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Integral evaluation of unconventional reservoir properties from multi-scale imaging and análisis

Evaluación integral de propiedades de yacimientos no convencionales a partir de imágenes y análisis a diferentes escalas

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Abstract
Since the production of conventional oil and gas is declining while costs are increasing, in recent years focus of interest directed toward unconventional reservoirs. The integral evaluation of unconventional reservoirs is based on multi-scale imaging and analysis, which includes X-ray Computed Tomography, X-ray Micro-Computed Tomography, Quantitative Evaluation of Minerals by Scanning Electron Microscopy and Focused Ion Beam Scanning Electron Microscopy, which can be integrated each other to provide a dataset that can assist in understanding the rock properties and can be used for understanding the rock properties based on their integral evaluation to improve reserves estimates and production efficiency, and mitigate all the associated risks. In this work, we highlight a mineralogy workflow for integral evaluation of unconventional reservoirs, involves imaging and analysis of unconventional rocks like tight sandstones, carbonates and shales, to study effects of clay, minerals and diagenetic processes and to carry out fast and accurate computations of rock properties, such as porosity and pore geometry (pore size, connectivity and distributions), absolute and relative permeability, fracture network, and flow simulations.

Keywords: unconventional reservoirs; multi-scale imaging; analytical techniques; petrophysical properties; reserves estimate.

Resumen
Dado que la producción de petróleo y gas convencionales está disminuyendo mientras que los costos están aumentando, en los últimos años se ha centrado el interés en los yacimientos no convencionales. La evaluación integral de yacimientos no convencionales se basa en imágenes y análisis a diferentes escalas, que incluyen la Tomografía Computarizada de Rayos X, la Micro-Tomografía Computarizada de Rayos X, la Evaluación Cuantitativa de Minerales mediante Microscopía Electrónica de Barrido y Microscopía Electrónica de Barrido con Haz de Iones Focalizados, que pueden integrarse entre sí para proporcionar un conjunto de datos que puede ayudar a comprender las propiedades de las rocas y utilizarse para mejorar las estimaciones de reservas y la eficiencia de producción, así como para mitigar todos los riesgos asociados. En este trabajo, destacamos un flujo de trabajo mineralógico para la evaluación integral de yacimientos no convencionales, que implica la obtención de imágenes y el análisis de rocas no convencionales, como areniscas compactas, carbonatos y lutitas, para estudiar los efectos de arcillas, minerales y procesos diagenéticos, y llevar a cabo cálculos rápidos y precisos de propiedades de las rocas, como porosidad y geometría de los poros (tamaño de poro, conectividad y distribuciones), permeabilidad absoluta y relativa, red de fracturas y simulaciones de flujo.

Palabras clave: yacimientos no convencionales; imágenes a diferentes escalas; técnicas analíticas; propiedades petrofísicas; estimación de reservas.

1. Introduction

The integral evaluation of unconventional reservoir properties through multi-scale imaging and analysis remains relevant and valuable even in the context of the global energy crisis. There are some reasons why these subjects continue to be important: (1) Diversification of energy sources: Despite the energy crisis, the world continues to heavily rely on fossil fuels. Exploration and exploitation of unconventional reservoirs, such as shale gas, can help diversify energy sources and reduce dependence on conventional resources. (2) Energy efficiency: Improved understanding of unconventional reservoir properties and associated technology can lead to more efficient energy extraction, which can be crucial for resource conservation. (3) Innovation and technology: Research in this field involves the development of new technologies and analysis approaches that can be applied in other areas. Innovation in reservoir evaluation can have a broader impact on the energy industry and address energy-related challenges. (4) Environmental considerations: The exploitation of unconventional reservoirs often raises environmental issues, such as wastewater management and hydraulic fracturing. Researching these properties can help address environmental challenges and promote more sustainable practices. Therefore, while the current energy crisis presents challenges, research in the evaluation of unconventional reservoirs remains relevant due to its potential to diversify energy sources, improve efficiency, and promote technological innovation in the energy industry. Research in this area can have a significant impact on the future of energy and environmental sustainability. Reservoir characterization is a very important process with the overarching goal of creating robust models that enhance the accuracy of reservoir property predictions, crucial for full-field and large-scale simulation models [1]. Achieving this objective necessitates a comprehensive evaluation of petroleum reservoir geology, drawing from a wealth of data sources, including drilled cores, core plugs, thin sections, and petrophysical logs, as well as laboratory analyses encompassing X-ray diffraction (XRD) assessments to define grain mineralogy and porosity-permeability data for reservoir quality assessment [2]. Furthermore, our understanding of reservoirs is rooted in a multifaceted foundation, incorporating geological, geophysical, petrophysical, and periodic or routine studies. While geological, geophysical, and geochemical data provide static insights into rock properties and reservoir structure, dynamic data emerge from the continuous monitoring, collection, and analysis of well production and related information [3]. In this context, innovative technologies have emerged as indispensable tools for comprehending rock properties through an integrated approach. These technologies encompass X-ray computed tomography [4-5], micro-computed tomography [6-7], scanning electron microscopy [8-9], Quantitative Evaluation of Minerals by Scanning Electron Microscopy [10-12], and Focused Ion Beam Scanning Electron Microscopy [8,13]. They serve as valuable assets in the quest for an all-encompassing grasp of reservoir characteristics. Digital Rock Physics (DRP) plays a pivotal role in investigating and calculating the physical and fluid flow properties of porous rocks, serving as a complement to traditional and unconventional petroleum reservoir characterization methods. It is, however, imperative to establish a well-defined workflow to maximize the potential of these new techniques in characterizing oil reservoirs. Such a workflow can provide insights across various scales, ultimately facilitating decision-making within oil field production strategies. As a response to this need, our work presents a comprehensive methodology and workflow tailored to extract the most valuable insights into the mineralogical and petrophysical attributes of both conventional and unconventional oil reservoirs.

