Well test analysis integrated with the geologic context of the Macaé Formation in Campos Basin, Brazil

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Abstract

The objective of this work is to present the well test analysis of some wells drilled in Campos Basin and tested in the Macaé Formation. This formation is composed, in the productive zones (Quissamã member), mainly by calcarenites, with the presence of dolomites, the facies varying according to depositional conditions, diagenesis, and location inside the basin. The results obtained by the well tests were integrated with the geological knowledge of the basin with the objective of relating them with the basin framework in terms of facies and depositional environment.

Introduction

The starting point for this work was the detailed analysis of well test data for the wells involved in this study, obtaining some formation parameters, like permeability, presence of fractures, productivity indexes, besides the skin factor of the wells. Some of the wells were previously acidized and, in this process, some artificial fractures were created. Rock and fluid parameters (porosity, water saturation, net thickness, oil shrinkage and compressibility) used as entry data for the analysis were provided by the Operators at their well and test reports.

The two wells that firstly inspired this work were drilled by Petrobras between 2008 and 2009, aiming the Macaé Formation, and presenting very distinct results in the drill stem tests (**Figure 1**). Both generated Evaluations Plans of Discovery (EPD). The first one, 1-BRSA-619-RJS, did not present natural production of hydrocarbons, producing during the well test only when N_2 was injected through coil tubing. On the other hand, the well 1-BRSA-713-RJS presented a high productivity, producing naturally an oil of better quality.

The well 1-BRSA-619-RJS is located about 75 Km southwest of Campos coast line, in water depths of the order of 102 meters. The well 1-BRSA-713-RJS is located about 110 Km southwest of Campos coast line, in water depths of the order of 976.5 meters. Combination of the differences in well test performance and their locations inside the basin made it possible to justify those differences based in different depositional environments.

After analyzing these wells, other well test data were collected and interpreted, increasing the amount of data for an integrated analysis of the formation in the basin, including wells previously tested and others that were tested afterwards.

In the next sections, a brief geologic summary of the basin geology will be presented, as well as the results from well test interpretation for some wells tested in the Basin in this formation. Finally, using the results from the interpretation, some conclusions about the variability of permoporosity features of the Macaé Formation will be presented.

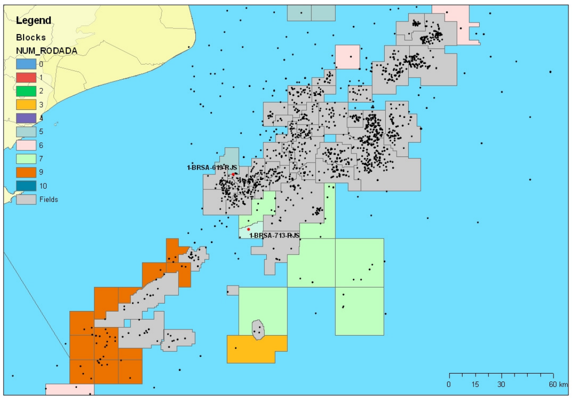

Figure 1 – General map of the central-south part of Campos Basin, showing the two first wells analyzed in red.

Brief geology summary of the basin

The Campos basin is a passive margin basin that was developed as the result of the Gondwana break up (South Atlantic Ocean opening) during the Early Cretaceous (Rangel and Martins, 1998). Its tectonic evolution begins with the extrusion of Cretaceous basalts over Precambrian pre-existing crystalline rocks, going through a rift phase (lake sedimentation) and followed by a siliciclastic and evaporitic phase that lasted until the Middle Cretaceous. After the Early Albian, an open marine sedimentation phase takes place, lasting to nowadays.

The basin is divided in three main exploratory compartments: proximal, intermediate and distal. The proximal compartment is basically located in shallow waters domain. Its rift section is structurally composed by horsts and grabens with large structural lows, where there is a predominance of sections of lagoonal sedimentation with considerable thickness along the whole basin. The initial part of the rift section is generally siliciclastic, followed by a section of coquinas (final phase) with intercalations of lagoonal shales. These shales are known as the main source rocks of the basin. The transitional phase is composed of a basal siliciclastic sequence followed by an evaporitic sequence.

