CSCanada
Advances in Petroleum Exploration and Development
Vol. 11, No. 2, 2016, pp. 6-15
DOI:10.3968/8502

ISSN 1925-542X [Print]
ISSN 1925-5438 [Online]
www.cscanada.net
www.cscanada.org

Lower Napo Shale Formation in the Oriente Basin: Analysis of Reservoir Formation Conditions and Prediction of Favorable Areas

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Received 29 May 2016; accepted 20 June 2016
Published online 26 June 2016

Zhang, H., & Li, J. (2016). Lower Napo shale formation in the Oriente basin: Analysis of reservoir formation conditions and prediction of favorable areas. *Advances in Petroleum Exploration and Development*, *11*(2), 6-15. Available from: URL: http://www.cscanada.net/index.php/aped/article/view/8502
DOI: http://dx.doi.org/10.3968/8502

Abstract

Considering the current situation of Ecuador being rich in oil and poor in gas sources, we evaluate the exploration priority of the shale gas potential of the primary oil- and gas-bearing basin in the country—the Oriente Basin. Richness criteria for shale gas reservoirs are proposed according to the evaluation. On the basis of the main lithological characteristics, geochemical factors, depth, distributional stability, and data availability, the lower shale rock of the Napo Formation in the Oriente Basin is selected from five potential source rocks as the shale rock that shows the greatest potential for shale gas. The reservoir formation conditions of the Napo Formation are studied. The thickness of the lower Napo shale rock is obtained by studying the 38 wells in the basin. Then, the depths of the lower Napo shale rocks are mapped by interpreting 29 seismic lines in the basin. Next, the distribution of the geochemical factors of the basin is derived by analyzing the outcome of the predecessors. Finally, the areas with favorably rich shale gas are predicted by studying the different reservoir formation conditions. The northwest (blocks 11 and 18), east (blocks 12, 67, 18, 31, and 63), and west areas (blocks 29, 20, 22, 28, and 70) of the basin are prospective areas that are rich in shale gas (oil). This study provides guidelines for the exploration and development of the shale gas in the Oriente Basin.

Key words: Ecuador; Oriente basin; Shale gas; Favorable exploration; Development area

INTRODUCTION

The Oriente Basin is one of the most prospective oil-bearing basins in the Republic of Ecuador, South America. This basin is a back arc foreland basin Located at the Amazon Plain. the Oriente Basin is bounded to the west by Ecuador and to the east and south by Peru, and it covers an estimated area of 100,000 km^2[1] (Figure 1). Many scholars have studied the petroleum geology of the basin and have found that the Napo Formation is a hydrocarbon source rock, which is equivalent to the Villeta Formation in Colombia (Putumayo Basin hydrocarbon source rock) in a large foreland basin system[2]. An example of another source rock is the Santiago shale[3-6]. Oil and gas are mainly preserved in the Cretaceous sandstones of the Hollin and Napo Formations (That are M1, M2, U, and T sandstones) with adequate reservoir physical properties[7-13]. Cretaceous sandstones have 6.3×10^8 t of proven recoverable oil reserves and 97.7×10^8 m³ of proven natural gas reserves. In 2004, the production of oil was $2,590\times10^4$ t, but the gas production was less than 100 million m^3[14]. The significant difference indicates that Ecuador is rich in oil but poor in gas sources. Developing its natural gas is a challenge for Ecuador. For instance, the gas production in the USA has dramatically increased because of the shale gas revolution. The development of shale gas and shale oil has offset declines in production from conventional gas reservoirs and has led to major increases in the natural gas reserves of the USA. The USA has become an oil exporting country largely because of shale gas discoveries.

Figure 1
Location of the Oriente Basin

Fortunately, the government of Ecuador and its related industries have already realized the importance of shale gas. However, the lack of funding and technology heavily limit the development of this source. Under this circumstance, the Ecuadorian government has set up the Prometheus Project with the following goals: To study the Oriente Basin, to define the proper shale gas reservoir intervals based on geological characterization, and to provide foundation for future shale gas development and exploration. This paper presents the results of the project.

1. PREFERABLE SELECTION OF SHALE GAS PLAY

Shale gas plays are made unique by the integration of source rocks and reservoirs. Prospective shale gas must satisfy the following criteria.

(a) Hydrocarbon source rock lithology. US source rocks are mudstone and carbonaceous shale, which are black, dark, and rich in organic material that can produce mass natural gas in the process while forming the material base for a shale gas reservoir. Meanwhile, prospective shale gas should come from hydrocarbon source rocks. Only qualified hydrocarbon source rocks with high organic carbon, which are suitable for the tectonothermal evolution of the lithosphere, may form shale gas and can be preserved in the layer (Table 1). To reach the shale gas enrichment level, additional criteria are required. TOC (Total Organic Carbon)should be more than 2%, and R_0 (vitrinite reflectance) should be more than 1.1%.

(b) Thickness. Total thickness should be greater than 20 m and preferably 30 m.

