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The Devonian Shales of the Madre de Dios Basin as an Unconventional Resource System

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1. Abstract

The Madre de Dios Basin, covering approximately 70,000 km^2 in Bolivia, has remained unexplored in terms of its hydrocarbon resources. The primary objective of this study was to assess its unconventional hydrocarbon potential, specifically shale oil.

To facilitate the analysis and evaluation of the unconventional potential of the Madre de Dios Basin, information from well data and 2D seismic surveys has been employed and integrated to construct a geological model aimed at comprehending the Devonian basin's configuration, serving as the principal objective as an unconventional reservoir.

Furthermore, the new geochemical analyses revealed values for the entire section (180 m approx.), with Total Organic Carbon (TOC) values over 2%, Hydrogen Index (HI) between 400 and 600 mg HC/g TOC, and low Oxygen Index (rarely exceeding 50 mg CO_2/g TOC). This is consistent with a high-quality, oil-prone, "rich" Type II kerogen. Furthermore, an exceptional basal section in the Lower Tomachi, informally referred to as "Tomachi Rich Net," exhibits TOC peak values up to 14%.

The assessment results that have followed a probabilistic analysis based on the Total Oil methodology of Jarvie (2012), have disclosed significant potential. This has successfully warranted a world-class consideration as an unconventional hydrocarbon source rock.

2. Introduction

The Madre de Dios Basin is in the northwest of Bolivia and is shared with neighboring countries Brazil and Peru (Figure 1). It covers an area of approximately 315,000 km^2, with roughly 35% situated within Bolivia (Beicip-Franlab, 2016). Morphologically, the region is densely covered with rainforest vegetation and traversed by various robust Amazonian-type rivers and swamps, which pose substantial challenges for any petroleum operations.

Geologically, the basin was once part of an intracratonic marine basin during the Paleozoic era before experiencing regional uplift during the Mesozoic. It possesses a stratigraphic record ranging from Precambrian to Cenozoic rocks.

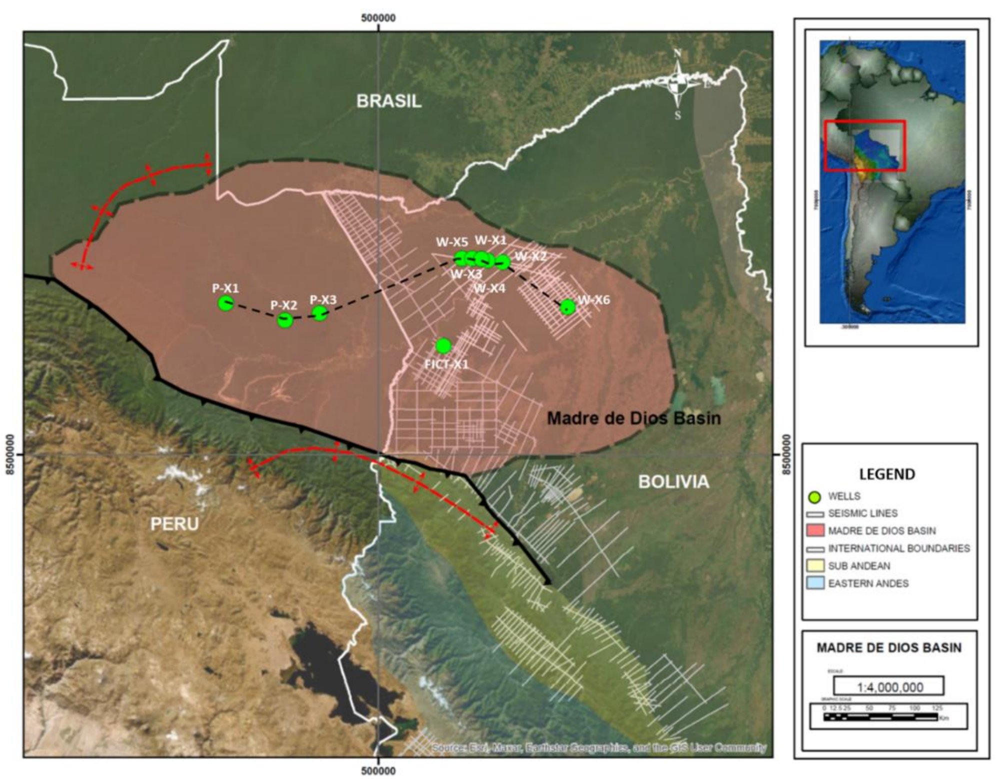

Figure 1. Location Map of the Study Area. The segmented black line corresponds to the location of the regional well section in figure 3.

Historically, the Upper Devonian, specifically the Tomachi Formation (Frasnian; Figure 2), has been cited as a potential source rock. Previously, Peters et al. (1997) and Bande et al. (2022) described Tomachi as a high-quality organic-rich rock with hydrocarbon-generating potential, deposited in a marine siliciclastic platform environment under suboxic to anoxic conditions. OBI (1991) also presented a valuable petroleum-source rock correlation between the oil produced from the Tomachi sandstone at 1266 m MD and three rock samples from well W-X1. The correlation is highly accurate with the sample at 1525 m MD, situated in the richest and closest section to the base of the Tomachi Rich. It was inferred that the produced oil was generated from this basal section.