Today the majority of the existing salt in the proximal compartment is displaced to deeper waters regions, mainly due to the basculation of the basin. In deep water regions these rafting mobilizations affected and structured the open marine sequence, including carbonate turtlebacks and turbidites sands. This latter fact is characterized by an intercalation of siliciclastics and carbonates, both structured by the salt mobilization over structural highs with turbidites close to it. The Tertiary section is composed, from the base to the top, of talus clays with turbidites, passing through coarse platform siliciclastics, intercalation of carbonates and talus clays.

In the transition from shallow to deep waters, the intermediate compartment is by far the one largely investigated by exploratory wells. The main existing oilfields under development and/or under production in the basin are located in this compartment: Marlin, Albacora, Roncador, Barracuda, Espadarte, among others. The main structural features in this compartment are: (1) basement highs and lows, (2) salt pillows affecting the overlying marine sequence, and (3) adiastrophic tectonics caused by the salt mobilization.

The distal compartment is still considered an exploratory frontier. Presently there are some exploratory activities under way – i.e., still under development –, in the South and North of the basin. Among these activities, in the South, we may cite the development of the Xerelete oilfield (late BC-2, now BM-C-35 block), and the on-going evaluation plan of discovery (EPD) in the BM-C-14 block, next to Xerelete, both operated by Petrobras. In the North, we may cite the development of the Wahoo oilfield (BM-C-30, operated by Anadarko) and the Itaipu oilfield (BM-C-32, operated by Devon). Both Wahoo and Itaipu are under EPD phase.

The main exploratory reservoirs investigated in the basin are the Carapebus (turbidites), Albian carbonates (e.g., Quissamã in shallow and deep waters) and lately, the presalt in deep and ultra-deep waters. These reservoirs play an important role with the source rocks from the rift sequence, linked through adiastrophic listric faults formed due to the rafting of the salt layers.

The main focus of this work is the Macaé formation, specifically concerning the Quissamã member. According to Winter et al. (2007), the Quissamã member is part of the drift supersequence K60, composed of marine sediments deposited under a thermal subsidence regime associated to adiastrophic tectonism (shallow platform). It corresponds to a distal portion formation, bounded by the Lagoa Feia formation (lower bound, Retiro member) and by a regional stratigraphic mark associated with a maximum flooding surface (the beta mark, upper bound). Lithologically, it is mainly represented by moderate to high energy carbonate sediments, composed of oolithic/oncolithic calcarenite banks with "shoaling upwards" profiles reaching up to 15 meters in thickness. The average porosity varies both laterally and in depth. The base of the K60 sequence is mainly composed of a carbonate tidal flat system, ranging in environment to supratidal, intratidal and lagoonal.

Exploratory scenario

The actual exploratory scenario in Campos basin, in terms of concession contracts, is extremely dynamic. Presently there are 22 active contracts (April 2011), totaling 35 exploration blocks. There are 47 producing oilfields under development, while the number of oilfields and gas fields together under development totalize 12. From September 2010 through March 2011, 16 EPD's are active and/or under way. The number of wells drilled so far in Campos, including all of its categories (wildcats, extension, production, etc), totalize more than 2,900, considering the whole history of exploration of the basin. In terms of seismic data (2D and 3D), there is a order of magnitude of 5,000-10,000 kilometers and square kilometers covering these two types of surveys in the basin.

In its three exploratory compartments (Rangel and Martins, 1998) – including shallow, deep and ultra-deep waters – Campos basin is largely covered by seismic, potential and electromagnetic data, including well data. Up to now, in terms of Brazil reserves, it is the biggest and most prolific offshore oil producer basin. With the emerging of the new high potential basins, such as Santos and Espírito Santo, Campos basin may be suppressed in the near future. However, in lately years it still has been proved prolific in terms of several and new exploratory frontiers, with the expansion of exploratory surveys towards deep waters and due also to discoveries in unusual plays.

In the following we describe some types of activities realized in several exploration contracts by diverse operators. The main companies actively acting in this scenario are: Anadarko, Devon, Maersk, OGX, Petrobras, RepsolYPF, Shell, Starfish and Statoil.

In the North of the basin, in block C-M-101 (BM-C-30), Anadarko is currently developing the Wahoo prospect oilfield. The Anadarko's block share common boundaries with block C-M-61 (BM-C-32), operated by Devon. To the Southeastern of this block, the Devon's block share boundaries with two blocks of the contract BM-C-31, operated by the consortium Petrobras/Shell. The rest of the area, its surroundings, is composed of several producing oilfields, including the high-potential fields belonging to Parque das Baleias, Parque das Conchas, and also the Frade and Roncador fields.