Table 1
Source Rock Criteria

Evaluation index		Quantitative criteria
TOC		More than 0.6%
R_0		More than 0.5%
H/C		More than 0.5
Chloroform bitumen A		More than 0.03%
Total hydrocarbon content (μ_g/g)		More than 100
	S_1+S_2 (mg/g)	More than 0.5
Rock eval pyrolysis	H_I	More than 0.6
	T_{max}	More than 435 ℃

(c) Depth. With today's technology, prospective shale gas at a depth of less than 3,000 m is developable.

(d) Composition of minerals. Shale gas development needs reservoir fracturing, and brittle minerals are a prerequisite for fracturing. Such development requires brittle minerals, quartz, and carbonate minerals to be more than 40%.

(e) Physical conditions. Physical conditions are fundamental for reservoirs and the development of adsorption and free gas. The shale gas reservoir permeability should be greater than 0.0003 mD, and porosity should be greater than 2%.

(f) Data availability. Constrained by current technology, only gas reservoirs with geological, seismic, and drilling data can be studied.

We systematically analyzed the formations of the Oriente Basin to determine its favorable shale gas plays. The evolution of the Oriente Basin has three different stages: the Paleozoic passive continental margin, the Triassic–Cretaceous back-arc rift basin, and the late Cretaceous foreland basin. The Paleozoic stage includes two formations. One is the Pumbuiza Formation, which consists of moderate metamorphic limestone, shale, silty mudstone, and sandstone. Above it is the Macuma Formation. The Mesozoic strata have two sub-strata: The Triassic–Jurassic rift strata and the Cretaceous strata. The Triassic–Jurassic rift strata include the Santiago Formation, the Chapiza Formation, and the Misahualli Formation. The overlying depression strata consist of the Hollin and Napo Formation, which are the main gas plays. Cenozoic orogenesis makes the Oriente Basin a foreland basin or a molasse basin. From the bottom to the top, the formations are as follows: The Tena Formation, the Tiyuyacu Formation, the Orteguaza Formation, the Chalcana Formation, the Arajuro Formation, and the Mesa Formation, which mainly consists of clastic rocks from the Cordillera Mountain in the west[15]. Among the criteria, (a) and (b) are essential for a favorable shale gas reservoir. Based on these criteria, five potential gas plays are found: The Macuma, Santiago, lower Napo shale, upper Napo shale, and Tiyuyacu formations (Figure 2).