2. Workflow for mineralogy research

The mineralogy research workflow, as depicted in Fig. 1, has been meticulously crafted to cater to the specific demands of characterizing unconventional reservoir rocks. It is within these unconventional rock formations that we have witnessed remarkable strides and significant market applications. Let's delve into the key stages of data acquisition illustrated within this workflow. Sampling and the meticulous examination of geological materials form the foundational steps in the digital workflow, which operates seamlessly across varying scales. This adaptable process plays a pivotal role in the characterization of unconventional deposits, where advancements in research and technology have translated into substantial advantages for the industry at large. The following are the critical processes through which we arrive at the determination of the most important properties:

Acquisition of data across multiple scales: The initial phase of the workflow involves the collection of data at macro, micro, and nano scales. This multilayered approach allows us to capture a comprehensive view of the rock's composition and properties. The data acquired at each scale contribute to the holistic understanding of the reservoir.

3D modeling of petrophysical properties: Following the data acquisition phase, the subsequent step is the creation of a 3D model that encapsulates the petrophysical properties of the reservoir rocks. This modeling process serves as a bridge between raw data and actionable insights, enabling us to visualize and analyze the complex interplay of properties within the reservoir.

This comprehensive workflow is meticulously designed to empower researchers and industry experts with the tools and methodologies needed to unlock the full potential of unconventional reservoirs. As technological advancements continue to reshape the landscape of mineralogical research, the practical applications of this methodology stand as a testament to the industry's capacity for innovation and progress.

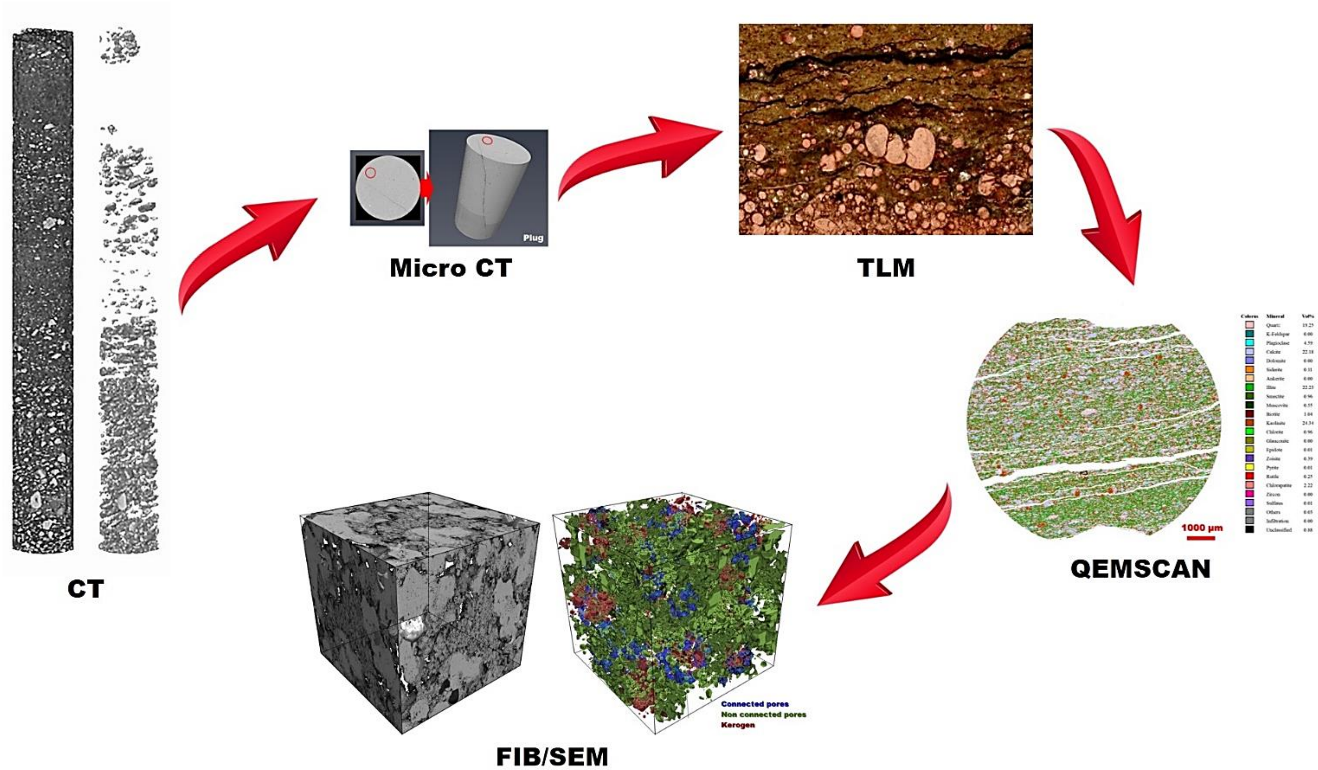


Figure 1. Workflow for mineralogy research from multi-scale imaging and analysis. Fuente: Autores.

