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**IDENTIFYING UNDRAINED LAYERS
FROM MATURE GAS RESERVOIRS
USING RESERVOIR SIMULATION
AND HIGH RESOLUTION GEOPHYSICAL INVESTIGATION**

Abstract: While big discoveries and major new developments deservedly grab the headlines, mature fields are the backbone of gas production. Revitalizing these fields extends their productive lives and offers significant opportunity to expand worldwide reserves.

Regardless of the definition, mature fields are a huge resource. With reserves categorized as proved or probable, attempts to expand reserve levels come at a relatively low risk. Revitalizing a mature field means taking measures that increase the value extracted from the field beyond original expectation. Using specialized software brings new opportunities in reservoir simulation of mature gas reservoirs. Combining these simulations with high resolution geophysical investigations, will offer a other perspective about mature gas reservoirs as well as the identification of potentially gas bearing layers which in the first place were not been identified through logging, and in addition to a eventual growth of gas resources but also gas reserves that could be exploited.

Identifying the thinnest gas saturated layers, determine the modification of gas resources and reserves values. The increase of volumes is a result of larger production surfaces, larger net thicknesses and also larger porosity attributed to this zones.

For mature gas reservoirs this kind of approach offers new perspectives.

Keywords: mature reservoir, decline curve, resources, reserves, 3D simulation, high resolution geophysical investigation, gas saturated layer, production surface, net thickness, porosity

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1. INTRODUCTION

Typically, in natural gas industry, the interest and major investments were focused on the early stage of the reservoir – the prosperity or the peak period. But times do change. In present, mature gas reservoirs, defined as reservoirs in a advanced stage of production decline or reaching the end of their productive life, must be considered as potential “fountains of youth”. In an industrial climate marked by increased demand, a higher importance must be given to intensification and production extension of a mature gas reservoirs, maximizing production decline and postponing their disappearance.

A wrong perception is sustained in many companies, namely that, mature reservoirs are synonyms with nearly exhausted reservoirs, and that these assume just a few challenges against new discoveries. Indeed, the majority of gas production in the world, comes from gas reservoir discovered from a long time ago, the pressing problems of these reservoirs are referring to economical growth of the decline rate and improvement of the final recovery rate. In principle, a number of possible options could be considered for maximizing the exploitation of mature gas reservoirs, although, both technical feasibility and the cost of every alternative must be evaluated carefully, before taking a decision. The expertise in different disciplines, as the knowledge possessed by the production and service companies must be well integrated, to design successful interventions, in the context of high risk associated to every intervention in gas reservoirs where the reserves are already depleted [1].

Redeveloping mature gas reservoirs must begin with the identification of the main production problems. The recognized problems can be addressed through remedial actions. Such remedial actions are usually used with the purpose of increasing gas well productivity. In principle, a number of possible interventions, like stimulation treatments, water and sand management, reduction of well-head pressure, could be taken into consideration for mature gas reservoir rejuvenation. However selecting the most adequate method requires correct and trustworthy information, about gas wells and reservoir historical [2].

In case of mature gas reservoirs, the reevaluation of gas resources and reserves, deduction of their performances in the past and their future predictions, as well as the definition and optimization of surface facilities, constitute a real support for future approaches. Today, modern investigation methods and also integrated soft packages, allows captures, analysis, correlations and high resolution interpretations. The maximization of mature gas reservoirs is a strict timely preoccupation, in conditions in which, mature gas reservoirs, in a advances stage of decline, represents 60% of the world’s natural gas production.

Mature gas reservoir rehabilitation, means in fact a complex of strategies and a series of sustained and concentrated actions, completed by an adequate management of exploitation process which purpose is to return and maintain a gas structure or some

productive layers at potential parameters. A successful reservoir management requires team and synergies effort. It is increasingly recognized the fact that reservoir management is not synonymous with reservoir engineering neither with reservoir geology. It's success requires integrated and multidisciplinary effort, and the players involved in this approach are those who are connected to the reservoir [1].

Routine technologies applied into developing new gas fields are ignored in case of mature reservoirs. While the growth of the value of goods through improving reservoir performances it is desired for centuries, production and recovery results were difficult and impossible to reach because decisive technologies, either were not available or were inadequate.