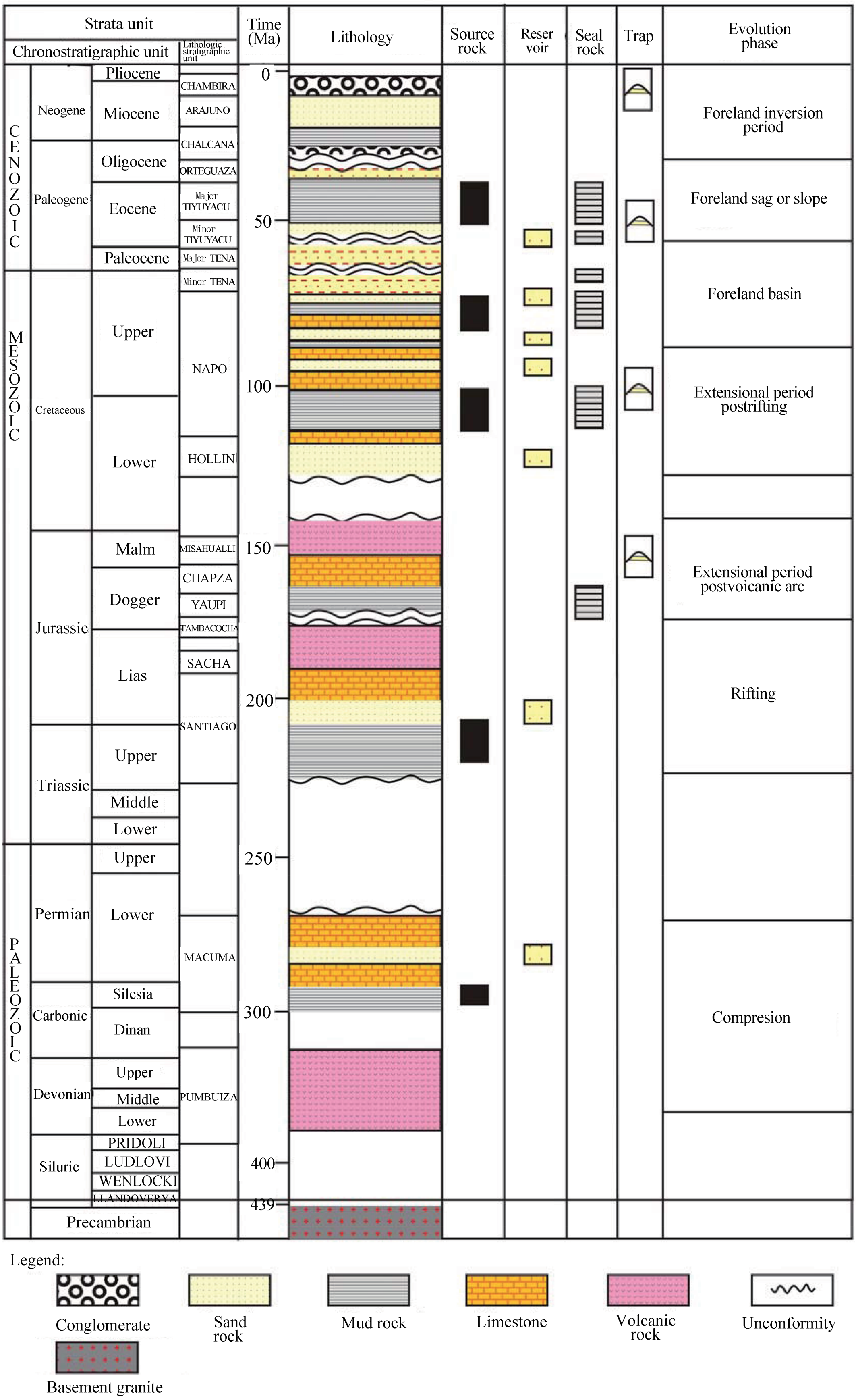

Figure 2
Comprehensive Column of the Oriente Basin

The development potentials of these formations are respectively analyzed. The Macuma Formation is composed of mudstone and thin layers of limestone that are deposited in a passive continental margin and carbonate continental shelf. At a depth of 5,000 m, drilling is difficult, and no data are available. Under the current technology and according to criteria (c) and (f), the Macuma Formation does not qualify for development. The Santiago Formation is made of shale, sandstone, and limestone. J. Gaibor sampled a part of available data for later study. Its TOC is between 2% and 3%, T_{max} is between 437 and 500, S_1 is between 0.3 and 1, and S_2 is between 0.25 and 5 (Table 1). This layer is generally considered a potential shale gas-bearing layer and is a hydrocarbon source rock in addition to Napo[3]. However, the Santiago Formation has two weaknesses. One weakness is its depth. The Santiago Formation is preserved underground at a depth of 4,000 m and is difficult to exploit. Second, the Santiago Formation is mainly located in the south of the Oriente Basin with a few wells and does not satisfy criteria (c) and (f). Meanwhile, the upper Napo shale and Tiyuyacu are very shallow and feature low thermal evolution, which is not suitable for source rock formation. Furthermore, the upper Napo shale is less stably distributed than the lower Napo shale. Both formations are not qualified for exploitation. The lower Napo Formation is made of ash black and abundant organic black carbonaceous shale. Moreover, engineers have found oil and gas at the boundary between Napo and Hollin (Figures 3 and 4), which satisfy source rock criteria: good thickness (15-20 m), stable distribution, proper depth (2,000-3,000 m), and an adequate amount of data, making this layer favorable.

2. ANALYSIS OF RESERVOIR FORMATION CONDITIONS IN THE LOWER NAPO FORMATION

2.1 Source Rock Analysis

The Napo Formation is generally considered the main source rock in the Oriente Basin[2,6]. It means that the most oil and gas of the Napo and Hollin Formation come from the source rock. The organic matter in the east basin is II-kerogen, whereas that in the middle and west basin is I-kerogen. The TOC values increase from less than 1% in the east to 10% in the west, with an average of 4.7%, which suggests that this area is rich in organic matter. The R_o values are between 0.4% and 0.6%, which indicates maturity. According to Curtis's research on Antrim shale in the Michigan Basin in the US, the R_o values are between 0.4% and 0.6%, and lots of shale gas are tested for biogenic shale gas[14]. Therefore, Napo shale formation does not satisfy the thermogenic gas threshold, but it does satisfy the biogenic gas threshold (Figure 5).

Figure 3
Lower Napo Shale Rock Samples in the COCA Outcrop in the Oriente Basin

Figure 4
Boundary Between the Napo Formation and the Hollin Formation

2.2 Reservoir Thickness and Distribution of the Lower Napo Shale Formation

After determining the study objectives, we use the well-logging data from different blocks to define the thickness and distribution of the play. According to the Oriente Basin depositional sequence, the lower Napo shale formation is between the T limestone of the Napo Formation and the C limestone of the Hollin Formation. The logging response characteristics are as follows.