The surrounding of the C-M-101 block is pointed out here due to its geologic similarities at the level of the exploratory opportunities in the post salt section – contractual objective of several contracts derived from ANP bid round number 7 – and, most recently, in the presalt section. In the distal compartment of the basin, either in North or South, the presalt section has been continuously investigated, with all oil companies deepening the drilling of their wildcat wells in order to reach the upper sag or the rift section. This has happened in the contracts BM-C-30, BM-C-31 and BM-C-32, in the

North, and contracts BM-C-33, BM-C-34 and BM-C-36, in the South.

In the area of the contract BM-C-36, of the two exploratory deep water blocks C-M-401 and C-M-403, part of the area of the block C-M-401 is targeted via an EPD operated by Petrobras (1-BRSA-713-RJS), with oil discoveries publicly announced. The rest of the area of the block C-M-401 and the totality of the area of the block C-M-403 are under way with exploration activities occurring during their second exploration period.

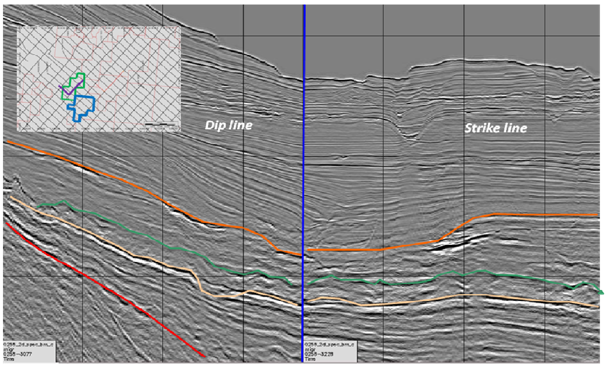

Figure 2 – Dip and seismic line through block C-M-401, where well 1-BRSA-713-RJS was drilled.

In the area of the contract BM-C-34, operated by Devon, the periods of the exploration of the blocks C-M-471 and C-M-473 were extended by ANP in order to "grant time" to the operators to investigate the same exploratory opportunities identified in the neighbor block C-M-101. The "granting-of-time strategy" has been commonplace in the management of the contracts belonging to blocks in Campos basin, since the commodity "drilling rig" has been introduced in the equation of investigation of hydrocarbons volumes. Since the drilling-rigs slots are completely allocated by previously established contracts to span for several years in the offshore sector, Devon signaled to ANP bringing to Brazil the drillship *Deepwater Discovery* in 2009 with the objective of investigating opportunities in the areas of the contracts BM-C-32 and BM-C-34. With the extension granted by ANP until 2013, at the present moment Devon generates expectations towards possible new and huge discoveries at BM-C-34 by the deepening of its wells in order to reach the presalt section and investigate the Atobá, Grazina and Fragata prospects along C-M-471 and C-M-473, respectively.

In the area of the contract BM-C-33 (C-M-539), the prospects investigated by RepsolYPF (Seat and Deep Seat) were concluded and completed. This contract is in its first exploration phase.

In the area of the contract BM-C-31, the block C-M-151 is finishing its first exploration period. In this block there exists one notification of drilling for a well in a prospect named Araticum. This well has a twofold objective: (1) fulfill the contractual commitment (in units of work), and (2) investigate the presalt section with the expectation of a discovery.

Among all exploration contracts active in Campos basin, we may cite the development of the Xerelete oilfield (late BC-2, now BM-C-35), located in the South of the basin. Since 2009, Petrobras evaluates, under an EPD, one conjugate area that belonged to the area of the contract BM-C-14 (now included in the ring fence of Xerelete), next to BM-C-35. This area is strategically located East of the Papa-Terra, Maromba and Peregrino gas fields, including also areas with accumulations with boundaries extrapolating beyond the area of the block BM-C-14 and entering areas of the Union. Presently, the contract BM-C-35 is in its second exploration period.

The central part of the basin does not have active concession contracts in exploration phase, just areas of development and producing oilfields. But, on the other side, inside one active trend of production fields some new discoveries in the Albian Quissamã play have been occurring. All these carbonate discoveries in the Quissamã have been properly declared to ANP, some of them are under EPD analysis.

