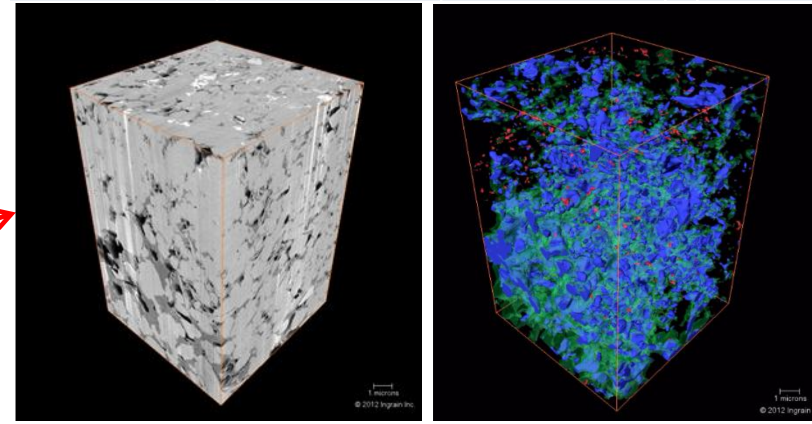




VMM: Infantas-1613 - Differences in Permeability Related to Pore Types and Sizes

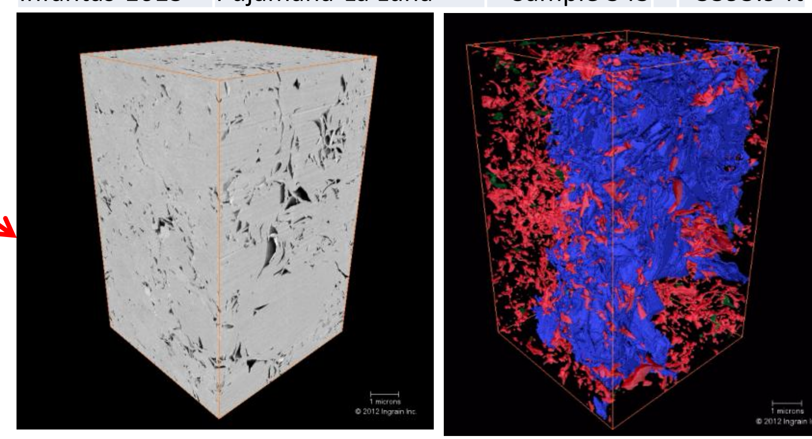


Infantas-1613	Salada-La Luna	sample 361	6019.7 ft



Porosity=10.84%, OM=14.4%, PA_OM=5.6%, K_Horiz.=6045nd, Ave pore diameter=180nm

Infantas-1613	Pujamana-La Luna	Sample 343	5595.9 ft



Porosity=10.79%, OM=2.56%, PA_OM=1.1%, K_Horiz.=297nd, Ave pore diameter = 45nm

- Sample 1 and 2 have similar porosities, but their permeability values differ.
- Sample 1 contains more organic porosity and is connected through the organic material. This sample has the highest permeability
- Sample 2 contains mostly inter-granular porosity

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Rock Quality Analysis – 3 Basins- 2 Formations

Averages	La Luna Fm VMM	La Luna Fm Catatumbo	Llanos Gacheta	Middle Wolfcamp	Eagle Ford
Depth Range (ft) Core Samples	2742- 12405	4057- 8310	5928-10876	5600-11000	3800-13000
Porosity (%)	6.3	4.8	5.1	5.6	7.5
Organic porosity (% of Total Porosity)	47%	71%	51%	47%	76%
Solid Organic Material (vol %)	7.7	8.1	4.7	8.2	9.6
Porosity Inside Organic Material	29%	20%	27%	47%	39%
Permeability (K_horizontal)	920	733	982	617	717
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
Likely Hydrocarbon Type	Mostly Oil	Mostly condensate	Conden-sate to gas	Oil to conden-sate	Oil to dry gas

Caution: Averages can be deceiving! There is large variability depending on facies, depth, organic pore type, and other factors.

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Summary

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- Rock quality of La Luna (VMM and Catatumbo) similar or better than many North America shale plays. Gacheta formation in Llanos may be prospective but data is limited.
- Rock property ranges;
  - Catatumbo – Poro; 3-12%; TOC (vol%) 5-27; Permeability 10 – 1000nd
  - VMM - Poro; 2-13%; TOC (vol%) 0-20; Permeability 10 – 10000nd
  - Llanos - Poro; 2-12%; TOC (vol%) 0-5; Permeability 10 – 1000nd (2 wells only)
- Rock quality compared to analogs.
  - La Luna, Catatumbo -----TOC higher, poro slightly lower, perm higher than Wolfcamp or LEF
  - La Luna, VMM-------------Porosity similar and permeability higher than middle Wolfcamp
  - Gacheta, Llanos-----------Porosity and permeability similar to Fayetteville
- Large variability by depth and well location.
- Some zones have high inter-granular porosity, which may host water.
- Tier 1 Unconventional Prospect: LaLuna; Catatumbo and VMM
- Tier 2 Unconventional Prospect: Lower Gacheta; Llanos

The authors gratefully acknowledge the Agencia Nacional de Hidrocarburos, Colombia for permission to present this material.

Understanding Organic Porosity Texture