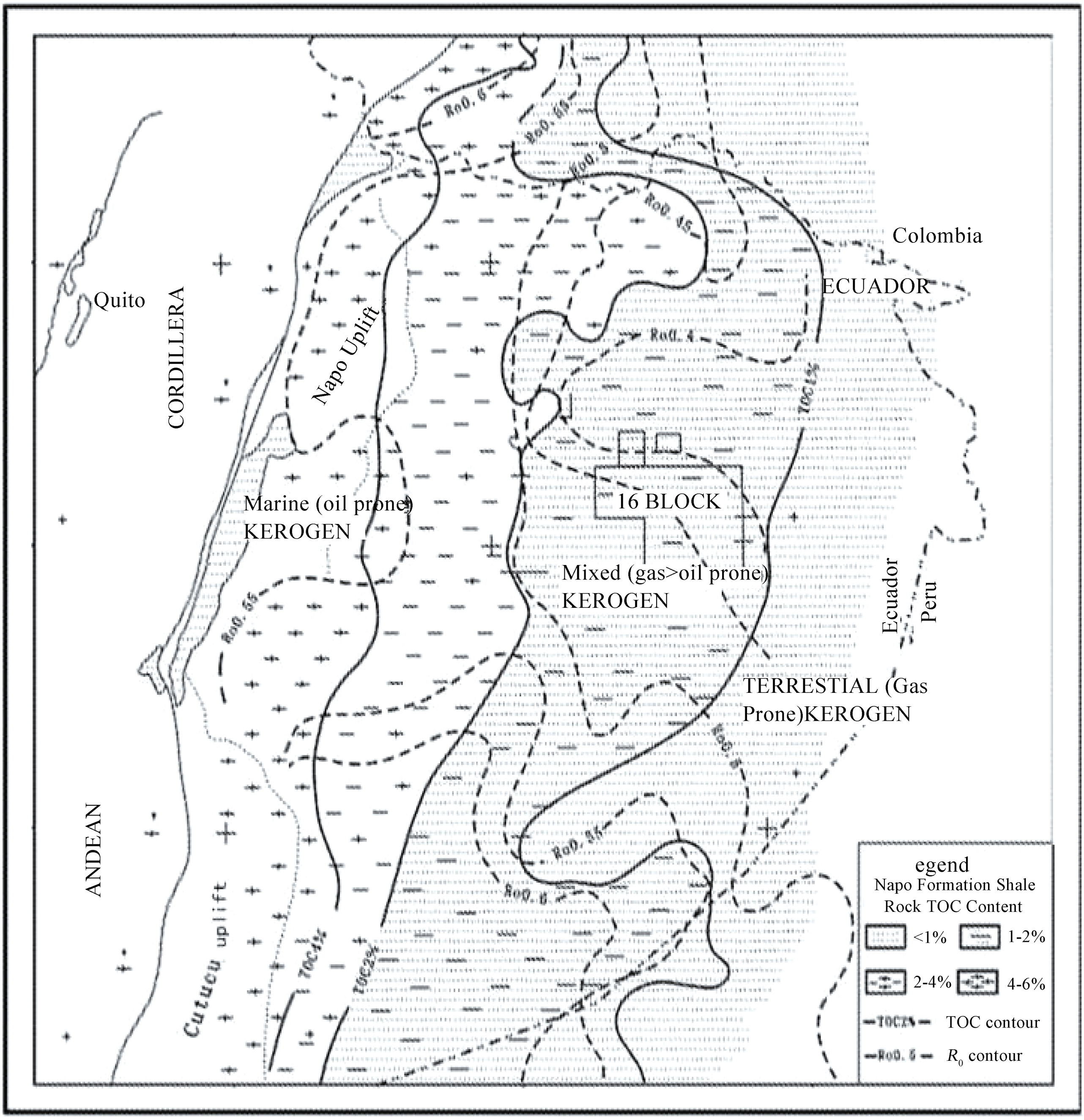

Figure 5
Geochemical Features of the Napo Formation Source Rock[2]