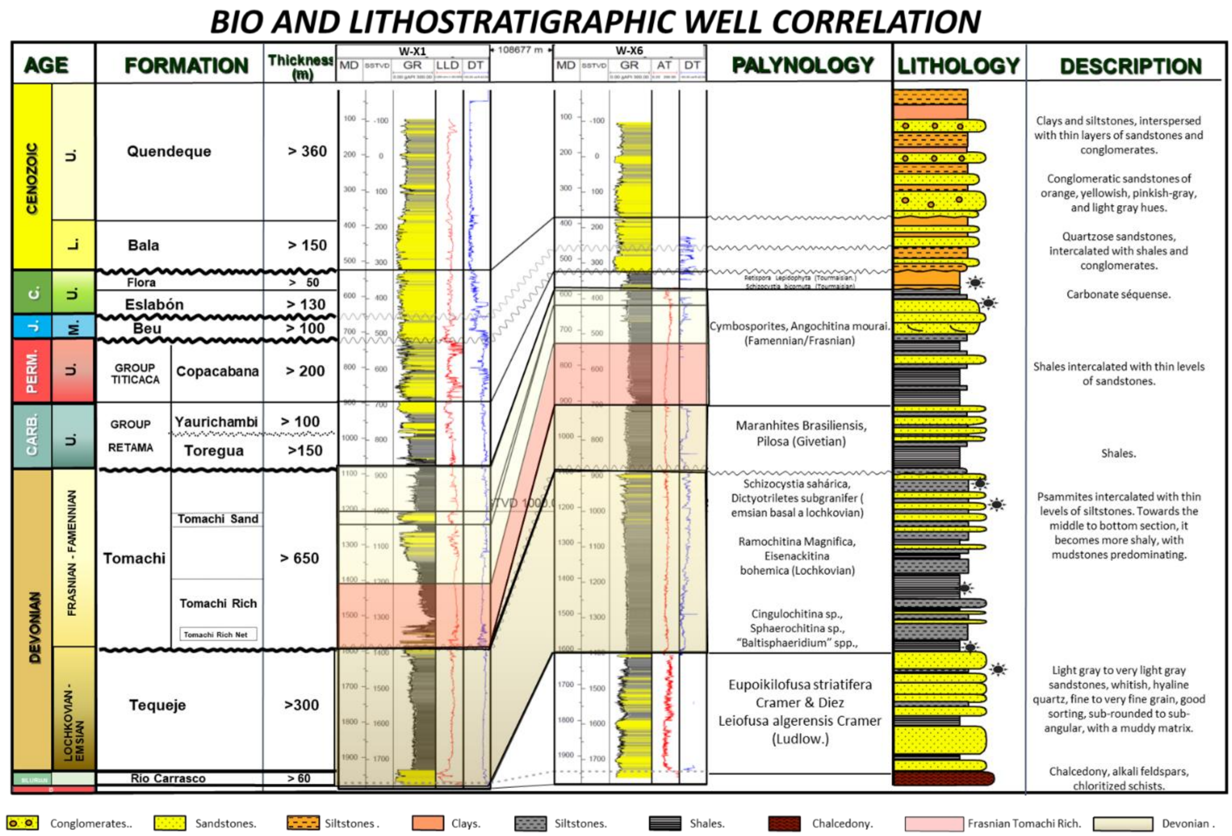

Figure 2. Stratigraphic Column of the Madre de Dios Basin and Biostratigraphic and Lithostratigraphic Correlation of Wells W-X1 and W-X6. The interval of the Tomachi Formation, informally identified as 'Tomachi Rich' of Frasnian age, is highlighted in red.

This study aims to incorporate evidence confirming the unconventional hydrocarbon potential associated with the source rock interval identified by these authors, following the methodology after Jarvie (2012), which has been successfully employed in several unconventional plays.

Regional seismic interpretation and produced maps reveal that the basin deepens in a southwest direction from the locations of the drilled wells in the Madre de Dios Basin. According to this interpretation, favorable conditions for hydrocarbon generation, particularly shale oil, would exist if the source rock extends into this area.

Based on the conducted studies and a comparison of results with parameters from similar source rocks, it is concluded that the Tomachi Rich Interval possesses the geological conditions to be considered a world-class source rock with great potential for unconventional hydrocarbons.

3. Methods

The stratigraphic sequence of the basin is known through subsurface data obtained from the wells drilled on the Bolivian side The logs from the W-X1 and W-X6 wells that penetrated the deepest intervals were correlated to build the complete stratigraphic framework (Figure 2 and Figure 3).