2. GEOLOGICAL RESOURCES AND RESERVES EVALUATION SIMULATION – CASE STUDIES

Gas reservoirs appear also in the form of lenses or with irregular forms, of relative low thicknesses and expansions, delimited by impermeable rocks or aquifers, being called in this case, lithologically, lentiliforme or irregularly delimited. Within a geological structure, a reservoir, in a geological sense, may include several isolated gas accumulations, with the same genesis, reported to the same gas supply and the same accumulation conditions.

For nearly half a century, reservoir simulation has been an integrated part of gas-reservoir management. Today, simulations are used to estimate production characteristics, calibrate reservoir parameters, visualise reservoir flow patterns, etc.

The main purpose is to provide an information database that can help the gas companies to position and manage wells and well trajectories in order to maximise the gas recovery [3].

Determination of hydrocarbon in place, reserves, and production potential requires an accurate physical description of the reservoir.

Reservoir engineering calculations require the formation of a mathematical model for the reservoir. This model should be based on the physical model that emerges from data obtained from the geological, geophysical, petrophysical, and log information. It is evident that in the majority of reservoirs the complexity is so great that it is not practical to expect a faithful mathematical description.

Furthermore, it is impossible to obtain a physical description of the reservoir that is 100 percent accurate. One knows the physical properties of the reservoir to a high degree of accuracy only at well locations. In between the wells, or in the part of the reservoir for which no subsurface data are available, the physical description can only be deduced. The more drilling, the better the definition of the reservoir.

Verifying the previous estimations through numerical simulation, by construction of some dynamical models for every hydrodynamical unit, offers the perspective of an ample approaching of evaluation of resources and gas reserves. Using this model is extremely indicated, because it considers all the available informations about the reservoir, as much as static behaviour and dynamical. The finality of numerical simulation consist actually from confirmation of initial resource for each exploitation objective, defining reserves and elaboration of a developing plan of the reservoir.

The most accurate resources and reserves evaluation was achieved by numerical simulation. This method incorporates all available information about the reservoir, considering both static and dynamic behavior with taking a minimum of assumptions.

Previous models were built in 2008 with the information available at that time.

The updated 2010 models incorporate the following:

- New 3D Seismic interpretation of a survey performed beginning of the year. Only limited 2D seismic data was available before.
- Applying new methodologies of existing open hole log reinterpretation.
- Added high resolution investigation logs recorded during workover operations.

That valuable set of data that become available justified to recalculate the reserves for all packages.

2.1. Methodology

Dynamic reservoir simulation models were built for each of the reservoir packages.

The objectives of these models are:

- Confirm the OGIP for each package.
- Define reserves.
- Design a field development plan consisting of workovers, well deepening and infill well drilling.

The models were built with uniform criteria as such many parameters are the same across all packages. Other features of the models are dependent on the properties of each package, their production history and prevalent uncertainties.

The dynamic models are based on static geological models generated in Petrel. No upscaling was applied. The structure was defined by the 3D seismic interpretation. The grid as modeled in Petrel was transferred as a corner point grid of 50 m × 50 m square cells, consisting of 172 cells in *I* dimension and 126 in *J* dimension, while *K* dimension varies for each package. The number of active cells in each case was reduced by shale intercalations and setting shale cells inactive.

The referred shale intercalations divide each layer of the respective package into hydraulically independent bodies. This fact enhances the description of the field and solves difficulties which were present in previous model realizations, especially the water gas contacts. The new models have multiple gas water contacts per package.

In the present models, once layers constituting each body were defined, their respective water gas contacts were estimated. This definition is based on gas-down-to for the wells producing from the respective body. Initially, the water gas contacts (WGC) were considered a few meters below the lowest proven gas (LPG). These depths had been adjusted to achieve a good quality history match, and finally lead to accurate OGIP values.

No aquifer was introduced in the model. This is based on regional trends observed in the field.

2.2. History matching

The first observation when attempting to match the production history was that the permeability was too low. This has been evident throughout the modeling process; a factor of at least 5 has to be applied to the lateral permeability calculated with the developed correlation outlined above. In the final model, factors of 5 to 40 are applied globally to horizontal permeability in x and y direction to all packages.

Vertical permeability is kept low because of the known shale intercalations which act as barriers to vertical flow and due to the low observed water production in the field. It is estimated to be lower or equal to 10% of the correlated horizontal permeability.