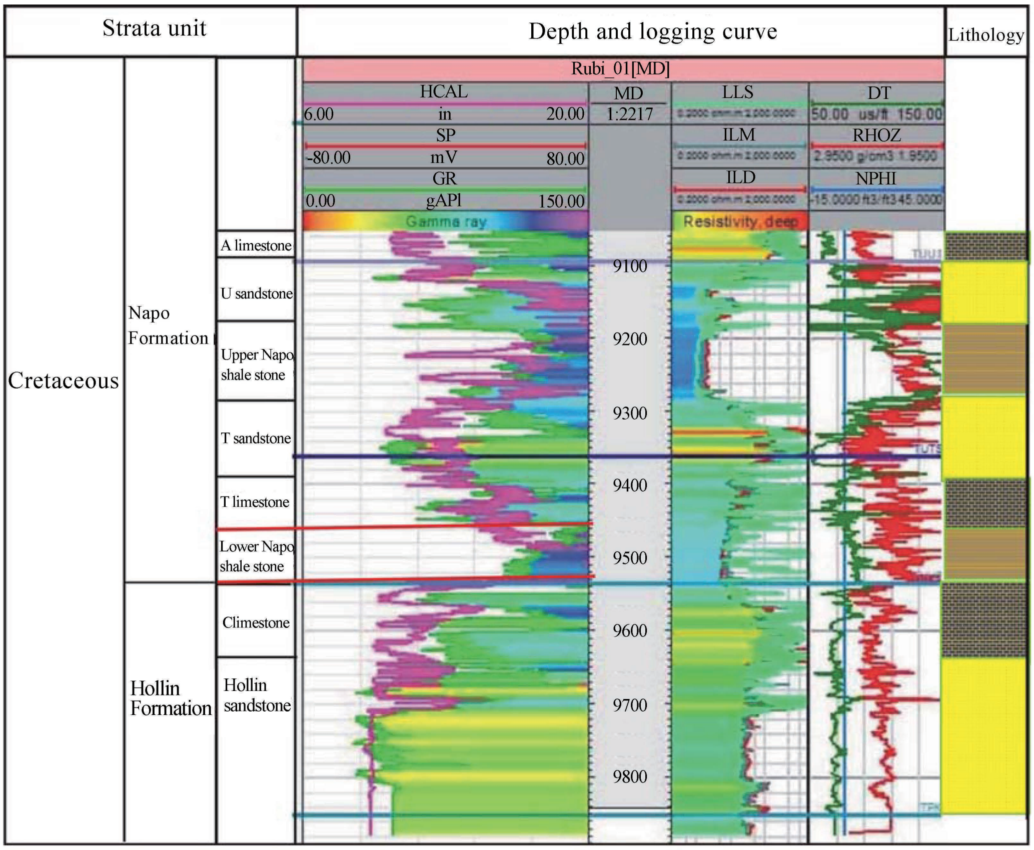

Figure 6
Logging Interpretation of the Rubi-1 Well

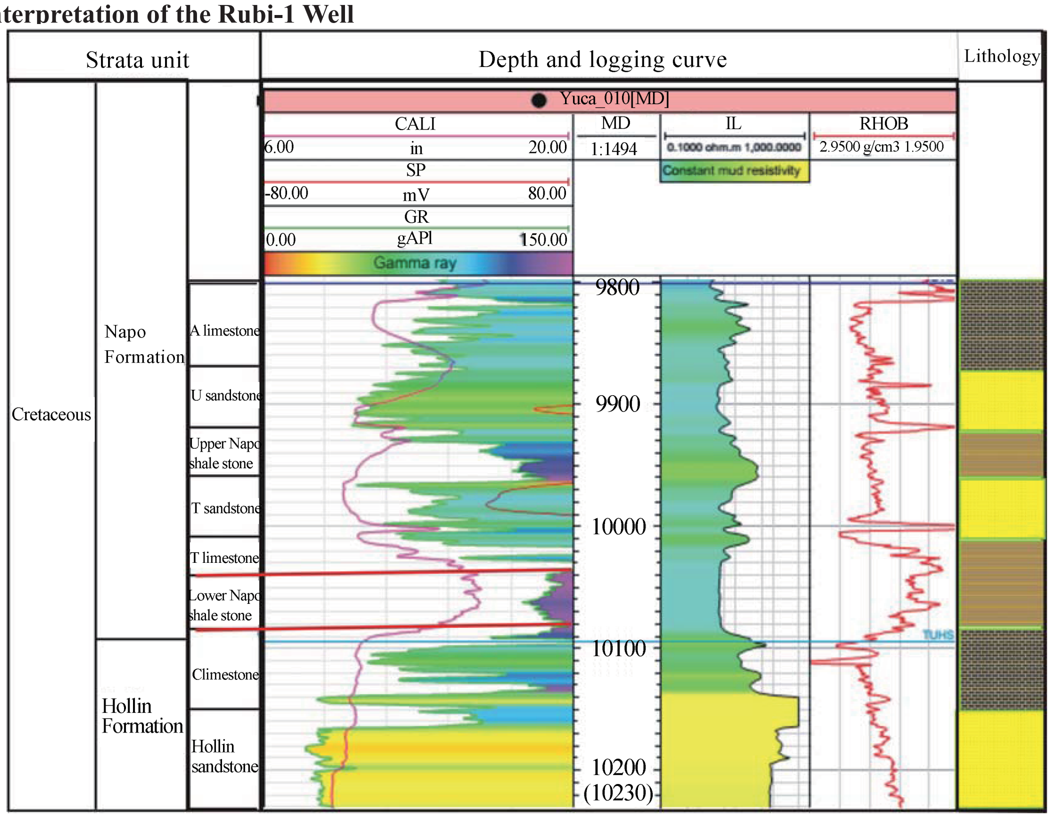

Figure 7
Logging Interpretation of the Yuca-1 Well

Table 2
Lower Napo Shale Stone Thickness of the Oriente Basin

Well	Lower Napo formation shale rock thickness (depth range) (unit: feet)
Amazonas-1(86)	45(9,985-10,030)
AUTAPI-1(28)	45(6,905-6,950)
BALSAURA-1(86)	40(10,116-10,156)
DANTA-1(83)	54(12,632-12,686)
Coca-1(7)	67(9,320-9,387)
DANTA-2(83)	65(12,820-12,885)
Garza-1(83)	38(12,282-12,320)
Guallino-1(70)	45(5,731-5,776)
Huito_001(86)	68(9,924-9,992)
Manati-1(80)	54(12,568-12,622)
Marañon-1(86)	60(10,120-10,180)
Masaramu-1(79)	61(13,866-13,927)
NASHIÑO-1(31)	62(7,578-7,640)
Ramirez-1(83)	42(12,520-12,562)
Tigrillo-1(80)	53(12,230-12,283)
Tzapino-1(22)	52(9,820-9,872)
Limoncocha-001(15)	60(9,800-9,860)
Pucuna-1(44)	60(9,670-9,730)
Charapa-001(50)	59(10,047-10,116)
Dureno-001(57)	58(9,964-10,022)
Shuhufindi-001(57)	44(9,330-9,374) s
Cuyabeno-020(58)	0.
OCHENTA-1	65(9,040-9,105)
PATA-1	70(9,890-9,960)
SACHA-1	53(9,765-9,818)
LIMONCOCHA-1	55(9805-9865)
EDEN-1	63(7,560-7,623)
Moretecocha-1	52(12,500-12,552)
FANNY-1	32(8,608-8,640)
YUCA-010	50(10,030-10,080)
PALANDA-1	45(10,212-10,259)
AUCA-1	60(10,028-10,088)
CURARAY-1	0
MASARAMU-1	62(13,872-13,934)
BOBONAZA-1	72(14,053-14,125)
ATACAPI-1(57)	34(8,564-8,598)
RUBI-1	65(9,465-9,530)
Aguarico-001	42(9,570-9,612)