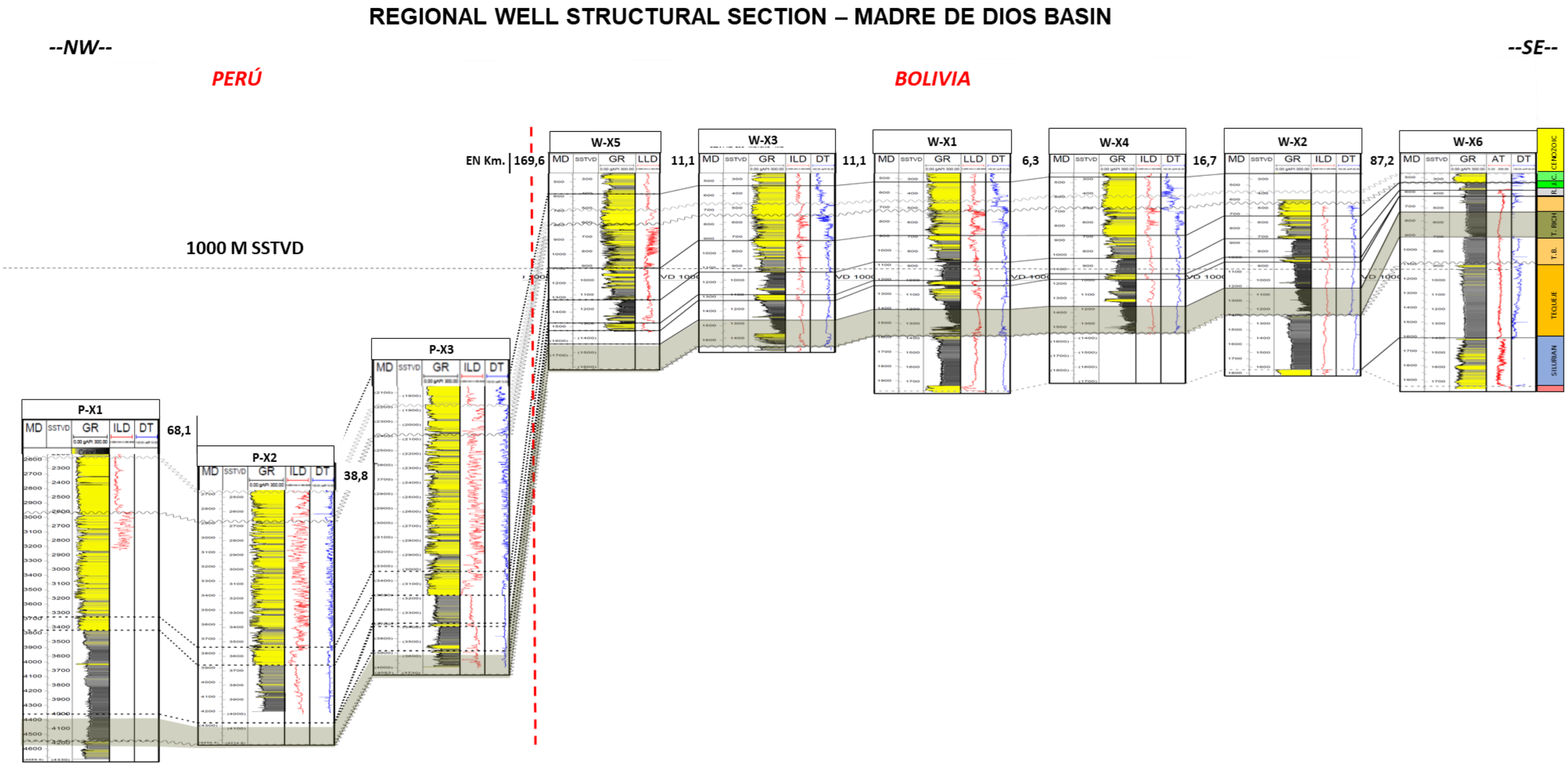

Figure 3. Regional Structural Section of Bolivian and Peruvian Wells in the Madre de Dios Basin. The linear distance between the Peruvian well P-X3 and the Bolivian well W-X5 is nearly 170 kilometers. The location of the wells is shown in Figure 1 in a segmented black line.

The data for the research corresponds to the geological and geochemical information from six (6) exploratory wells drilled on the Bolivian side of the basin, limited geological information from three wells on the Peruvian side (Figure 3), along with more than 80 lines of 2D seismic data covering a total length of 3250 km and various publications from both Peru and Bolivia. This information was integrated to establish a geological model of the basin and to identify areas where the Tomachi Formation is situated under favorable conditions for hydrocarbon generation, as well as to determine the deepest part of the Devonian in the basin (Figure 4).

From the regional time-domain seismic interpretation, we derived the basin model extending towards the Bolivian side, providing insights into the tectonic behavior of the basin (Figure 4).

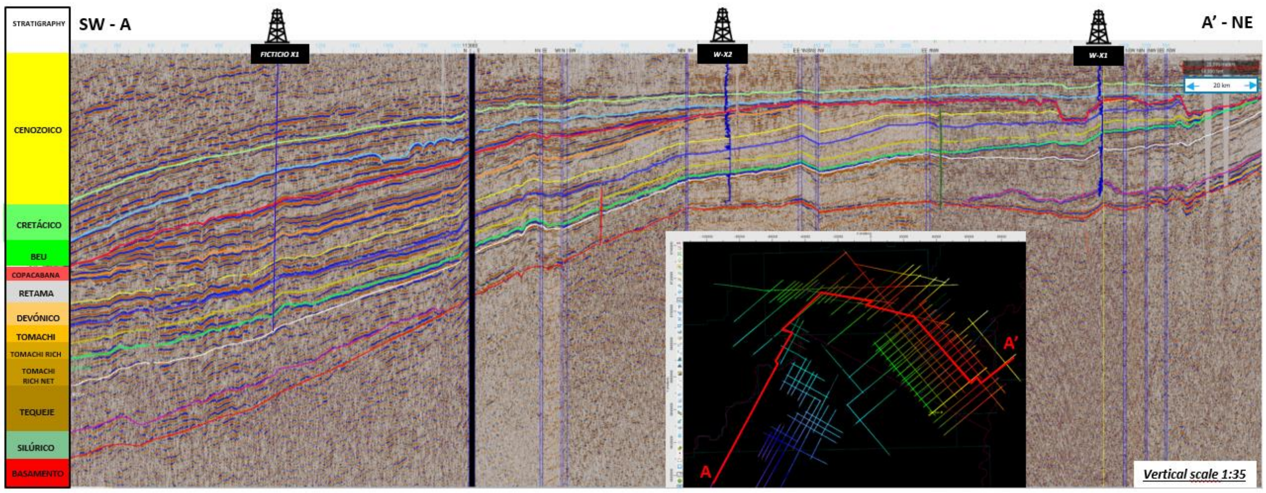

Figure 4. Time-domain seismic interpretation of the key stratigraphic levels in the Madre de Dios Basin.

The geochemical data for this study is primarily based on the screening of the W-6 well, drilled by YPFB in 2021, on the W-X1 well (OBI, 1991) and on the W-X2 well (Mobil, 1993). These reports include Total Organic Carbon (TOC), Programmed Pyrolysis, and Vitrinite Reflectance (Ro) measurements; core samples from W-X1 and cuttings from W-X2. Afterwards, pyrolysis and Ro measurements were performed on samples from the W-X6 well (Figure 5).

The Tomachi Formation is the proposed source rock to be analyzed as the primary hydrocarbon generator in the basin. Within the area, it has been subdivided into two units: the Frasnian Tomachi “Rich” and the Famennian Tomachi, based on the top and bottom boundaries (Figure 2).

Based on the developed geological and tectosedimentary model, 1D geochemical modeling was performed at three positions within the study area, including two drilled wells and one pseudo-well. A multi-1D section connecting these three positions was also created. The results were used to understand the regional thermal conditions of the source rock, to determine the extent of the kitchen and to simulate the hydrocarbon generation, retention, and expulsion values.

