The volumetric potential assessment of the oil shales of Tremembé Formation, Taubaté Basin, Brazil

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Abstract

This assessment of the volumetric potential of the oil shales of Tremembé Formation (Oligocene, Taubaté Basin, Brazil) was based on the sedimentological study of 2457 total organic carbon and 1007 Rock–Eval pyrolysis analyses of core samples from nine survey wells drilled in the central portion of Taubaté Basin. Along a 240-m-thick package in the upper part of Tremembé Formation, thirteen chemostratigraphic units with thicknesses varying from 10 to 35 m were identified. The upper interval (unit L), 30 m thick, exhibited the highest organic content and original generation potential and was thus studied in detail. In unit L, oil yield maps were constructed, seeking to identify the most attractive areas for industrially exploiting the oil shales, and volumetric calculations employing a probabilistic Monte Carlo method were conducted to quantify the potentially recoverable oil volume. Three exploratory scenarios based on yield values (S1 + S2) were considered for calculating the oil volumes, seeking to offer different exploratory scenarios for decision making. For the scenario that considered only average yields above 100 mg HC/g rock, the recoverable oil volume is 525 million bbl (P90) to 884 million bbl (P10); for the scenario that considered only average yields above 80 mg HC/g rock, the recoverable oil volume is 1.4 billion bbl (P90) to 2.6 billion bbl (P10); and for the scenario that considered only average yields above 60 mg HC/g rock, the recoverable oil volume is 3.6 billion bbl (P90) to 5.4 billion bbl (P10).

Keywords Organic geochemistry · Chemical stratigraphy · Area yields · Volume calculation · Monte Carlo method

Introduction

Brazil has an enormous potential for unconventional resources to be explored in the different sedimentary basins within its territory, and in particular, its oil shales. Among the unconventional hydrocarbon resources in Brazil, those related to the oil shales of the Tremembé Formation in Taubaté Basin, in São Paulo state (Fig. 1), have historically attracted the greatest attention regarding their economic recovery potential (e.g., Abreu 1936; Padula 1969; Dyni 2006). These resources were industrially exploited until the mid-1900s, by the extinct Conselho Nacional de Petróleo (CNP—National Petroleum Council), through an extraction plant in Pindamonhangaba, SP, with a processing capacity of up to 10 thousand barrels per day (Milani and Araújo 2003). Technological limitations and management decisions by Petrobras, recently created at that time, led to the decommissioning of that oil extraction plant. However, in the last 10 years, that situation has been quickly changing in a positive fashion.

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Fig. 1 a Map showing the location of the Taubaté Basin. b Simplified geological map of Taubaté Basin, showing the wells studied Source modified from Riccomini 2004

The determination of the quantity, quality and maturation of the organic matter is parameters utilized in assessing the generation potential and the economic attractiveness of unconventional resources.

With the exception of unpublished reports, updated geochemical data that cover the mid- and upper sections of the Tremembé Formation are not available in the literature, at this time. Thus, the present study sought to assess the quantity and quality of the organic matter present in Tremembé Formation, employing TOC and Rock–Eval pyrolysis analyses. Based on those data, a chemostratigraphic sectioning of this unit was proposed, as well as a geochemical correlation of the subunits among the studied wells. Maps showing the distribution of the generation potential (S₂) of the most promising intervals were also constructed, seeking to characterize the best region for possible economic exploitation of the oil shales. Finally, a volumetric assessment of hydrocarbons (in bbl), under three different exploration scenarios, was made for the chemostratigraphic subunits considered to be the most important.

Geological setting of Taubaté Basin

The Taubaté Basin is located between the Mantiqueira Range and the Serra do Mar range, in Paraíba valley, in eastern São Paulo state, Brazil. Taubaté Basin is part of a set of Cenozoic Tetrogenic Basins and is elongated along the ENE direction, approximately 170 km long and 20 km wide. Its average sedimentary thickness is 500 m, reaching a maximum thickness of 800 m (Fernandes 1993). Its elongated and oriented shape follows the main tectonic–structural traces (framework) of the crystalline basement in the southeastern region of Brazil.