Towards the South of the basin, Brazilian holding OGX operates the contracts BM-C-39 (C-M-466), BM-C-40 (C-M-499), BM-C-41 (C-M-592), BM-C-42 (C-M-620) and BM-C-43 (C-M-621), bided in Round 9. Since then more than 20 wells have been drilled along these blocks. The present aggressive exploration campaign leaded by OGX mainly concentrates its efforts in areas located around the Cabo Frio high – the Volcanoes Complex. It is important to note that among all the drilled wells in this area all of them reported discoveries of oil or gas. But currently OGX pays most of its investigation for the Waimea prospect, located in block C-M-592.

Recently, Statoil announced the beginning of oil production in the Peregrino field, located in shallow waters, 85 Km west of the Rio de Janeiro coastline. The initial production is estimated to reach 100 M bbl per day (thousands of bbl/d), involving blocks BM-C-7 and BM-C-47.

Very recently (April / 2011), Maersk Oil Brasil announced to ANP one test for oil in the Quissamã play in the well 1-MRK-3-RJS, drilled in block C-M-560 (BM-C-37), Southern part of the basin, near the Cabo Frio high. The horizontal and vertical facies variability and the structural complexity (fractures and faults) represent high risk, so the Carambola-A prospect must be first be tested for its lateral extension and connectivity. In this part of basin the Cabo Frio high is considered prolific in terms of production of hydrocarbons and discoveries associated to different stratigraphic levels. The elements "generation" and "migration" are always present. The effectivity of the remaining elements "reservoir" (existence and quality) and "accumulation" (seal and trapping) must then be tested in order to develop future findings.

Presently the exploration scenario in Campos basin comes to a standstill in the sense of a emerging new exploratory landmark in Brazil: the production sharing in presalt areas. The existing exploration contracts will be honored to its completion. Considering that this new reality will come into play in the next years, discoveries in the Quissamã play are expected to continuously happen in non-bided areas in the transition from shallow to deep waters. In terms of basin analysis and water depth, the discoveries in the Quissamã represent a new exploratory play in deep water. In shallow waters domain, the Quissamã play is a common and very well known (prospected) reservoir, like in Bonito, Linguado and Pampo fields, among others.

In the next section we describe the well tests realized in the Quissamã member in the wells recently drilled in the areas of the blocks C-M-333 (1-BRSA-619-RJS) and C-M-401 (1-BRSA-713-RJS). The Quissamã reservoir identified in these wells are composed of oncolithic to oolithic high to low energy calcarenites. **Figure 2** shows one composite dip and strike seismic section showing the morphology of the exploratory opportunities identified in the Cretaceous and Albian section (ANP interpretation).

Results

• 1-BRSA-619-RJS

The Quissamã member in this well was a secondary target, in a relatively small anticlinal structure near the Enchova Paleocanyon.

This well was tested in the interval from 1968 to 1988 meters (measured depth), in the calcarenites of Macaé Formation (Quissamã Member), after an acid fracturing. The test was composed by 2 drawdown periods, intercalated by a buildup.

The well produced during the drawdown period by N_2 injection in the test column made with coil tubing, and the average oil rate was 152.9 m^3/d (962 bbl/day). The oil density was 22.3°API.

Analyzing the log-log plot of the buildup, it can be noticed the presence of a linear flow, characteristic of the reservoir flowing to a vertical fracture, that could have been generated by the acid fracturing carried out before the test.

Thus, some parameters were calculated in the specialized plots, for radial flow (Horner plot) and linear flow (square root plot), with the aid of the commercial software PanSystem®, and after that, a data fitting was made, considering the analytical model of vertical fracture of infinite conductivity, coherent with the fact that the fracturing was made in carbonates, with acid, not using any proppant.

In **Figures 3** and **4**, it is shown the log-log and semi-log plots with the adjusted curves generated by the parameters that were considered better adjusting with the gauge data.

• 1-BRSA-713-RJS

The main objective of this well was testing a “turtleback” structure at the level of the Quissamã Member, on an Albian carbonatic shelf deposited under high energy conditions in shallow waters, over a basement paleohigh.

This well was tested in the interval from 3,022 to 3,067 meters (measured depth) in the calcarenites of Macaé Formation (Quissamã Member). Two well tests were conducted, the first one before and the second one after a matrix acidizing operation.