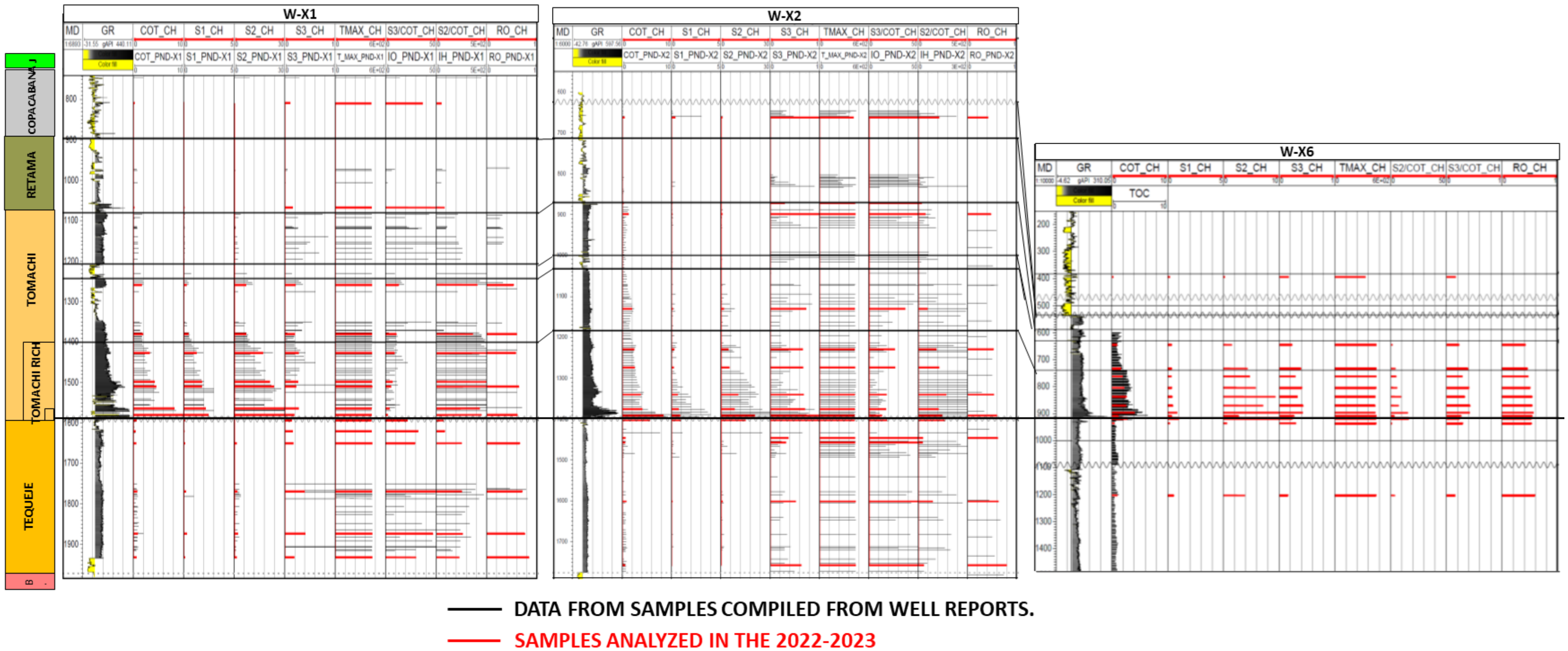

Figure 5. Correlation of Total Organic Carbon, Pyrolysis, and Vitrinite Reflectance Data from Wells W1, W2, and W6.

The geochemical analysis of the three drilled wells also allowed the delimitation of the kitchen area, following the S1 peak of the programmed pyrolysis that represents the free hydrocarbons, together with the Oil Saturation Index (OSI). The crossover of the S1 and the TOC (%) curves with depth is an indicator of the potential producible free oil intervals when the S1 exceeds the TOC. In this context, Jarvie (2012) suggests the same scenario of potential producible free oil with a threshold value of 100 mg HC/g TOC. Recent studies related to the Vaca Muerta formation in the Neuquén Basin (Argentina) have lowered this minimum threshold to 75 mg HC/g TOC (Elías et al., 2014) and assume that between 70 and 80 mg of oil per gram of TOC is retained by organic-rich rocks, limiting production in the absence of open fractures or enhanced permeability.

In Jarvie (2012) the oil crossover premise is verified in various play examples and the author proposes an equation for volumetric estimation of shale-oil resources using S1 and S2 values. However, this equation is considered reliable only for basins with sufficient source rock data. In the Madre de Dios Basin study area, programmed pyrolysis has been conducted in only three wells, which is not enough to provide a reliable basis for S2 geochemical modeling. The pyrograms from well W-X1 exhibit well-defined and unimodal S2 peaks, with a low probability of labile hydrocarbons in this peak.

Based on the aforementioned information, Equation 1 was applied for the OSI estimation:

$$OSI = \frac{S1 * 100}{TOC}$$

Equation 1. Estimation of the OSI. Modified from Jarvie (2012).

Where:
OSI: Oil Saturation Index
S1: S1 Pyrolysis Peak
TOC: Total Organic Carbon

4. Results

A detailed analysis of the available data was conducted using the Crossover concept between TOC and S1. Although there is no crossover between the curves, it can be observed that as we go deeper into the Tomachi Rich interval from W-X6 to W-X1, the TOC and S1 curves progressively converge (Figure 6).

The outcomes of the OSI results in the three wells, together with the structural elevation data of the top of the Tomachi Rich, allowed us to obtain a gradient through a single regression (Figure 7, left). Based on this information, a depth for the 100 OSI (Jarvie, 2012) intersection was projected at approximately -2500 m TVDSS and the 75 OSI (Elías et al., 2014) at -1950 m TVDSS (Figure 7, right). These elevations are depicted in the 3D structural representation of the top of the Tomachi Rich (Figure 7, left).