2.1. X-ray computed tomography (X-ray CT)

X-ray CT is a non-destructive imaging technique that harnesses the power of X-ray technology and sophisticated mathematical reconstruction algorithms to unveil cross-sectional slices of rock formations [14], vividly portrayed in Fig. 2a. It stands as a formidable tool, adept at preserving the wealth of information attainable from rock core sections, all the while complementing the realm of digital rock physics. This makes it an invaluable asset in the oil and gas industry for in-depth examinations of core internal structures and the assessment of the abundance and distribution of rock-forming mineral phases, as exemplified in Fig. 2b. In practice, X-ray CT plays a multifaceted role that extends beyond mere visualization. One of its primary functions is the ability to segment core sections, facilitating the detailed examination of the distribution of coarse-grained portions. The volumetric measurement of these coarse sections contributes significantly to our understanding of the reservoir's composition. Furthermore, X-ray CT comes to the fore when it comes to identifying high-quality rock intervals that exhibit notable characteristics such as elevated porosity and total organic carbon (TOC) content [4]. The nuanced interactions within X-ray CT imaging merit attention. Wellington and Vinegar [14] underscore the duality of high-energy and low-energy images. High-energy images demonstrate heightened sensitivity to bulk density, a phenomenon rooted in the Compton Scattering effect, while low-energy images exhibit a greater propensity for capturing mineralogical nuances, attributable to the Photoelectric Absorption effect. Following the X-ray CT scanning process, a series of computations come into play to derive logs for bulk density (RhoB) and effective atomic number (Zeff). These logs, in turn, yield quantitative data on bulk mineralogy, lithology, porosity, rock facies, and depositional sequences [4,15]. Therefore, X-ray CT serves as a conduit to unlock a wealth of information regarding the reservoir's intricate composition and provides critical insights that guide decision-making processes within the oil and gas industry.

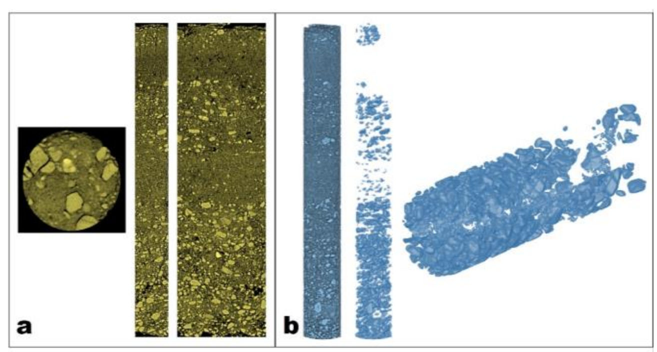


Figure 2. (a) Left, Axial view (XY plane) of a whole core section. Center, XZ plane. Note heterogeneities of the material that composes the rock sample. Right, 0° to 360° view of the whole core section. (b) Left, Rendered volume of the core. Middle, Segmented coarse grain portion from the core sample. Right, Perspective for the Spatial distribution of the coarse grain portion. Fuente: Autores.

2.2. X-ray micro-computed tomography (X-ray µCT)

X-ray µCT, a non-destructive technique for 3D imaging, becomes the step from the macro to the nano scale, since with this analysis and thanks to the resolution reached, it is determined to make the most detailed analyses and which are key to evidence the mineralogical characteristics of the material of interest, it is noteworthy that performing X-ray µCT analysis is not simple and even less so is the correct interpretation and integration of the data at the reservoir level, however there are parameters that are key to define and that are subject to the type of material that is being analysed, such as the size of the sample, the voltage and the power in such a way that the characteristics observed in the material are a faithful reflection of the rock and not a by-product of a bad data acquisition. Each selected plug sample from the whole core was scanned by X-ray µCT, which were carried out at multiple depths based on whole core X-ray CT scanning and information about principal zones of interest (Fig. 3). X-ray µCT allows to identify rock types and their distribution within them and to select locations for thin sections and micro-plugs.

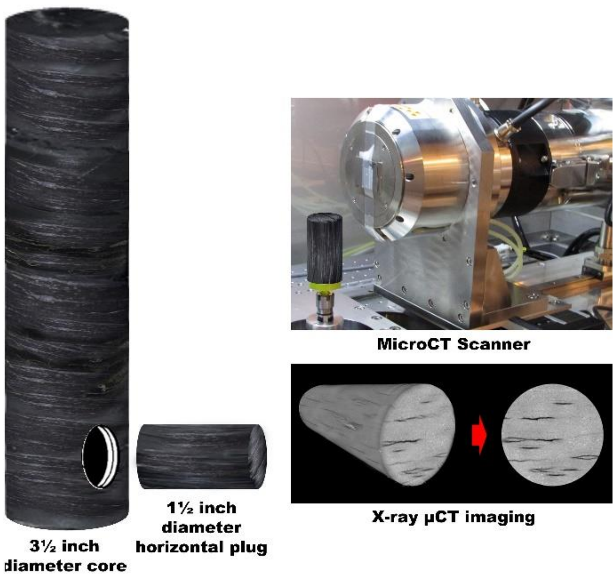


Figure 3. Left, plugging from a whole core. Right top, imaging with a X-ray µCT scan. Rigth bottom, X-ray µCT 3D image of the plug and vertical slice through the 3D image. Fuente: Autores.

A series of projection images from different angles (0 to 360°) are collected by rotating the plug around its axis. These projection images are processed to generate 2D X-ray µCT slices, which subsequently are input date to construct a 3D image of the plug. The complexity of the X-ray µCT is counteracted by the great benefits obtained when analyzing materials with this technique, since images taken correctly are the door to discover the details in mineralogy that our material has and what will lead us to make a segmentation within the rock volume of the most representative features that will be inserted in the dynamic model of the reservoir, through the second stage which corresponds to the inverse process since we go from the nano scale to the macro scale to the simulate scale in the reservoir model all the details of mineralogy, porosity, organic matter found in the acquisition and processing of information.