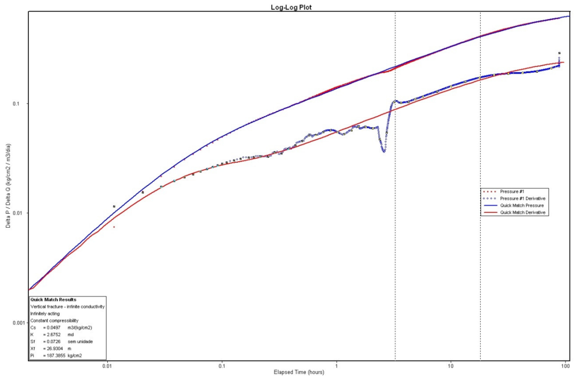

Figure 3 – Log-log plot of the buildup of well test in 1-BRSA-619-RJS, with the adjusted curve.

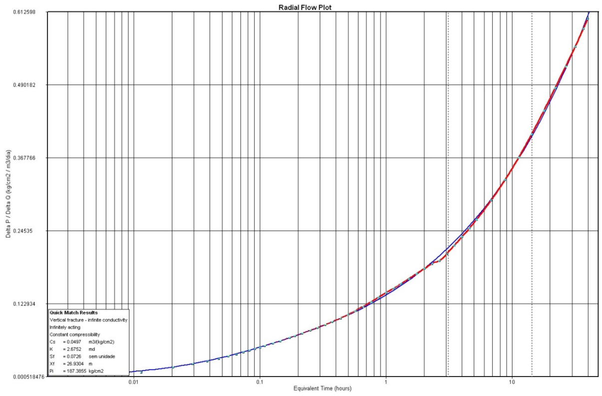

Figure 4 – Semi-log plot of the buildup of well test in 1-BRSA-619-RJS, with the adjusted curve.

Figures 5 and **6** are the log-log and semi-log plots with the adjusted curves generated by the parameters that were considered better adjusting with the gauge data.

The first test was composed by 5 drawdown periods, each one followed by a buildup, being the last three dedicated to production logging and downhole fluid sampling. The well started to produce naturally in the second drawdown, and the average oil rate was 375 m^3/d (2,359 bbl/day) at a choke size of 32/64”. The oil density was 28°API.

Analyzing the log-log plot of the buildup, there is a period of stabilization in the derivative that, followed by a drop, could be interpreted as a spherical flow regime followed by the presence of some kind of limit maintaining the pressure.

Thus, some parameters were calculated in the specialized plots, for radial flow (Horner plot) and linear flow (square root plot), with the aid of the commercial software PanSystem®, and after that, a data adjust was made, considering the model of partial penetration (that could be responsible for the spherical flow) with the presence of a single fault with boundary conditions of constant pressure (for example, it could be the contact with an aquifer). The model adjusting did not provide a good fitting.

Based on the results of the first test, the well was acidized, and the second test was carried out. The first stabilization of the derivative on the log-log plot was in a lower level with respect to the first test, and the curve drop started at a later moment, indicating that some restriction at the perforations must have been removed.

This test was composed by 3 drawdown periods, each one followed by a buildup, all of them for flow rate measurements. The average oil rate increased to about 510 m^3/d (3208 bbl/day), at the same choke size of 32/64", showing the improvement in productivity due to the acidification.

This time the fitting to a theoretical model was made employing a radial homogeneous flow with a barrier of constant pressure.

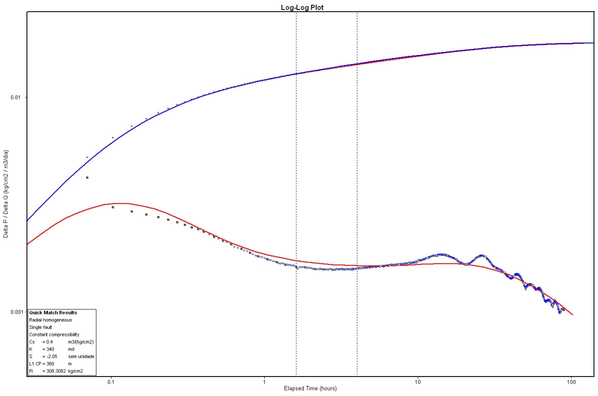

Figure 5 – Log-log plot of the second buildup of the post-acidification well test in 1-BRSA-713-RJS, with the adjusted curve.