For the estimation of the P10 area, the section of the formation with TOC over 2% was selected, with an average thickness of 180 m. OSI was calculated for each well by averaging the TOC and S1 values using Equation 1. Subsequently, depth (TVDSS) was plotted against each OSI value, resulting in a slope line. As previously mentioned, when the OSI value exceeds 75 mg of oil per gram of TOC, it delineates a zone with potential for liquid hydrocarbon production, in this case, situated below -1800 m TVDSS. Similarly, for the P90, the calculation was performed for the section with TOC greater than 4%, with an average thickness of 28 m (Figure 8).

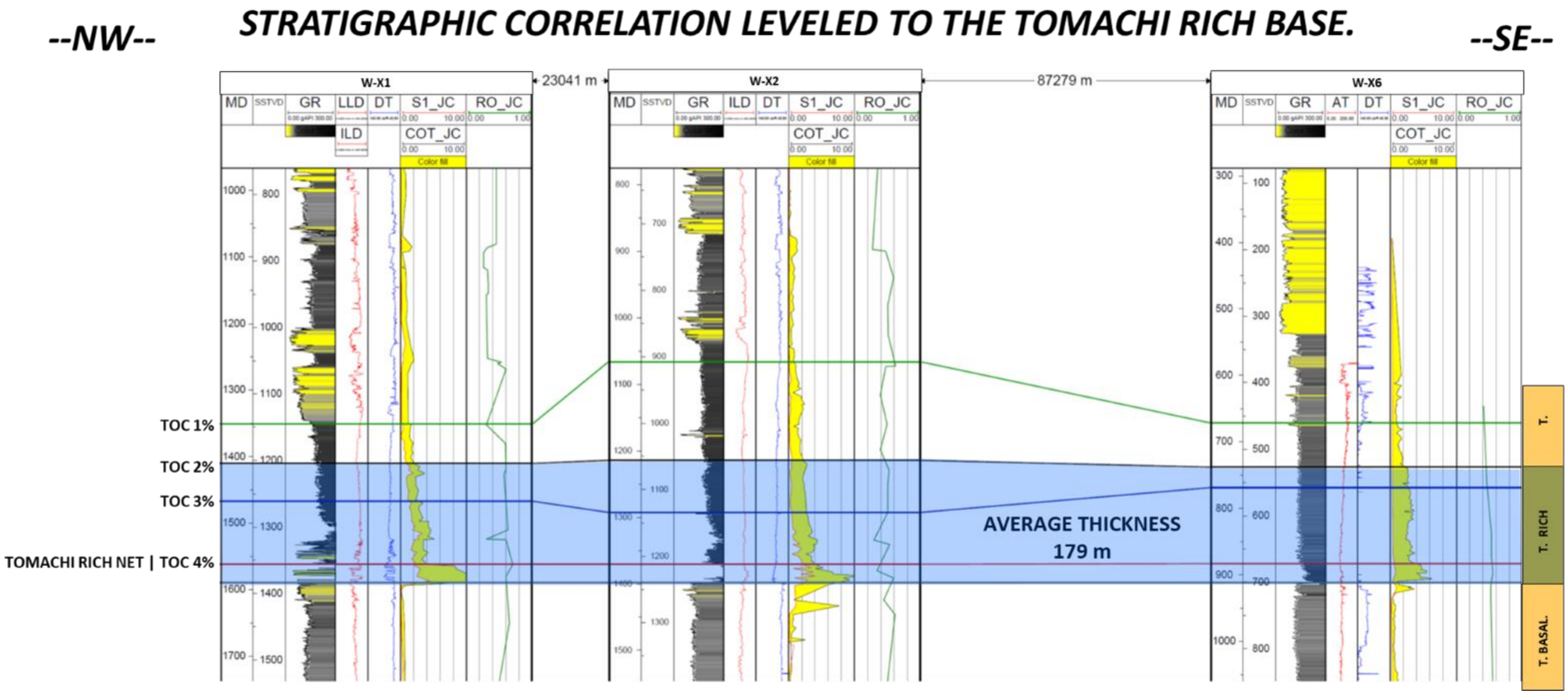

Figure 6. Cross-Section between W-X1, W-X2, and W-X6 with profiles of TOC (%wt) and S1 (mg HC/g rock).