2.3. Transmitted light microscopy (TLM)

A petrographic examination conducted on thin sections of reservoir rocks plays a pivotal role in unraveling the intricate mineralogical intricacies that underpin the genesis of secondary porosities. These secondary porosities, in turn, hold the key to augmenting the petrophysical properties of porosity and permeability, consequently enhancing the overall quality of the reservoir rock. Within the realm of diagenetic processes, a myriad of events wield influence over the degree of mineral impregnation. Notably, the accretion of clay aggregates and the presence of matrix clays bearing evidence of chloritization stand as pivotal factors. Additionally, the transformation of feldspars into carbonates significantly impacts the porosity and permeability of the rock. Petrographic porosity within arenites tends to manifest high values, with much of it being secondary in nature, originating from dissolution processes. The proportion of matrix material and the presence of diagenetic minerals exercise control over this petrographic porosity. Particularly noteworthy is the dissolution and fracturing of framework grains, including feldspar, chert, lithic, and to a lesser extent, quartz. These processes generate supplementary porosity and permeability within the rock, effectively interconnecting with any residual intraparticle porosity (Fig. 4). An intriguing observation often encountered in these rock formations pertains to dissolution processes that give rise to micro-scale porosities of considerable significance. These dissolution processes exhibit a proclivity for microcrystalline chert grains and potassium feldspar grains. Notably, the sparse presence of plagioclase feldspars suggests an intensive dissolution process, which may have resulted in the complete eradication of plagioclase grains from the rock matrix. This holistic petrographic analysis unveils a profound understanding of the mineralogical intricacies that dictate reservoir rock quality, providing invaluable insights for reservoir assessment and management strategies.

Fig. 5 provides a detailed visual representation of key microscopic features found in rock reservoirs, offering insights into the mineralogy and diagenesis within the reservoir of interest. Fig. 5a reveals some intriguing features: “syntaxial silica overgrowths”. Syntaxial overgrowths are mineral growths that develop in optical continuity with another existing mineral, in this case, detrital quartz. The syntaxial silica overgrowths are indicated by red arrows. This suggests that silica has grown over the pre-existing quartz. In Fig. 5b features related to illite-type clays are observed. These appear as “bridges” or “menisci” connecting grains within the rock matrix. These clay bridges can be significant barriers to rock permeability, hindering the flow of fluids through the rock. They can also limit the migration of fine particles within the reservoir when subjected to high flow pressures, which can be crucial in hydrocarbon production.

Fig. 5c depicts a feature similar to the one described in Fig. 5b, suggesting a repetitive or common distribution of these clay bridges in the sample. Fig. 5d showcases an intriguing feature known as “coating cements”. These cements are pre-diagenetic clays that envelop grains in the rock framework, resembling “coats”. The red arrows indicate where these cements are located. Additionally, in this part of the figure, different stages of potassium feldspar dissolution due to interaction with low-pH formation waters are shown. This dissolution increases the solubility of potassium feldspar and can have significant implications for altering the mineral composition of the rock.

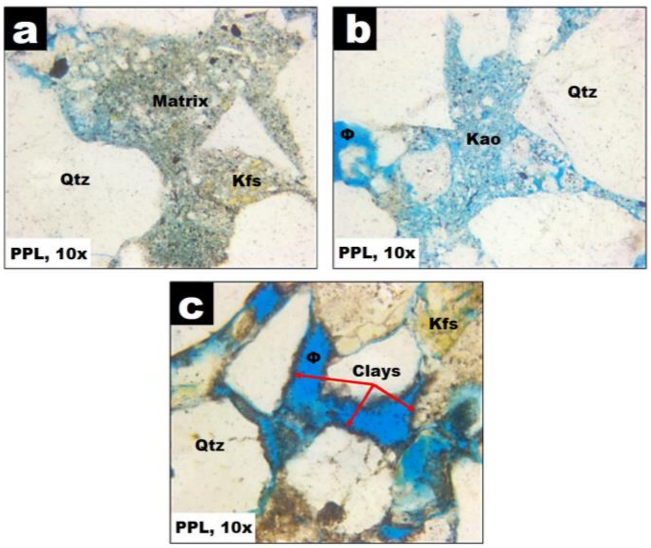


Figure 4. (a) Clay-silty matrix; (b) kaolinite crystals filling pores; (c) pre-diagenetic clay minerals that border the “coating cements” grains. Quartz and potassium feldspar lining by clays. Qtz, quartz; Kfs, potassium feldspar; Kao, kaolinite; Φ, porosity. Fuente: Autores.

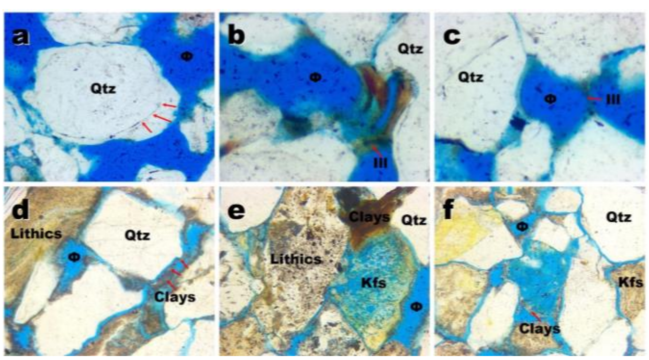


Figure 5. (a) Syntaxial silica overgrowths in optical continuity with detrital quartz (red arrows). PPL, 10x. (b) Bridges or menisci of illite-type clays between the grains, which constitute barriers to permeability and potential migration of fines by stimulating the reservoir with high flow pressures. PPL, 20x. (c) Similar to the previous one. PPL, 20x. (d) Coating cements: pre-diagenetic clays that surround the grains of the framework as “coats” (red arrows). Different stages of dissolution of potassium feldspar due to interaction with formation waters of low pH, which increases its solubility. Qtz, quartz; Kfs, potassium feldspar; Kao, kaolinite; Ill, illite; Φ, porosity. Fuente: Autores.