It is important to point out that the measured water rates are considered inaccurate because of the way they are measured and tracked over time. In the currently existing water production data inconsistencies are present and as such lower significance in the history matching is given to the water rates as compared to the gas rates.

The final bottom-hole pressures were approximated by tuning the productivity indices of the wells in the last stages of production. The productivity indices take into account several phenomena occurring in the borehole besides skin, like scale or salt deposition, water loading and sand deposits, which are changing over time.

2.3. Forecast and development scenarios

Once an acceptable history match is obtained, a base forecast is run. This base case is the “No Further Action” scenario (scenario I) considering no changes to the currently existing wells and predicting forward with the current conditions using the last historic production as the upper limit and being controlled by the last observed bottom-hole pressure. Next step is a forecast with the proposed infill wells, deepening and workover

operations. The locations were selected based on poorly drained areas and some potentially bypassed layers of gas. Several trials were made to define the best locations as well as workover options.

2.4. Numeric simulation by packages

The production and pressure match obtained for each package resulted in values of OGIP which are very close to the most likely volume calculated by material balance and by volumetrics as per new structure extension. The volumetrics restricted to the lease area are significant lower, therefore would be very difficult to have a history match (e.g. the reservoir pressure would be much lower than those recorded, either the reservoir properties would need to be artificially improved to yield more volume in smaller area).

Package VIII+IX+X

The development case was performed with drilling the proposed well L3 and to workover LM143 and LM137 (Tabs. 1 and 2, Fig. 1). The infill well has an average well bottom-hole pressure and productivity index multiplier as its neighbors assigned.

Table 1
Targets for development of VIII+IX+X package

Target	Type	Comment
L3	Infill combined	Combined with target XI_3, location coordinates not changed, XI_3 moved NW out of the forest area instead of VIII_1
LM137	Workover (dual)	Can be picked up by LM137 if completed dual with XIII+XIV, XI+XII is produced by LM119 (qg = 17 km ³ /day)
LM143	Picked up by LM143 deepening	Picked up by LM143 deepening once XI+XII (6 km ³ /day) is depleted.

Table 2
Initial rate for the proposed wells of VIII+IX+X package

Target	Initial rate [km ³ /day]
L3	55
WO LM137	23
WO LM143	40
Total	–

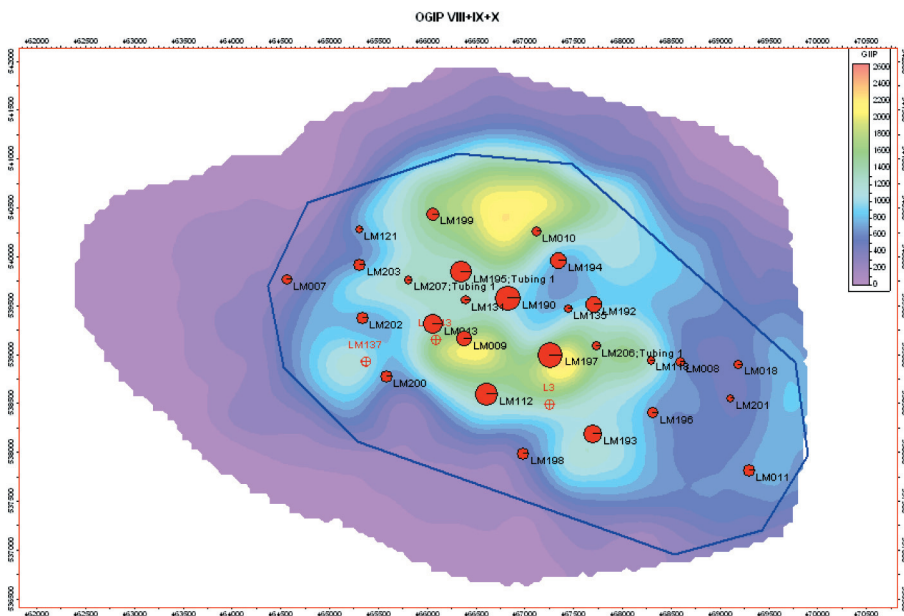


Fig. 1. Geological resource distribution map for VIII+IX+X package

The net increase in reserve incremental from production accounts to 9%.