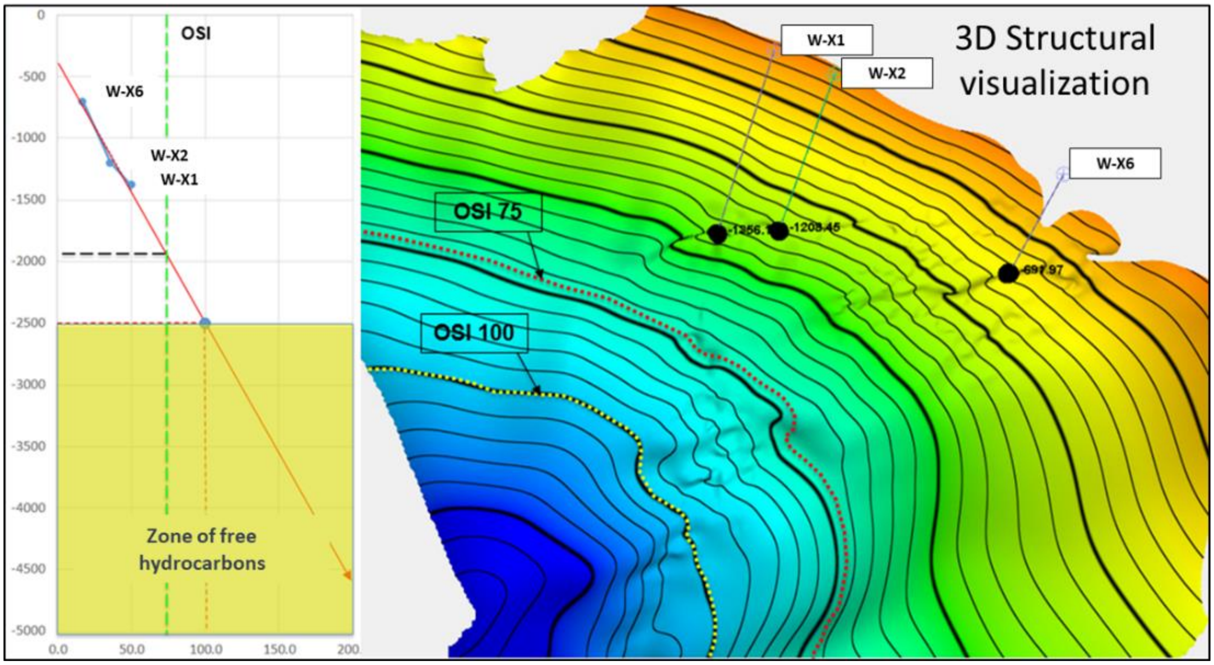

Figure 7. Left: Gradient of the average OSI from wells W-X1, W-X2, and W-X6, where the representative line intersects the elevation corresponding to OSI values of 75 and 100. Right: Structural representation at the top of Tomachi Rich, where structural curves corresponding to OSI values of 75 and 100 have been marked.

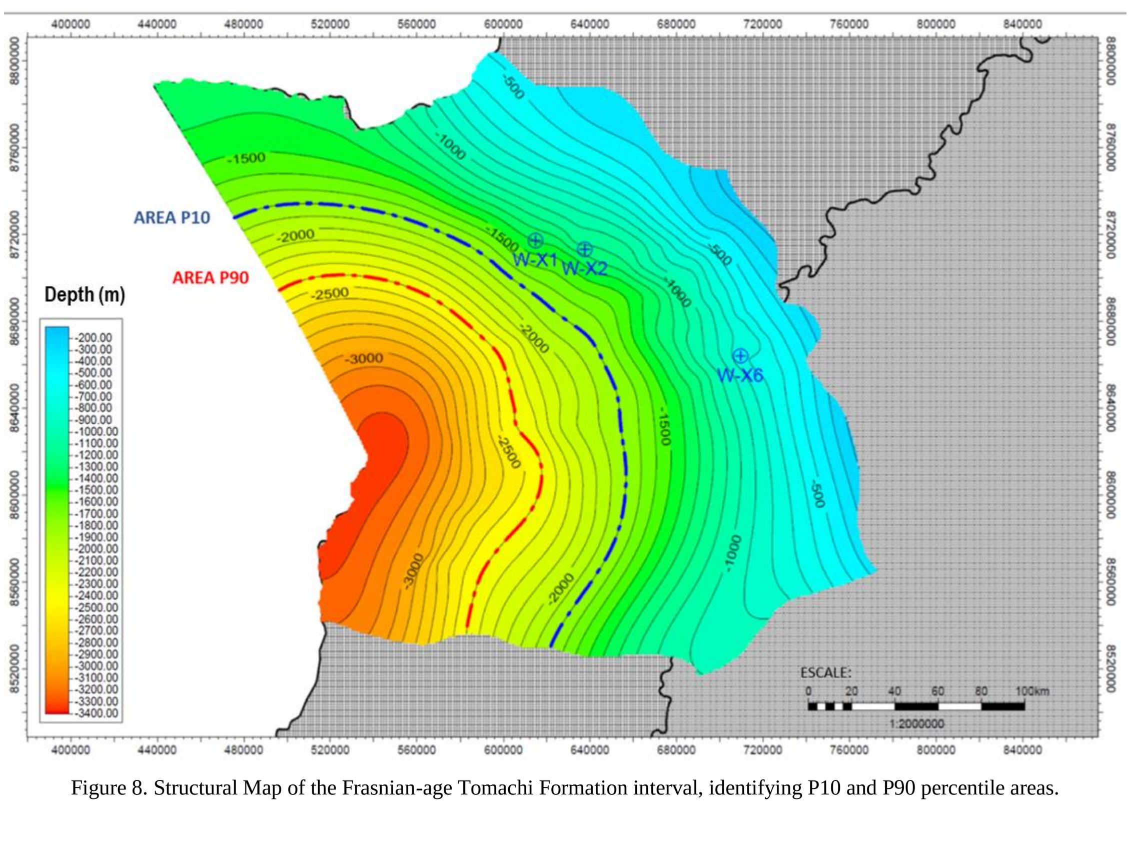

Figure 8. Structural Map of the Frasnian-age Tomachi Formation interval, identifying P10 and P90 percentile areas.

Regarding the thickness of the Tomachi Rich Interval, it is observed that the variation in the potential kitchen area or P10, as per seismic interpretation, ranges from a minimum of slightly less than 200 m to an absolute maximum of 300 m (Figure 9).