Taubaté Basin is classified as an intracontinental rift basin, due to its structural elements, such as predominance of normal faults, asymmetric compartments in section and plan view, and faults with inversion of rotational direction (Fernandes 1993).

According to Riccomini (1989), its fill history can be divided into two phases. The first phase, syntectonic with rifting, corresponds to a distensive phase, in which alluvial and lacustrine sediments of the Taubaté Group were deposited during the Paleogene. In the second phase, after diastrophic tectonism, fluvial sediments of the Pindamonhangaba Formation and alluvial and colluvial Quaternary sediments were deposited (Fig. 2).

As conceived by Riccomini (1989), the Taubaté Group is composed of the Resende, Tremembé and São Paulo formations.

The Tremembé Formation is situated in the intermediary portion of Taubaté Group, being composed of sediments associated with a lacustrine system, represented by massive green argillites, shales rhythmites and marls, dolomites and sandstones. Riccomini (1989) interprets Tremembé Formation as a lacustrine system of the playa-lake type. This system is better developed in the central portion of Taubaté Basin, and to a lesser extent, in São Paulo Basin, both of which are part of the Continental Rift of Southeast Brazil (CRSB). The maximum thickness attained in this unit is approximately 400 m (Sampol 2007).

This formation always raised academic and economic interest, which resulted in numerous studies regarding various paleontological, stratigraphic, tectonic, geophysical,

geochemical and economic aspects (e.g., Suguio 1969; Mezzalira 1989; Riccomini 1989; Marques 1990; Padilha et al. 1991; Fernandes 1993; Riccomini et al. 2004; Torres-Ribeiro 2004; Zalán and Oliveira 2005; Freitas 2007; Torres-Ribeiro and Borghi 2007; Chagas et al. 2009; Duarte 2012). This formation is widely known for its rich and diversified fossiliferous content, including references to remains of leaves, angiosperm tree trunks, sponge spicules, wormholes, gastropods, ostracods, crustaceans, insects (Lepidoptera), fishes, birds, reptiles (crocodilians and chelonians) and mammals (Chiroptera, Toxodontidae, Rodentia) (Mezzalira 1989). The pollen content of samples from Tremembé Formation, intercepted by CNP well #42, led Lima et al. (1985) to suggest an oligogenic age for this unit. According to Mendonça Filho et al. (2010) and Chagas et al. (2009), the bituminous shales with high organic carbon content and high S2 and HI are predominantly composed of amorphous organic matter or fresh water microplankton.

Fig. 2 Lithostratigraphic chart of Taubaté Basin. Also illustrated are its tectonic phases
Source Riccomini et al. (2004)

Table 1 Information regarding the wells studied

Wells	Location		Elevation of the well (m)	Final depth (m)	Total samples for TOC	Total samples for Rock–Eval pyrolysis
TMB-03-SP	x: 446347	y:7461042	565	240	627	362
POT-01-SP	x: 467070	y:7473429	532	100	394	80
PND-02-SP	x: 449312	y:7462094	537	80	230	139
MOR-02-SP	x: 459163	y:7469999	531	80	288	153
TMB-01-SP	x: 444704	y:7462094	549	55	207	86
PND-01-SP	x: 448938	y:7461699	567	53	162	57
MOR-01-SP	x: 462388	y:7465951	561	55	180	79
RO-01-SP	x: 468250	y:7467128	558	55	194	0
QUI-01-SP	x: 439603	y:7453490	573	55	175	51

Materials and methods

Samples were analyzed from nine shallow wells (varying from 53 to 241 m deep) (Table 1), which were drilled with a rotary rig owned by the State University of Rio de Janeiro (UERJ), in locations shown in Fig. 1.

From all the wells analyzed, approximately 650 m of cores was recovered. These cores were sedimentologically described, and the faciological characteristics of the section were emphasized, in terms of its main attributes, such as lithology, color, structure and fossils. The sampling for geochemical analyses followed an average spacing of 20 cm, which occasionally varied, due to the faciological characteristics of the deposits. A total of 2457 samples were collected for determination of TOC, sulfur and insoluble residue. Based on the TOC results, 1007 samples were selected for Rock–Eval pyrolysis analyses. These analyses, as well as pycnometry, were performed by Laboratório de Estratigrafia Química e Geoquímica Orgânica—LGQM (Chemical Stratigraphy and Organic Geochemistry Laboratory) of the Faculty of Geology (FGEL) of UERJ. The distribution of the samples according to the well from which they came can be seen in Table 1.