Shale is mudstone and includes a large amount of radioactive substances. Furthermore, shale rocks contain large quantities of organic matter. Many radioactive substances exist in organic matter, and this feature causes the gamma ray values of shale stone to be extremely high. In particular, shale stone full of shale gas has a very high gamma ray value.

Shale is easily soaked by mud and then collapses, and it has many natural fractures. Therefore, shale expanding into Caliper curves is common.

Mud matter and water in shale result in low resistivity values. However, if the shale stone contains hydrocarbons, the resistivity values increase. Therefore, shale full of shale gas shows moderate to high resistivity values. The resistivity values of the lower shale in the Napo Formation are moderate to high. Thus, the lower shale contains gas or oil (Figures 6 and 7).

Shale and mudstone show low acoustic velocities and high slowness. When their organic matter content is high, the slowness values considerably increase.

In addition, shale and mudstone have high porosity and low density values. Therefore, shale shows low RHOB.

A total of 38 wells from different blocks in the Oriente Basin are chosen for this study, and their logging curves are analyzed. According to the logging response characteristics, the lower shale rocks are identified, and their thicknesses are given. Then, the thickness distribution contours are drawn (Table 2, Figure 8). The lower Napo shale stone is widely distributed in the basin, and its thickness ranges from 15 m to 25 m. Two depocenters are located in the northeastern block-18 and southern block-81, and the thickness is relatively large near the eastern block-16. Two thin thickness areas are found in the northern block 58 and middle block-17.

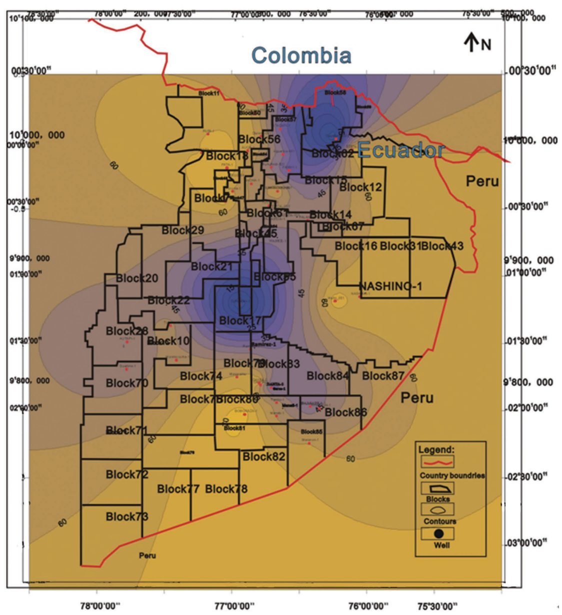

Figure 8
Lower Napo Shale Stone Thickness Contour of the Oriente Basin

2.3 Reservoir Depth Variation of the Lower Napo Shale Formation

To determine the shale distribution in the entire basin, 29 seismic lines from different blocks in the basin are chosen. The seismic lines are named from 1 to 29 (Figure 9).

All the 29 seismic lines, as well as the horizon of the lower Napo shale formation, are interpreted. The top and lower boundaries of the layer are selected along with the reflected seismic events. The interpretation criteria for the lower Napo shale formation are as follows (from the Agip Company).

In the seismic sections, a large part of the messy reflections (no reflection events) correspond to the upper shale rocks and sand rocks of the Napo Formation. Below this part, the first strong reflection event is A limestone, which is continuous and obvious. Among those events, the continuous bottom one is marcador limestone, which is below the A limestone. The top of the marcador limestone is also at the bottom of the lower shale stone of the Napo Formation. Inner shale rocks have no reflection characteristics, but between the shale rocks and above layer limestone rocks (T limestone), significant lithology differences exist. Therefore, the upper shale stones of the Napo Formation also show a strong reflection event.

On the basis of the aforementioned criteria, 29 seismic lines are interpreted, and the lower shale stones are defined. From the interpreted lines, the lower shale stone depth and thickness variation can be studied (the top and bottom layers of the lower Napo shale formation are represented in the map as green and black lines, respectively, Figure 11, Figure 12).