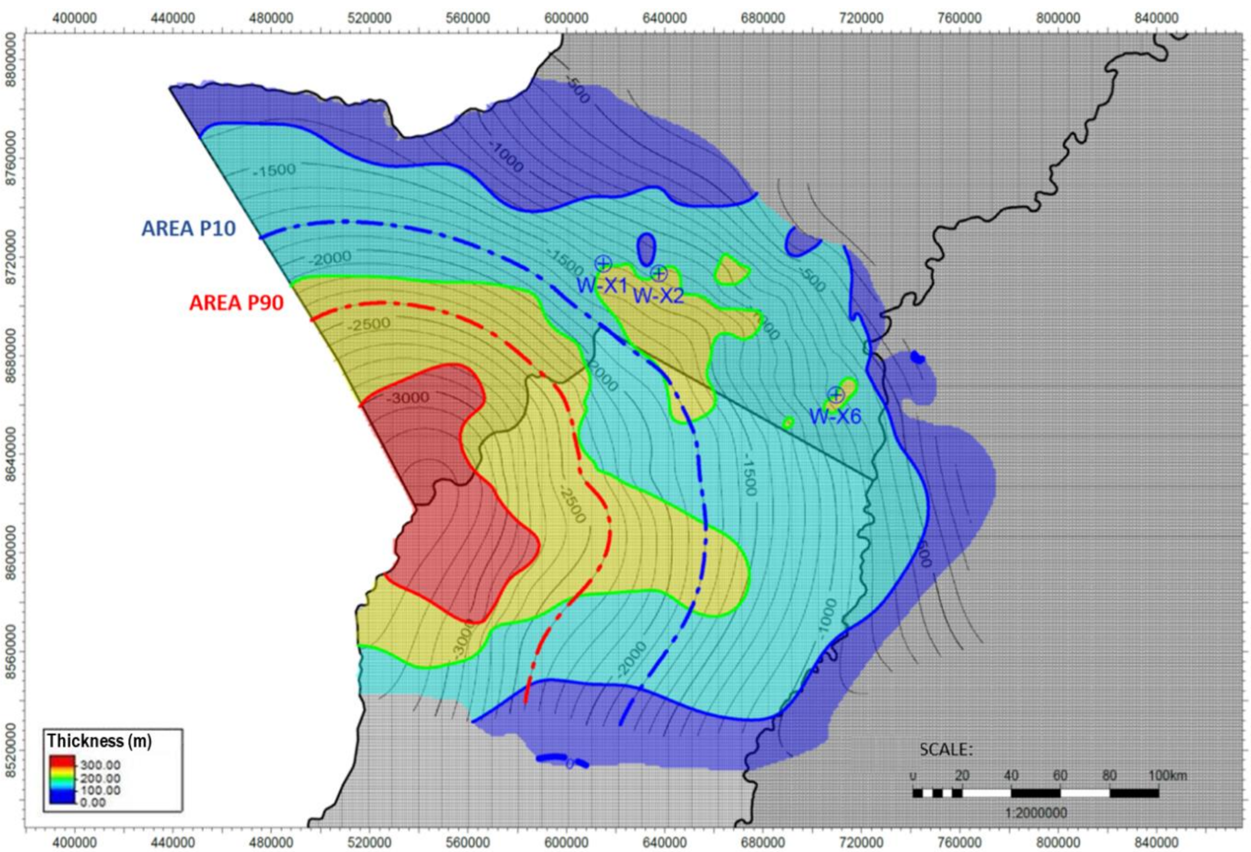

Figure 9. Structural Map at the base of the Tomachi Rich with isopachous curves of that stratigraphic unit spaced every 100 meters. The probable Tomachi Rich kitchen area (P10) has been delineated.

Also, geochemical modeling, based on geological and thermal reconstruction, allowed the simulation of the current thermal maturity and the subsequent oil window for each location (Figure 10), especially for the fictitious one. In the case of the W-X6 well, erosion of the Copacabana Formation and part of the Retama Formation during the Triassic is observed, followed by a hiatus before the onset of Beu Formation sedimentation during the Jurassic. Two subsequent prolonged hiatuses were interrupted by the deposition of the Cretaceous-Tertiary interval of the Eslabón-Flora assemblage, concluding with the Orogenic Tertiary. For this well, the thermal maturity of the Tomachi Rich is less than 0.6% Ro (Figure 10, right). The reconstruction for the W-X1 well is similar, with a slightly higher thermal maturity of the Tomachi Rich, at just above 0.65% Ro (Figure 10, left).

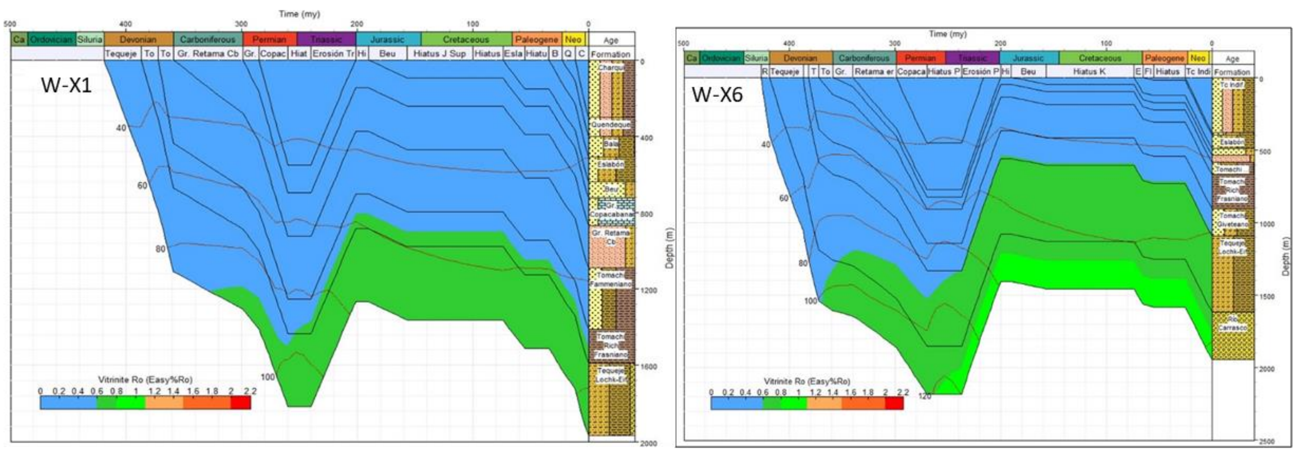

Figure 10. Geological History, Burial, and Thermal Maturity of Wells W-X1 (left) and W-X6 (right), Madre de Dios Basin.

The creation of a modeled multi-well section among the three locations allowed the estimation of the distance from the wells to the boundaries of the generation window, intersecting the top and base of the source rock (Figure 11) and confirming the extent of the estimated percentiles. The corresponding line to 0.65% Ro represents the possible maximum extension (P1) for the kitchen of the Tomachi Rich interval and is located 10 km from the W-X1 well and at a depth of 1800 m (approx. -1600 m above sea level). Although this value may indicate low maturity and does not correlate with the analysis using OSI, other worldwide recognized cases, such as the Middle Bakken and Eagle Ford in the United States, published a lower maturity limit of 0.5% Ro. These variations in thermal maturity to fit within the generation window may be attributed to specific characteristics of each source rock, primarily the organic richness and other geochemical and geological factors.