Fig. 6 illustrates photomicrographs of sandstones from various sedimentary formations in Colombia, showcasing significant variations in grain size. Grain size in sandstones plays a pivotal role in particle sorting and is a critical factor in determining petrophysical properties of the reservoir, including porosity and permeability. Fig. 6a shows a photomicrograph of an extremely coarse-grained sandstone originating from the Paleozoic era in the Central Cordillera of Colombia. The presence of very coarse grains in this formation suggests its potential to host substantial porosity. Porosity is a crucial feature in assessing fluid storage capacity and flow within the reservoir. Fig. 6b exhibits a photomicrograph of a coarse-grained sandstone from the Mugrosa Formation in the Middle Magdalena Valley. In this formation, the grain size is slightly coarser than that in the Central Cordillera. Grain size directly influences porosity, and in this case, the sandstone is likely capable of retaining significant porosity and, therefore, potentially good permeability. Fig. 6c shows a medium-grained sandstone from the La Victoria Formation, a unit within the Honda Group, dating to the Miocene in the Upper Magdalena Valley. Here, we observe a more moderate grain size. Medium-grained sandstones often exhibit intermediate porosity and permeability properties, which can impact their fluid storage and flow capabilities. Fig. 6d illustrates a fine-grained sandstone from the Mirador Formation, located in the Llanos Orientales Basin and dating from the Miocene. In this formation, the grains are notably smaller. Fine-grained sandstones typically have lower porosity and permeability compared to coarse-grained ones, which can influence hydrocarbon production and flow capacity.

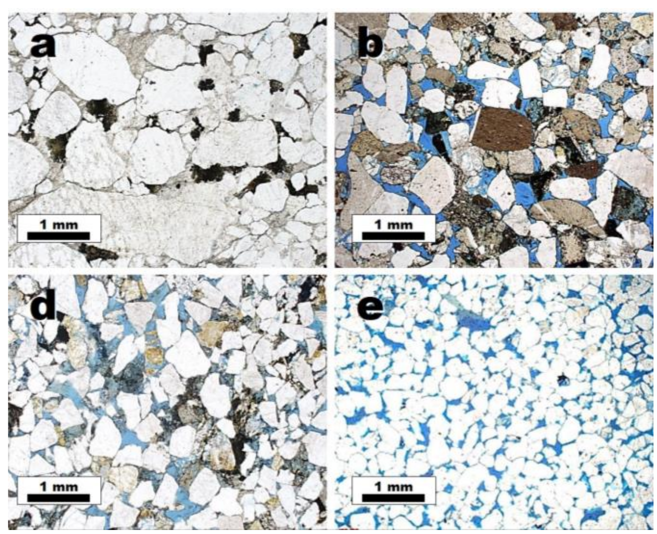
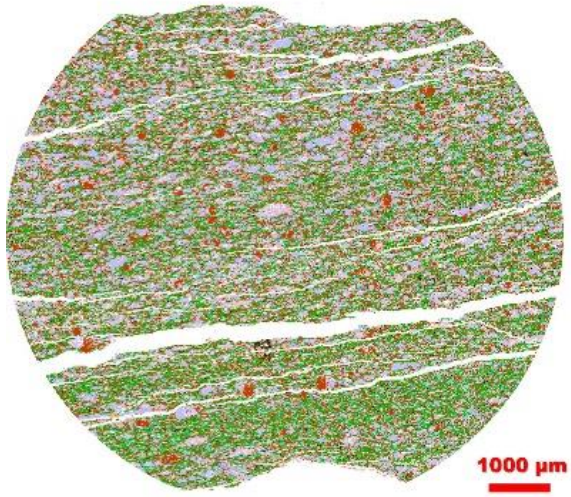


Figure 6. (a) Very Coarse-Grained Sandstone from the Paleozoic in the Central Cordillera. PPL, 4x. (b) Coarse-Grained Sandstone from the Mugrosa Formation in the Middle Magdalena Valley. PPL, 4x. (c) Medium-Grained Sandstone from the La Victoria Formation, Honda Group, Miocene in the Upper Magdalena Valley. PPL, 4x. (d) Fine-Grained Sandstone from the Mirador Formation, Miocene in the Llanos Orientales Basin. PPL, 4x. Fuente: Autores.

2.4. Quantitative Evaluation of Minerals by Scanning Electron Microscopy (QEMSCAN)

QEMSCAN, the Quantitative Evaluation of Minerals by Scanning Electron Microscopy, represents a cutting-edge analytical technique that's instrumental in the characterization of geological materials, particularly in the context of unconventional reservoirs. It hinges on the amalgamation of Backscattered Electron (BSE) and Energy Dispersive (EDS) X-ray data to automate the intricacies of image analysis. The unique selling point of QEMSCAN lies in its adeptness at identifying minerals and producing highly detailed digital images, all at a microscale level. In comparison to conventional methods, QEMSCAN offers an unparalleled advantage by delivering comprehensive mineralogical data in a single streamlined process, affording an exceptional degree of resolution and numerical detail. A typical mineral list of an analysed sample by QEMSCAN is QEMSCAN, the Quantitative Evaluation of Minerals by Scanning Electron Microscopy, represents a cutting-edge analytical technique that's instrumental in the characterization of geological materials, particularly in the context of unconventional reservoirs.