Total organic carbon (TOC)

The rock samples were ground, weighed, decalcified and weighed again (RI=insoluble residue data). Then, they were analyzed in a Leco SC-632, with the TOC values reported as % relative to the weight of the original sample. Part of the samples that exhibited TOC values equal or greater than 0.5% were selected for pyrolysis analyses.

Rock–Eval pyrolysis

The samples were weighed and then analyzed in a Rock–Eval 6 pyrolyzer from Vinci Technologies, following the procedures indicated by Espitalié et al. (1985). The

following parameters were read: S1 (in milligrams of hydrocarbons per gram of rock—mg HC/g rock), S2 (in mg HC/g rock), S3 (in mg CO₂/g rock) and temperature at which the peak in S2 occurs (Tmax, in °C).

The pyrolysis data, together with the TOC data, allowed the calculation of the hydrogen index (HI = S2/TOC × 100) and the oxygen index (OI = S3/TOC × 100).

Density

In order to measure the density of Tremembé shales, different methods were employed: volume calculation with a caliper, pycnometry, fluid displacement and gas pycnometer. Considering the lower costs involved, and faster and more practical operation, density assays were performed by pycnometry, according to the procedures described by Silva 2007. In this study, a 25-ml pycnometer was utilized.

To determine the average density of the oil shales from the most promising intervals, samples from well TMB-03-SP were utilized, which was drilled next to the area with the highest organic content in the basin. Then, 19 samples were selected, with different degrees organic enrichment. Since oil shales are rocks that can hold water in their matrix, it was necessary to submerge the samples in resin in order to seal the material. The densities of the samples were calculated based on the equation described in Silva 2007.

Volume

Probabilistic simulations describe techniques that reach approximate solutions to quantitative problems, via random sampling from a universe of possible solutions. The Monte Carlo method (also known as Monte Carlo simulation) explicitly represents the uncertainties of a problem, specifying input variables with a given probability distribution, and then performs numerous calculations to find a set of deterministic solutions, based on random sampling of the values for the input variables (Jones 2009).

The Monte Carlo method was utilized to calculate the rock volume and volume of the oil that could be recovered from the Tremembé Formation, based on available input parameters. A probabilistic calculation tool was utilized: the “Probabilistic Assessment Tool Using Monte Carlo Method,” version 2.1, which works within a spreadsheet in Microsoft Excel© (Microsoft Office 2013 package).

Seeking to offer different exploratory scenarios for decision making, depending on distinct technological and/or economic factors, three scenarios were considered for the volume calculation. These scenarios are based on distinct values for the yield from the oil shales (cutoff values). In the first scenario, only areas limited by a cutoff yield greater than 100 mg HC/g rock were considered. In the second scenario, the possibility of economic viability of areas with an intermediary cutoff yield of 80 mg HC/g rock is considered. In the third scenario, economic viability of areas with a cutoff yield of 60 mg HC/g rock is considered. These values were chosen considering that the maximum yield found for the different units was 100 mg HC/g rock, and that the average of the different units was 69 mg HC/g rock. Thus, the maximum yield (100 mg HC/g rock) was utilized for the first scenario, a

value slightly lower than the average (60 mg HC/g rock) was utilized in the third scenario, and an average of those two values (80 mg HC/g rock) was utilized for the second scenario.

It is worth noting that probabilistic results are presented for each scenario, with confidence levels of P90, P50 and P10. These confidence levels correspond to 1P or proven reserves (90% chance that the actual recoverable amount is equal or greater than the value indicated), 2P or proven plus probable reserves (50% chance that the actual recoverable amount is equal or greater than the value indicated) and 3P or proven plus probable plus possible reserves (10% chance that the actual recoverable amount is equal or greater than the value indicated), respectively (SPE-PRMS 2007).