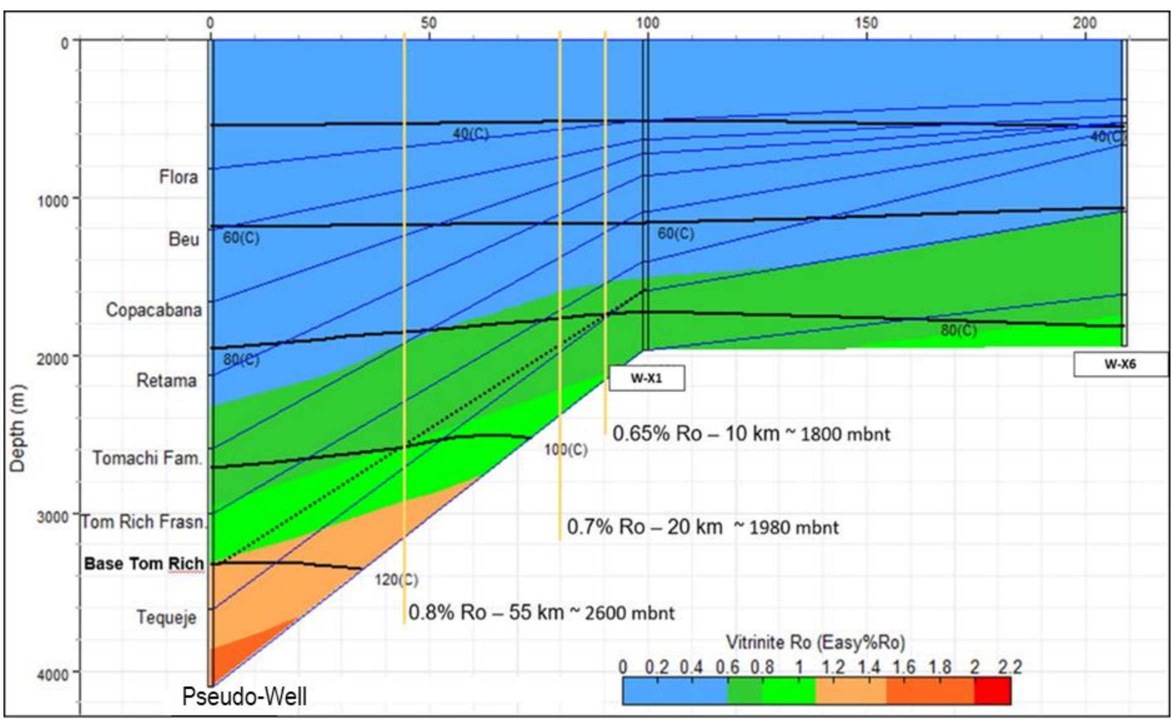

Figure 11. Multi-well section illustrating the boundaries of the generation zones, top and base of the Tomachi Rich, and the absolute maximum, maximum, and minimum limits of the Tomachi Rich kitchen extension.

5. Discussion.

Based on the regional seismic interpretation of the Tomachi Rich interval, which covers part of the Madre de Dios Basin, it is evident that the basin deepens toward the western zone of the Madre de Dios Area wells. Considering this information, it is interpreted that if the Source Rock were to extend into this area, it would exhibit suitable conditions for entering the hydrocarbon generation zone.

The multi-well geochemical model allowed for inferences regarding the extent of thermal maturity windows, which combined with the structural map at the base of the Tomachi Rich interval, permitted to establish the maximum and minimum extent of the kitchen. However, the oil sample of 34° API and 0.7% VRE produced from the Tomachi sandstone (W-X1 well) is genetically correlated with the Basal Section (Mobil, 1992), indicating that the oil window of the source rock lies to the west of the drilled wells. It is essential to consider this factor: so far, there are no drilled wells in the highest unconventional potential area.

It is important to point out about two risk factors in the evaluation of this unconventional play. There is an important uncertainty about the possible reservoir behavior due to scarce and limited information concerning the clay content. Additionally, a recent publication of regional scope (Bande et al., 2022), suggested a basin ward decreasing of the Tomachi source rock quality, based on geochemical information of Peruvian wells, though it was not available for this analysis.

It is worthwhile to establish cooperation agreements between Peru and Bolivia to integrate the available geological, geochemical, and geophysical data, thus creating a comprehensive database that enables regional assessments of the Source Rock with lower geological uncertainty, particularly regarding the extent of the hydrocarbon kitchen."

6. Conclusions.

The results of the evaluation of the Madre de Dios and Río Beni areas show that there is a huge potential for Unconventional Hydrocarbon Resources associated with the Tomachi Rich Interval (Frasnian).

Based on this study, it was confirmed that, in the wells drilled in the Bolivian portion of the Madre de Dios Basin, the potentially generating section at the base of the Tomachi Formation has Ro values around 0.6%, indicating low to early thermal maturity. However, one of the wells discovered oil in a sandstone from the same formation, confirming the existence of a nearby kitchen. Determining the position and extent of this kitchen was one of the objectives achieved with this work, emphasizing the potential of the 'Tomachi Rich Net' interval as a reservoir for unconventional resources.

Regional seismic interpretation of the Tomachi interval reveals that the basin deepens in a southwest direction from the location of the already drilled wells. If the source rock extends to this area while maintaining the levels of organic richness measured in the wells, there would be favorable thermal maturity conditions for hydrocarbon generation.

The multi-well geochemical model allowed for inferences regarding the extent of thermal maturity windows. Combined with the structural map at the base of the Tomachi Rich interval, it was possible to establish the maximum and minimum extent of its kitchen.

Based on the conducted studies and comparisons with similar worldwide source rocks, it is concluded that the Tomachi Rich Interval could meet the technical conditions to be considered a World-Class Source Rock for Unconventional Hydrocarbons.

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