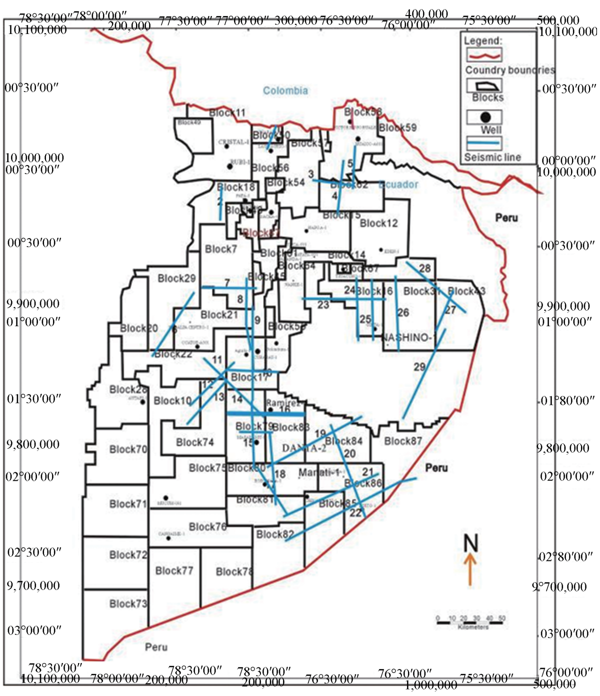

Figure 9
Seismic Line Distribution of the Oriente Basin

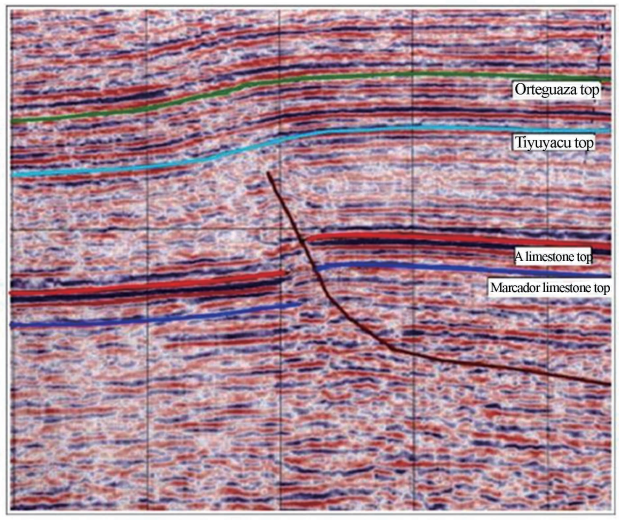

Figure 10
AOI-89-39 Seismic Line Interpretation Result of the Oriente Basin (According to the Agip Company, 2008)

Lines 5 and 9 are chosen to show the seismic line interpretations. According to these seismic line interpretations , conclusions can be drawn as follows.

(a) Lower Napo shale stones are widely distributed in the entire Oriente Basin.

(b) In the north of the basin, specifically in seismic lines 3, 4, 5, 6, 7, and 8 (blocks 58, 29, 21, and 45), the shale stone depths range from 7,000 ft to 8,000 ft and are suitable for development. However, in the south of the basin, beginning from seismic lines 9 to 22 (blocks 74, 79, 83, 84, 75, 80, 81, and 82), the shale stone depths are larger at 10,000 ft and are not favorable for development. In the east of the basin, from seismic lines 23 to 29 (blocks 16, 31, and 13), the shale stones are very shallow at depths ranging from 6,000 ft to 9,000 ft and are thus favorable for development.