The input variables for the volumetric calculation employing the Monte Carlo method are the following: average thickness (m), average area (km²), average rock density (g/m³), average yield (S1 + S2, mg HC/g rock), average conversion factor of rock to oil and their respective standard deviations. The total volume of recoverable oil is obtained by multiplying together all these variables.

The areas in each subunit were obtained based on the polygon of the 60, 80 or 100 mg HC/g rock isoline. Thus,

Fig. 3 TOC, S₂, HI and T_{max} in well TMB-03-SP in Tremembé Formation

in each scenario, the areas of the respective isolines varied according to the distribution of the occurrence of the average yield. These maps were constructed with Geosoft Oasis Montaj version 6.4.2.

The average thickness of each subunit was obtained based on the top and base of the chemostratigraphic units of economic interest, as defined in each of the wells considered in the volume calculation.

The average density value adopted represents an average of the values obtained for the shale samples with high yields. This value is comparable to those adopted by other authors cited, such as Campos (1952), who adopted an average density of 1.6 g/cm^3 , and Castro and Silva (1952), who adopted an average density of 1.4 g/cm^3 . As to the value for the conversion factor, a value of 0.9 was used, based on the study of Soldan et al. (1988).

Results and discussion

In the nine wells studied, data from TOC, sulfur, RI and Rock–Eval pyrolysis were integrated. To illustrate the vertical distribution of the TOC and the Rock–Eval pyrolysis values in the upper section of the Tremembé Formation, the

TMB-3-SP well (Fig. 3) was utilized as an example, since among all wells, it penetrated the thickest section of Tremembé Formation (240 m). The Tmax values show that the organic matter of Tremembé Formation is thermally immature in well TMB-03-SP (Fig. 3). As with the Tremembé Formation, the organic matter in that entire area is thermally immature (Bergamashi et al. 2010; Mendonça Filho et al. 2010). That is due to the thinness of the total sedimentary package of the Taubaté Graben (Marques 1990).

Based on TOC, S2 and HI data, the section of well TMB-3-SP was subdivided into 13 chemostratigraphic units, informally named A to M (Fig. 3). Unit L is the interval with the highest organic matter enrichment in Tremembé Formation; thus, it raises the greatest interest, from the point of view of hydrocarbon generation. Given this potential, a more thorough analysis was performed, in order to characterize the interval in greater detail.

Based on the TOC values, it was possible to identify seven chemostratigraphic subunits in the section of unit L, informally named L1 to L7, from the base to the top. The correlation of these subunits among the wells is presented in sections A–A' and B–B', whose stratigraphic datum utilized was the top of the first layer of smectitic argillite (Figs. 4 and 5). In the correlation sections, subunits L2 and L4,

Fig. 4 Correlation A–A' between wells TMB-01-SP, TMB-03-SP, PND-02-SP and MOR-01-SP, based on TOC data

characterized by the red color in Figs. 4 and 5, are associated with the smectitic argillite intervals normally identified by their low TOC (<1%) values. Subunits L1, L3, L5, L6 and L7 are characterized by elevated average values of TOC, varying from 3 to 16% (Table 2). These subunits are discussed in greater detail later in this work, considering their greater organic matter enrichment.

Considering that the organic matter is thermally immature, the S2 and HI values are the original values, which permits assessing their generation potential. In units L1, L3, L5, L6 and L7, values of S2 above 10 mg HC/g rock and HI values between 400 and 850 mg HC/g TOC indicate an excellent potential for oil generation. In units L2 and L4, values of S2 below 10 mg HC/g rock and HI values below 200 mg HC/g TOC indicate a poor to good generation potential for gas.

As to the types of organic matter, as shown in the van Krevelen diagram (Fig. 6), units L1, L3, L5, L6 and L7 are composed of Type I to Type II organic matter, and units L2 and L4 are composed, respectively, of Type III and Type IV organic matter. The different types of kerogen are due to the fact that units L1, L3, L5, L6 and L7 are composed of shales deposited in an anoxic environment, corresponding

to deep lake depositional phases, while units L2 and L4 are composed of smectitic argillites deposited in an oxic environment, corresponding to shallow lake depositional phases (Riccomini et al. 2004; Torres-Ribeiro and Borghi 2007; Bergamaschi et al. 2010; Setta et al. 2012).