Package XI+XII

Two main accumulations were discovered, one can be tapped-in by perforating LM117 which is uneconomic, the other can be developed by an infill well in the south east of the field, named L3 (Tabs. 3 and 4, Fig. 2). Two other infill wells were identified, which target proven undeveloped and probable reserves and are combined with targets in packages VIII+IX+X and XIII+XIV.

Next a forecast was run considering drilling of proposed infill wells L3, L6 and L14.

Table 3
Targets for development of XI+XII package

Target	Type	Comment
L6	Infill combined	Combined XI+XII with XIII+XIV
L3	Infill combined	Combined XI+XII with VIII+IX+X; this well to be moved out of the forest to VIII_1
L14	Infill combined	Combined XI+XII with XIII+XIV. Probable

Table 4

Initial rate for the proposed wells of XI+XII package

Target	Initial rate [km ³ /day]
L6	21
L3	19
L14	55
Total	—

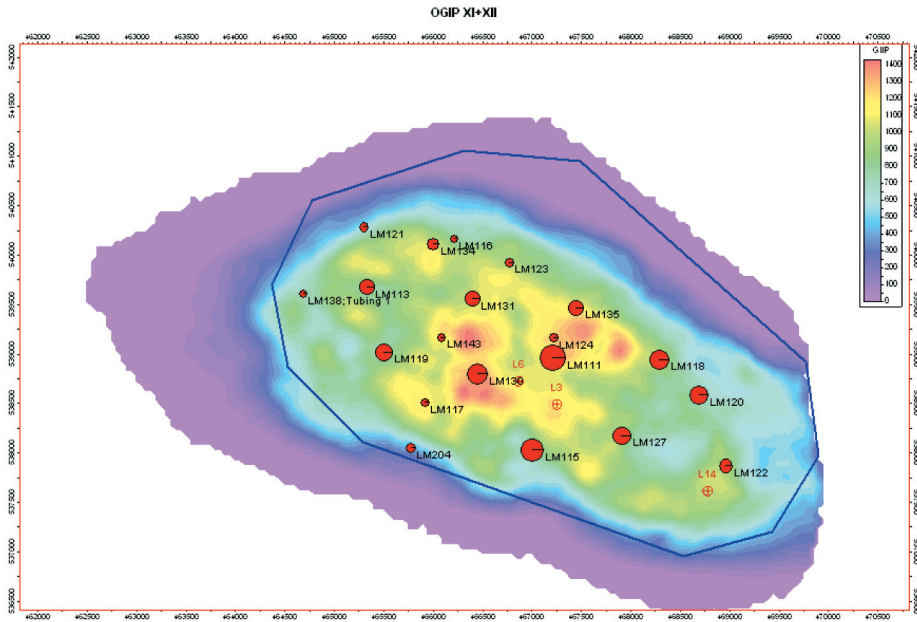


Fig. 2. Geological resource distribution map for XI+XII package

The net increase in reserve incremental from production accounts to 11%.

Package XIII+XIV

A screening process was performed with the objective to select the best candidates for deepening and infill drilling. Originally LM121 was proposed to be deepened, but resulted in no significant production incremental because it is in an area of poor reservoir properties. It was subsequently discarded (Tabs. 5 and 6, Fig. 3).

The net increase in reserve incremental from production accounts to 17%.

Table 5

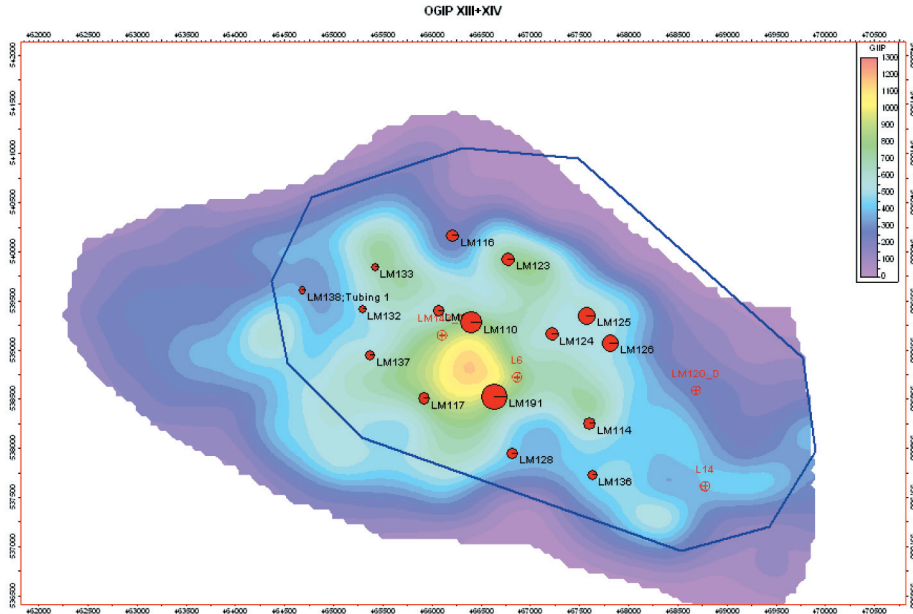
Targets for development of XIII+XIV package