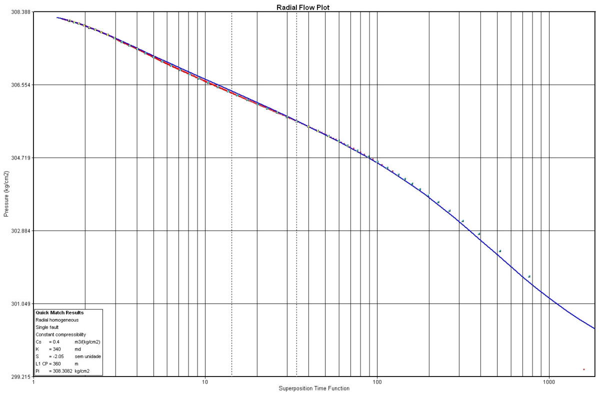

Figure 6 – Semi-log plot of the second buildup of the post-acidification well test in 1-BRSA-713-RJS, with the adjusted curve.

On Table 1, the main parameters from well test interpretation are compared. It can be noticed that the results from 1-BRSA-713-RJS are much better, indicating that its reservoir is located in a place in the basin with better permoporosity features. It is interesting to note that, in terms of porosity, based in well log interpretation, both wells have similar results (around 19 per cent), indicating that in the case of well 1-BRSA-713-RJS the pores are more connected or the presence of natural fractures is higher or even there is less cementation.

Due to these results, as announced by Petrobras in press releases, the well 1-BRSA-713-RJS will be submitted to an Extended Term Test to better investigate the reservoir.

As happened in other cases, in this type of reservoir the productivity can be sharply enhanced by drilling horizontal wells. Besides the usual advantage provided by this type of well, exposing more the well in the formation, it can cross natural vertical fractures, that may substantially increase the productivity.

Table 1 – *Parameters from well test interpretation*: k – *permeability, in* mD; DR – *damage ratio*; PI – *productivity index, in* (m^3/d)/(kgf/cm^2); p_i – *initial static pressure of the reservoir, in* kgf/cm^2.

Well	k	DR	PI	p_i	Remarks
1-BRSA-619-RJS	2.68	0.3	1.30	195.1	Fracture lenght of 26.9 meters
1-BRSA-713-RJS	340	0.7	54.8	316.6	Constant pressure barrier at 360 meters

• Other wells

Some other tests that presented intervals in the Quissamã Member that showed potential for producing were considered in this work. Some of these well data are still confidential, so they cannot be named here.

There can be observed a certain pattern in the results. The wells in deeper water depths usually exhibit greater permeabilities and, mainly, much bigger productivity indexes. The ones located in shallower water depths exhibits poorer reservoir quality. The greater productivity index can be ascribed, also, to better oil quality and thicker reservoirs.

For the deep water wells, the permeability calculated from well test data showed an estimated average value of 40 mD, and productivities indexes ranging between 10 and 20 (m^3/d)/(kgf/cm^2). Some of these wells (for example, the 6-BRSA-647D-RJS, 3-BRSA-363D-RJS and 6-BRSA-5147-RJS), located inside already existing fields, are already producing.

For the shallow water wells, the permeability calculated from well test data showed an estimated average value of 20mD, and productivities indexes around 1 (m^3/d)/(kgf/cm^2).

Conclusions

The analysis of well test data indicated that there is a great variability in rock properties of Macaé Formation along the basin. In the range of this analysis, the wells located in greater water depths exhibited better performances in terms of productivities, indicating greater permeabilities and/or thicker reservoir contributing to the well.

All the wells analyzed showed a negative skin, naturally or due to previous stimulation, mainly by a matrix acid treatment. It seems mandatory to acidize the wells in order to attain acceptable productivities indexes. The simple injection of acid can, in some cases, induce small fractures around the well. In other cases, it is necessary to proceed in fact an acid fracturing, and even after this treatment the well cannot naturally produce hydrocarbons, needing, for example, a gas-lift.

It can be also concluded that the reservoir performance is greatly influenced by natural fractures, as can be seen by the great increase in productivity caused by a horizontal well.

In terms of spatial distribution along the basin, the tests have been showing that the Macaé reservoir is strongly dependent on several factors such as depositional environment, paleoclimate and early diagenesis. These features directly influence on the sedimentary facies of the Quissamã as being a good or not a good player for hydrocarbons. Another contributing factor is fracturing, which acidizing has proved to be worth in all the tests. These are the main context in which the Quissamã play is being related in geological terms in Campos basin.

Acknowledgments

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