The minimum parameters required for assessing oil shale potential vary according to the geology and legislation of each country (BYNI 2006). In the case of Brazil, the sole production reference is the PetroSix operation of Petrobras, which extracts oil from the black shales of Irati Formation (Padula 1969; Milani et al. 2007). In the two intervals exploited, the shales are thermally immature and exhibit average values of TOC above 10%, average values of HI of 600 mg HC/g TOC, depth of up to 60 m and thicknesses of 3 to 6.5 m (Milani et al. 2007). As can be seen in Table 3, units L1, L3, L5, L6 and L7 are potentially attractive for industrial production of oil shale since they contain thermally immature ($T_{max} < 440\text{ }^{\circ}\text{C}$) black shales with high TOC average content (from 7% to 13%), good organic matter quality (average values of HI from 484 to 641 mg/g), which are close to the surface (depths from 10 to 65 m) and have thicknesses of 2 to 9 m, with average total net thickness of 31 m.

Fig. 5 Correlation B-B' between wells QUI-SP, TMB-01-SP, PND-02-SP, MOR-02-SP and POT-01-SP, based on TOC data

Table 2 Thicknesses of chemostratigraphic subunits L1, L3, L5, L6 and L7, and respective average values of TOC (in %), yield (S1 + S2 in mg HC/g rock) and HI (in mg HC/g TOC). x—absent units. y—well did not completely penetrate the unit

Subunit	Data	Wells							
		QUI-SP	TMB01-SP	TMB03-SP	PND01-SP	PND02-SP	MOR02-SP	MOR01-SP	POT01-SP
L7	Thickness (m)	8	x	12	11	7	9	7	11
	TOC	5.14	x	15.63	12.95	14	12.51	15.67	13.15
	S1 + S2	52.5	x	118.98	104.1	119.19	87.89	119.1	89.34
	IH	544.92	x	691.47	649	721.66	591.33	678.98	612.57
L6	Thickness	2	x	3	4	x	2	3	2
	TOC	5.56	x	9.47	5.56	x	3.02	8.85	5.53
	S1 + S2	18.65	x	30.82	19.92	x	19.3	81.61	18.3
	IH	320.31	x	615.38	533.5	x	471.17	593.78	370
L5	Thickness	7	8	4	4	8	7	6	6
	TOC	5.85	11.11	12.28	11.89	14.12	8.72	9.02	8.99
	S1 + S2	55.53	93.15	83.83	44.07	124.2	49.4	80.65	69.14
	IH	615.06	649.48	648.49	555.1	750.24	515.8	659.19	591.92
L3	Thickness	5	5	2	5	10	2	4	6
	TOC	5.41	9.61	13.39	9.27	10.23	10.43	7.03	7.03
	S1 + S2	54.96	89.1	98.06	63.71	77.33	77.1	50.91	50
	IH	568	636	645	586	631	504	609	546
L1	Thickness	5	10	9	6	y	10	10	15
	TOC	3.63	8.71	11.38	10.83	y	10.84	9.39	8.03
	S1 + S2	30	77.49	85	68.13	y	84.29	58.04	54.43
	IH	477	661	660	557	y	642	585	540

Fig. 6 van Krevelen diagram showing the different types of organic matter for the studied units

Maps of average TOC values were constructed for subunits L1, L3, L5, L6 and L7, in order to show the regions with greatest organic matter enrichment (Fig. 7). However, in unit L1, at well PND-02-SP, TOC data, as well as S1 + S2, were

not considered in constructing the maps, since in that location unit L1 is not complete.

Hydrocarbon yield maps for subunits L1, L3, L5, L6 and L7 (Fig. 8) summarize the distribution of the average yields (in mg HC/g rock) of S1 + S2 for each well (Table 2), indicating areas potentially more favorable from an economic point of view. In constructing these maps, arbitrary yield values near zero were considered next to the edges of the basin. This premise was adopted considering the predominance of sandy facies in these areas, as shown by Vidal et al. (2004).