Colorus	Mineral	Vol%
	Quartz	19.25
	K-Feldspar	0.00
	Plagioclase	4.59
	Calcite	22.18
	Dolomite	0.00
	Siderite	0.11
	Ankerite	0.00
	Illite	22.23
	Smectite	0.96
	Muscovite	0.55
	Biotite	1.04
	Kaolinite	24.34
	Chlorite	0.96
	Glauconite	0.00
	Epidote	0.01
	Zoisite	0.39
	Pyrite	0.01
	Rutile	0.25
	Chlorapatite	2.22
	Zircon	0.00
	Sulfates	0.01
	Others	0.03
	Infiltration	0.00
	Unclassified	0.88

Figure 7. Mineralogy by EDS obtained during QEMSCAN analysis for a typical sample of shale. Note how the clay minerals (in green) are distributed in roughly subhorizontal bands. Fuente: Autores.

It hinges on the amalgamation of Backscattered Electron (BSE) and Energy Dispersive (EDS) X-ray data to automate the intricacies of image analysis. The unique selling point of QEMSCAN lies in its adeptness at identifying minerals and producing highly detailed digital images, all at a microscale level. In comparison to conventional methods, QEMSCAN offers an unparalleled advantage by delivering comprehensive mineralogical data in a single streamlined process, affording an exceptional degree of resolution and numerical detail.%), calcite (22.18 wt%), quartz (19.25 wt%), and minor plagioclase (4.59 wt%), apatite (2.22 wt%) and biotite (1.04 wt%). Trace amounts (< 1%) of siderite, smectite, muscovite, chlorite, epidote-group minerals, phosphates, rutile, sulphates and pyrite are also present. The unclassified category, referred to as 'Other,' serves as a catch-all for materials that don't conform to the identified mineral phases. Undoubtedly, QEMSCAN offers tremendous value in understanding the mineralogical, structural, and textural features of geological samples. This high-resolution mapping sheds light on mineral distribution within the rocks, bringing into focus zones enriched in clay minerals and organic matter. These insights are paramount in reservoir evaluation and optimizing hydrocarbon production strategies, echoing the observations made by Ahmad [16]. However, it's important to be cognizant of QEMSCAN's limitations. While it excels in mineral identification and mapping, it may fall short in delivering information regarding total porosity and total organic carbon (TOC wt.%), both of which are crucial factors influencing reservoir quality and hydrocarbon content. To bridge this gap, a comprehensive approach emerges. By quantitatively correlating QEMSCAN findings with results obtained from complementary techniques, such as X-ray diffraction, on the same core samples, the mineralogical profile gains further validation and richness.

The integration of QEMSCAN data with additional analytical methods reinforces the robustness of geological assessments, especially in the context of unconventional reservoirs, which often exhibit intricate mineralogical compositions and heterogeneity. By employing a multi-faceted approach, reservoir engineers and geoscientists can make more informed decisions about hydrocarbon reserves, production strategies, and risk mitigation. Consequently, in a landscape where unconventional reservoirs are gaining increasing importance due to declining conventional oil and gas production and rising costs, the role of advanced techniques like QEMSCAN in reservoir characterization is unequivocally critical. The fusion of data from multiple sources enriches our understanding of these complex geological systems, ultimately contributing to more effective resource management and energy sustainability in the face of global challenges.

2.5. Focused Ion Beam Scanning Electron Microscopy (FIB/SEM)

The 3D reconstruction of the area of interest stands as a pivotal development in the field of geological analysis, offering profound insights into the composition and properties of rocks. This advanced technique employs Focused Ion Beam Scanning Electron Microscopy (FIB-SEM) in tandem with digital reconstruction methodologies, allowing for the intricate visualization of rock-forming minerals, organic matter, and porosity on an individual basis. At the heart of this innovative approach lies the FIB-SEM system, a technological marvel. It captures a high-resolution SEM image of a rock sample's ion beam-polished surface and subsequently employs the ion beam to delicately slice away mere nanometers of the rock. Each slice is meticulously imaged, and this process can be iterated a staggering 500 times for each sample. These individual images are not just a sequence but the building blocks for something grander: a single comprehensive 3D volume. This 3D rendering mirrors the rock's complex internal structure, highlighting the spatial distribution and arrangement of minerals, organic components, and pore spaces. Nevertheless, achieving a holistic understanding of these intricate 3D digital rocks involves several critical steps. Segmentation and image processing come to the forefront, enabling the creation of vRock digital reservoir rocks. These digital models essentially function as geological avatars, meticulously separating the solid minerals, organic material, and pore spaces into distinct 3D objects. This separation provides the basis for a wide array of analyses, delving into fundamental aspects of rock properties. The insights derived from this 3D approach are nothing short of transformative for the field. Standard analysis protocols can encompass evaluating connected and isolated porosity, scrutinizing kerogen volume fraction and its distribution, and mapping absolute permeability across three dimensions (x, y, and z). Fig. 8 illustrates the wealth of information that can be extracted from this 3D digital rock framework. The potential impact of 3D FIB-SEM imaging and digital reconstruction is immense. By examining rocks with unparalleled precision, scientists and engineers can gain a deeper understanding of unconventional reservoirs, shedding light on critical parameters that influence hydrocarbon production, such as porosity, permeability, and the presence of organic matter. Additionally, this technology offers a glimpse into the intricate diagenetic processes and mineralogical variations that shape rock properties. As unconventional reservoirs gain prominence in the energy landscape, owing to the decline of conventional oil and gas production and escalating global energy demands, the capacity to scrutinize these reservoirs at the microscale opens up new horizons. The fusion of 3D FIB-SEM imaging and digital reconstruction techniques equips geoscientists with a powerful toolset to navigate the complexities of unconventional reservoirs, make informed decisions about production strategies, and bolster energy sustainability in an ever-changing world.