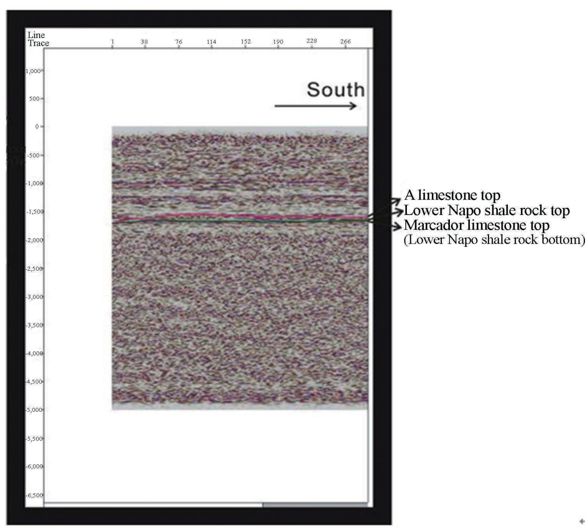

Figure 11
Interpretation Result of Seismic Line 5

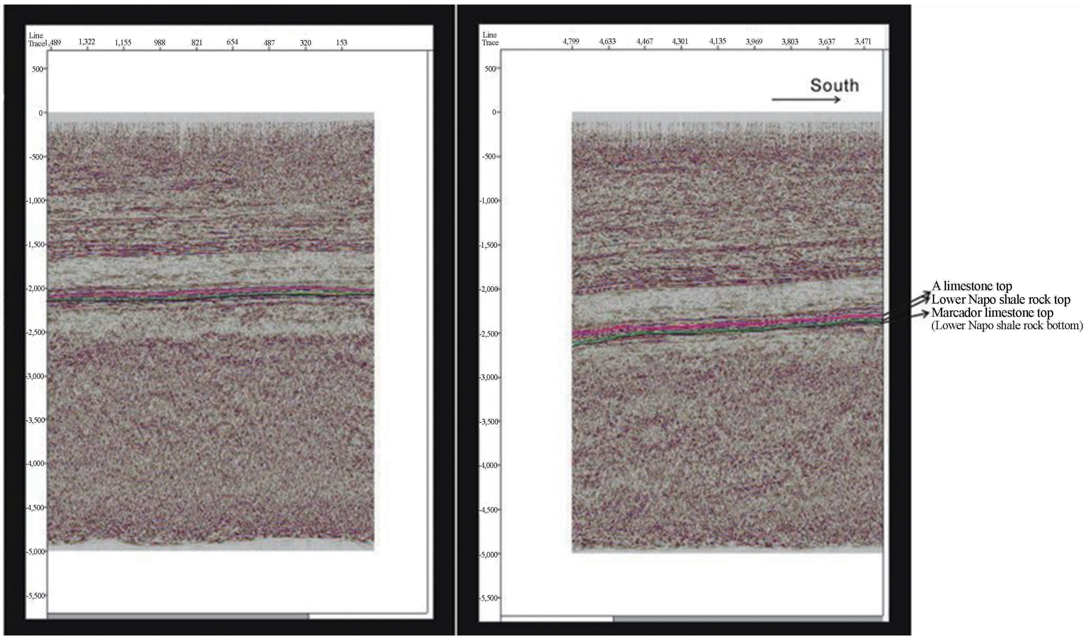

Figure 12
Interpretation Result of Seismic Line 9

3. PREDICTED FAVORABLE AREAS FOR THE EXPLORATION OF LOWER NAPO SHALE GAS

We divide the entire basin into six areas. They are the northwest area (blocks 11, 18, 56, and 7), north area (blocks 58 and 62), west area (blocks 29, 20, 22, 28, and 70), middle area (blocks 55, 22, and 17), east area (blocks 12, 67, 18, 31, and 63), and south area (blocks 79, 83, 84, 75, 80, 81, 77, 78, 82, 85, and 86). According to the analysis of the thickness and depth variation, we define the favorable areas for shale gas (oil) enrichment (Figure 13).

In the north and middle areas, shale stones are very thin. Thus, their shale gas potential is extremely low (Figure 13).

In the south area, the lower shale stone is formed in deep sea, with a depth of more than 4,000 m (12,000 ft). Developing this area would be expensive. Therefore, this area has no shale gas (oil) potential (Figure 13).

In the northwest and east areas, shale rocks are thick and extremely shallow. These areas have abundant shale gas and are thus easy to develop. Moreover, the northeast area has high vitrinite reflectance and can easily produce a large amount of oil and gas. Therefore, these two areas are prospective areas for shale gas (oil) formation (Figure 13).

In the west area, shale rocks are thicker and thinner than those in the northwest and east areas, respectively; these shale rocks are also shallow and easy to develop. Shale rocks in the west area also have high vitrinite reflectance. Therefore, the area is regarded as a prospective area for shale gas (oil) formation (Figure 13).

In summary, we choose the northwest, west, and east areas as prospective (high gas potency) areas (Figure 13).

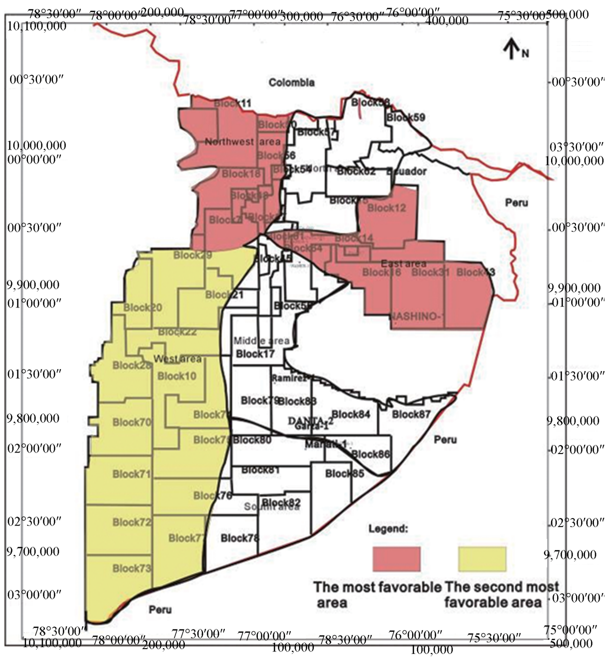

Figure 13
Predicted Favorable Areas for the Exploration of the Lower Napo Shale Gas in the Oriente Basin

CONCLUSION

(a) By analyzing the geochemical index, thickness, depth of burial, distributional stability, and data availability, we choose the lower Napo shale in the Oriente Basin as the main shale gas-bearing play. The organic matter in the lower Napo shale is rich and mature, the thickness and depth are favorable, its distribution is stable, and available data are abundant. Therefore, it is a prospective shale gas reservoir.

(b) According to the logging data and seismic line interpretation results, the lower shale rocks are distributed in the entire basin. The thickness is 15 m and is relatively high in the northwest, south, and west areas. As for the depth, the north area is shallow, and the south area is deep.

(c) The general analysis shows that the northwest, east, and west areas are favorable areas for exploration and development.

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