Figure 8 shows the chemostratigraphic units and the isolines for yields of 60, 80 and 100 mg HC/g rock (red). It can be observed that the isolines of greatest yield (100 mg HC/g) surround wells TMB-03-SP and PND-02-SP, in most of the seven subunits, thus representing the area of greatest potential.

Volumetric calculation considering a yield cutoff of 100 mg HC/g rock

Initially, a high cutoff yield was considered (average yield greater than 100 mg HC/g rock), seeking to establish a parameter for an exploratory scenario that is more restricted in terms of area and yield. This represents a conservative scenario (Fig. 9).

Table 3 Dados de quantidade (COT), qualidade (IH), maturação (Tmax), profundidade, espessura, litologia para as unidades de maior interesse para recurso de oil shale

	L1	L3	L5	L6	L7
TOC (%)	10	9	10	7	13
IH (mg HC/g TOC)	600	559	622	484	641
Tmax (°C)	< 440	< 440	< 440	< 440	< 440
Depth (m)	35–65	20–65	12–55	15–50	10–45
Thickness (m)	8	6	6	2	9
Lithology	Black shale	Black shale	Black shale	Black shale	Black shale

Fig. 7 Map showing the regions (wells) that are richest in TOC, for each subunit

With a cutoff yield of 100 mg HC/g rock, and with the input data regarding areas, thicknesses, densities and yields for this case, the Monte Carlo simulation resulted in an aggregated economically viable rock volume for subunits

L1, L3, L5, L6 and L7 of 1.0 billion tons of oil shale, for the P90 confidence level. For the P50 and P10 confidence levels, the economically viable rock volumes are, respectively, 1.2 billion and 1.5 billion tons of oil shale (Table 4).

Fig. 8 Map of yield distribution (S1 + S2, in mg HC/g rock), by subunit, utilized to estimate the average of the areas and their standard deviation. The isolines of 60, 80 and 100 mg/g show the respective areas enclosed, utilized in the Monte Carlo calculations

Fig. 9 The chemostratigraphic units and the isolines for yields of 60, 80 and 100 mg HC/g rock (red). It can be observed that the isolines of greatest yield (100 mg) surround wells TMB-03-SP and PND-02-SP,

For the recoverable volume of oil for those same subunits, the Monte Carlo simulation resulted in an aggregated recoverable oil volume of 525 million bbl, 686 million bbl and 884 million bbl, for the P90, P50 and P10 confidence levels, respectively.

The contribution of oil from each subunit is shown in Fig. 10, where subunit L7 stands out as the one with the greatest proportional contribution, providing approximately 89% of the total. This unit is the thickest, has the largest area and exhibits the greatest yield, in relation to the others.

in most of the seven subunits, thus representing the area of greatest potential

Volumetric calculation considering a yield cutoff of 80 mg HC/g rock

With a yield cutoff of 80 mg HC/g rock, and with the input data regarding areas, thicknesses, densities and yields for this case, the Monte Carlo simulation resulted in an aggregated economically viable rock volume for subunits L1, L3, L5, L6 and L7 of 3.2 billion tons, for the P90 confidence level. For the P50 and P10 confidence levels, the economically viable rock volumes are, respectively, 3.8 billion and 4.4 billion tons of oil shale (Table 5).

Table 4 Probabilistic result for the yield cutoff of 100 mg HC/g rock, considering the sum of subunits L1, L3, L5, L6 and L7

Rock volume (million tons)		Oil volume (million bbl)	
P90	1.0	P90	525
P50	1.2	P50	686
P10	1.5	P10	884

Fig. 10 Contribution toward total oil by each subunit, for the yield cutoff of 100 mg HC/g rock**Table 5** Probabilistic result for the yield cutoff of 80 mg HC/g rock, considering the sum of subunits L1, L3, L5, L6 and L7

Rock volume (billion tons)		Oil volume (billion bbl)	
P90	3.2	P90	1.4
P50	3.8	P50	2.0
P10	4.4	P10	2.6