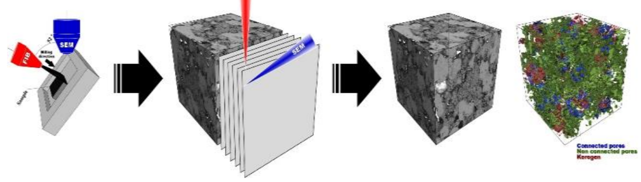


Figure 8. From image processing and segmentation, through model reconstruction and visualization, to pore network modelling workflow. Fuente: Autores.

3. Discussion

The objective of this work is to propose an alternative to the new challenges in the characterization of rocks for hydrocarbon exploration and production. Therefore, the multiscale workflow allows to know the physical and chemical characteristics of some sample starting with a macroscopic scale and ending on a nanoscopic scale, which allows obtaining more and more accurate information about a specific property, for example porosity and permeability, type of porosity, pore shape, pore throat size, connectivity between pores, continuity of interporal space, etc., which is very important in the production plans of a conventional or unconventional reservoir [15,17-18] and the use of tools that allow to investigate from the outside of the rocks to its interior allows to reconstruct detailed map of properties such as porosity and permeability, taking into account that the workflow is a route map that allows step by step to validate the information as the level of detail increases. Finally, the results obtained with each technique provide information on the characteristics of the rock on a different scale, that is, the result in each method corresponds to the measurement scale of the technique, so the results of each technique are complementary, taking into account that as the scale is increased and a result is obtained it depends on the result at the previous scale, this allows digital rock models to be simulated with greater precision showing the intrinsic characteristics of each sample, making the model a realistic image of rock. This methodological workflow proposal can

be used for conventional and unconventional reservoir samples, for example Shale gas, tight sands, etc.
The evaluation of unconventional reservoir properties through multi-scale imaging and analysis represents a crucial endeavor, given the shifting dynamics in the global energy landscape. Our discussion revolves around several key aspects and implications arising from this integral evaluation of reservoir properties:

3.1. Diversification of energy sources

As conventional oil and gas production declines, the world's energy needs continue to grow. This necessitates a diversification of energy sources, and unconventional reservoirs, such as shale gas, play a significant role in achieving this diversification. By better understanding and efficiently harnessing these resources, we can reduce our reliance on conventional energy sources, bolstering energy security.

3.2. Enhanced energy efficiency

A deeper comprehension of unconventional reservoir properties, coupled with evolving technology, contributes to more efficient energy extraction. Efficiency in energy production is not only vital for resource conservation but also paramount in addressing the current energy crisis. The ability to extract more energy from each reservoir with less waste is crucial for sustainability.

3.3. Technological innovation

Research in the field of unconventional reservoirs is driving technological advancements that extend beyond the energy sector. Innovations in imaging, analysis, and data integration are transferable to other fields, enhancing our capacity to solve broader challenges related to material science, environmental conservation, and more.

3.4. Addressing environmental concerns

The exploitation of unconventional reservoirs often raises environmental concerns, such as wastewater management and hydraulic fracturing. By closely examining the properties of these reservoirs, researchers and industries can develop practices that mitigate environmental risks and promote sustainable energy extraction.

3.5. Integration of multi-scale imaging and analysis

Unconventional reservoir evaluation benefits from a multi-scale approach that encompasses various analytical techniques, including X-ray CT, X-ray µCT, transmitted light microscopy, Quantitative Evaluation of Minerals by Scanning Electron Microscopy (QEMSCAN), and Focused Ion Beam Scanning Electron Microscopy (FIB-SEM). These methods, when integrated, provide a comprehensive dataset crucial for understanding rock properties, improving reserve estimations, and enhancing production efficiency.

3.6. Role of X-ray CT and X-ray µCT

X-ray CT and X-ray µCT offer non-destructive imaging capabilities that allow us to explore the internal structures of rocks with remarkable precision. These technologies are fundamental in visualizing and characterizing the abundance and distribution of mineral phases within unconventional reservoir rocks. Their role in assessing high-porosity intervals and total organic carbon content is particularly noteworthy, aiding in strategic decision-making for resource extraction.

3.7. Petrographic analysis

The petrographic study in thin sections brings to light the diagenetic processes and mineralogical intricacies of reservoir rocks. Understanding secondary porosities, often formed through dissolution and mineral alteration, is key to improving reservoir quality. This in-depth analysis offers a window into the geological history of these formations, providing valuable insights for reservoir management.

3.8. QEMSCAN and FIB-SEM integration

QEMSCAN's ability to identify minerals and produce detailed digital images, combined with FIB-SEM's capability for 3D reconstruction, is invaluable for the analysis of unconventional reservoirs. These techniques provide a multi-dimensional understanding of mineralogical, structural, and textural features within the rocks. QEMSCAN's accuracy in mineral mapping and FIB-SEM's ability to create 3D representations significantly contribute to reservoir characterization and hydrocarbon production strategies.

4. Conclusions

In conclusion, the integral evaluation of unconventional reservoir properties through multi-scale imaging and analysis is a critical pursuit in the evolving energy landscape. By combining advanced imaging and analytical techniques, researchers and industry experts can unlock the full potential of unconventional reservoirs. This comprehensive understanding of rock properties, mineralogy, and petrophysical attributes is pivotal for making informed decisions regarding hydrocarbon reserves and production efficiency. Additionally, the insights derived from these analyses mitigate risks and promote sustainable energy practices, considering the environmental challenges associated with unconventional reservoirs.
The collaborative use of X-ray CT, X-ray µCT, petrographic thin section analysis, QEMSCAN, and FIB-SEM provides a multidimensional perspective on unconventional reservoirs, enhancing our ability to navigate the complexities of these geological systems. As unconventional reservoirs continue to

gain prominence, the integration of cutting-edge technology equips us with a powerful toolkit for addressing the challenges of declining conventional resources, rising energy demands, and the need for more sustainable energy practices. Ultimately, this integral evaluation is instrumental in shaping the future of energy production and environmental conservation on a global scale.

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References

[1] Anifowose, F. A., Labadin, J., Abdulraheem, A., Ensemble machine learning: An untapped modeling paradigm for petroleum reservoir characterization. J. Petrol. Sci. Eng. 151 (2017) 480-487.

[2] Mehrabia, H., Esrafili-Dizajia, B., Hajikazemib, E., Noorib, B., Mohammad-Rezaeib, H., Reservoir characterization of the Burgan Formation in northwestern Persian Gulf. J. Petrol. Sci. Eng. 174 (2019) 328–350.

[3] Satter, A., Iqbal, G. M., Reservoir Engineering: The Fundamentals, Simulation, and Management of Conventional and Unconventional Recoveries, in: Satter, A. and Iqbal, G. M. (Eds.), Reservoir Engineering, Elsevier Science Publishers, New York, 2015, 486p.

[4] Al-Marzouq, A. M., Al-Ghamdi, T. M., Koronfol, S., Dernaika, M. R., Walls, J., Shale Gas Characterization and Property Determination by Digital Rock Physics. Saudi Aramco J. Technol. (2014) 2-13.

[5] Martínez-Martínez, J., Fusi, N., Galiana-Merino, J. J., Benavente, D., Crosta, G. B., Ultrasonic and X-ray computed tomography characterization of progressive fracture damage in low-porous carbonate rocks. Eng. Geol. 200 (2016) 47-57.

[6] Han, Y., Hu, D., Matzar, L., Numerical computation of elastic properties for porous rocks based on CT-scanned images using direct mapping method. J. Petrol. Sci. Eng. 122 (2014) 346-353.

[7] De Boever, W., Derluyn, H., Van Loo, D., Van Hoorebeke, L., Cnudde, V., Data-fusion of high-resolution X-ray CT, SEM and EDS for 3D and pseudo-3D chemical and structural characterization of sandstone. Micron 74 (2015) 15-21.

[8] Slatt, R. M., O'Brien, N. R., Pore types in the Barnett and Woodford gas shales: contribution to understanding gas storage and migration pathways in fine-grained rocks. AAPG Bull. 95(12) (2011) 2017–2030.

[9] Curtis, M. E., Cardott, B. J., Sondergeld, C. H., Rai, Ch. S., Development of organic porosity in the Woodford Shale with increasing thermal maturity. Int. J. Coal Geol. 103 (2012) 26-31.

[10] Goodall, W. R., Scales, P. J., An overview of the advantages and disadvantages of the determination of gold mineralogy by automated mineralogy. Miner. Eng. 20(5) (2007) 506-517.

[11] Anderson, K. F. E., Wall, F., Rollinson, G. K., Moon, Ch. J., Quantitative mineralogical and chemical assessment of the Nkout iron ore deposit, Southern Cameroon. Ore Geol. Rev. 62 (2014) 25-39.

[12] Dieterich, M., Kutchko, B., Goodman, A., Characterization of Marcellus Shale and Huntersville Chert before and after exposure to hydraulic fracturing fluid via feature relocation using field-emission scanning electron microscopy. Fuel 182 (2016) 227-235.

[13] Zhou, Sh., Yan, G., Xue, H., Guo, W., Li, X., 2D and 3D nanopore characterization of gas shale in Longmaxi formation based on FIB-SEM. Mar. Petrol. Geol. 73 (2016) 174-180.

[14] Wellington, S. L., Vinegar, H. J., X-Ray computerized tomography. J. Petrol. Technol. 39(8) (1987) 885-898.

[15] Walls, J. D., Sinclair, S. W., Eagle Ford Shale Reservoir. Properties from Digital Rock Physics. First Break 29(6) (2011) 97-101.

[16] Ahmad, M., Petrophysical and mineralogical evaluation of shale gas reservoirs (A Cooper Basin Case Study). PhD Thesis, The University of Adelaide, 2014.

[17] Loucks, R. G., Reed, R. M., Ruppel, S. C., Hammes, U., Preliminary classification of matrix pores in mudrocks. Trans. Gulf Coast Assoc. Geol. Soc. 60 (2010) 435–441.

[18] Sayed, M. A., Al-Muntasheri, G. A., Liang, F., Development of shale reservoirs: Knowledge gained from developments in North America. J. Petrol. Sci. Eng. 157 (2017) 164–186.