Fig. 11 Contribution toward total oil by each subunit, for the yield cutoff of 80 mg HC/g rock

For the recoverable volume of oil for those same subunits, the Monte Carlo simulation resulted in an aggregated

Fig. 12 Contribution toward total oil by each subunit, for the yield cutoff of 60 mg HC/g rock**Table 6** Probabilistic result for the yield cutoff of 60 mg HC/g rock, considering the sum of subunits L1, L3, L5, L6 and L7

Rock volume (billion tons)		Oil volume (billion bbl)	
P90	8.1	P90	3.6
P50	9.3	P50	4.5
P10	10.6	P10	5.4

recoverable oil volume of 1.4, 2.0 and 2.6 billion bbl, for the P90, P50 and P10 confidence levels, respectively.

The contribution of oil from each subunit is shown in Fig. 11, where subunit L7 again stands out as the one with the greatest proportional contribution, providing approximately 82% of the total (Table 6).

Volumetric calculation considering a yield cutoff of 60 mg HC/g rock

A third scenario was utilized, which considered the possibility of exploiting oil shale layers with average cutoff yields of 60 mg HC/g rock. With this cutoff yield, and with the input data regarding areas, thicknesses, densities and yields for this case, the Monte Carlo simulation resulted in an aggregated economically viable rock volume for subunits L1, L3, L5, L6 and L7 of 8.1 billion tons, for the P90 confidence level. For the P50 and P10 confidence levels, the economically viable rock volumes are, respectively, 9.3 billion and 10.6 billion tons of oil shale (Table 6).

For the recoverable volume of oil for those same subunits, the Monte Carlo simulation resulted in an aggregated recoverable oil volume of 3.6, 4.5 and 5.4 billion bbl, for the P90, P50 and P10 confidence levels, respectively.

The contribution of oil from each subunit is shown in Fig. 12, where subunit L7 once again stands out as the one with the greatest proportional contribution, providing approximately 55% of the total.

The volumetric calculations showed that subunits L7 and L5 contribute the most toward the total recoverable volume of oil in the three scenarios studied. In Fig. 8, it can be seen that those two subunits exhibit the highest potential for oil shale between wells PND-02-SP and TMB-03-SP.

Conclusions

The upper section of Tremembé Formation, involving an interval approximately 240 m thick, was subdivided into 13 chemostratigraphic units, informally named A to M, from the base to the top. Unit L, approximately 35 m thick, represents the interval with the greatest organic matter enrichment; thus, from a hydrocarbon generation point of view, it holds the most interest. This unit was further subdivided into seven subunits, of which five exhibit the greatest exploratory attractiveness: L1, L3, L5, L6 and L7. Among these, subunits L5 and L7 exhibit a high yield factor. For subunit L7 the yield is highest at wells TMB-03-SP, PND-02-SP and MOR-01-SP, and for subunit L5 the yield is highest at well PND-02-SP. In the areas next to the edge of the basin, such as in wells QUI-01-SP, RO-01-SP and POT-01-SP, the yield factors tend to be smaller; thus, they represent areas of low economic interest.

Considering the three scenarios investigated for subunits L1, L3, L5, L6 and L7, the one that considers only the areas that exhibit the highest yield (minimum cutoff yield of 100 mg HC/rock) indicates significant recoverable oil resources of approximately 525, 686 and 884 million bbl, for confidence levels of P90, P50 and P10, respectively. An intermediary scenario with minimum cutoff yield of 80 mg HC/rock indicates substantial recoverable oil resources of approximately 1.4, 2.0 and 2.6 billion bbl, for confidence levels of P90, P50 and P10, respectively. Finally, a more optimistic scenario that considers the possibility of exploiting oil shale layers with average cutoff yields of 60 mg HC/g rock, indicates very substantial recoverable oil resources of 3.6, 4.5 and 5.4 billion bbl, for confidence levels of P90, P50 and P10, respectively. Thus, the volumetric calculations performed utilizing Monte Carlo simulations indicate the existence of significant amounts of hydrocarbons that can be recovered from the oil shale, by applying industrial recovery methods to the most enriched levels.

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