Name	Type	Comment
L6	Infill combined	Identified by Nextwell and RE. Moved 100m to west to combine with XI_2
L14	Infill contingent	Contingent on LM120. Probable
LM120	Deepening	Probable
LM143	Deepening	–

Table 6

Initial rate for the proposed wells of XIII+XIV package

Well	Initial rate [km ³ /day]
L6	47
LM143	37
LM120	35
L14	48
Total	–

**Fig. 3.** Geological resource distribution map for XIII+XIV package

3. IDENTIFICATION OF GAS RESOURCES AND RESERVES THROUGH HIGH RESOLUTION INVESTIGATIONS – CASE STUDY

RST logging (Reservoir Saturation Tool) is one of the most modern investigation methods, based on the transmission of neutron pulses, a cutting-edge technology, raised to the state of the art. RST logging holds the capability to identify the thinnest gas potential layers, not yet unexploited, through determination of reservoir saturation.

The RST reservoir saturation tool incorporates a pulsed neutron generator and a dual-detector spectrometry system that measures elemental concentrations, including carbon and oxygen, and the formation neutron-capture cross section (σ) during a single trip in the well.

Loggings were recorded throughout the whole interval opened by the gas wells, while the wells were in production. This technology has the advantage that identifies the layers potential, without losing gas production and without the necessity of a installation, reducing in this way the time and the costs.

The RST tool is combinable with tools that use the telemetry system of the PS Platform production services platform. Measurements made with the RST tool in combination with the PS Platform suite of cased hole tools are the basis for efficiently identifying bypassed hydrocarbons, evaluating and monitoring reserves in mixed-salinity and gas environments, conducting formation evaluation behind casing, measuring three-phase holdup, and diagnosing well problems independently of well deviation [3].

An electronic generator in the RST tool emits high-energy neutrons in precisely controlled bursts. The RST tool in turn measures the gamma rays that result when the high-energy neutrons interact with the wellbore fluids, casing, cement, matrix, and fluid-filled porosity to cause inelastic scattering, thermal neutron capture, and activation. With its ability to log flowing wells because of shielding-enhanced detector sensitivity, the RST tool does not require pulling tubing or killing the well, and reinvasion is avoided.

Evaluation of gas saturation and reservoir production was conducted using instruments handled by cable, introduced into the tubing without the need to mobilize an installation which extracts the tubing from the gas well. This strategy leads to low costs and risks regarding the evaluation of gas potential layers, from the following considerations:

- tubing not necessary to be extracted to carry out the investigation, thus an installation is not needed,
- the gas well is not removed from production throughout the investigation,
- the operations are not interrupted while logging informations are evaluated,
- formation deterioration risk through penetration of the intervention fluid during the investigation phase is eliminated,
- significant reduction of safety and environmental risks.

The use of a sourceless generator of neutrons instead of a conventional chemical radioactive source both simplifies logistics and improves operational safety.

DSI logging combines the capacity of data acquisition through sonic unipole and dipole logging. The transmitter part contains a unipole piezoelectrical transmitter and two dipole electrodynamic transducers, perpendicular to each other. To initiate the propagation of the compression and shear wave in formation, to the unipole transducers are applied an electrical impulse at sonic frequencies. For collecting the Stoneley wave a specific low frequency impulse is used. The dipole transmitters are also brought to low frequency to initiate the bending wave around the wellbore.

As a component part of the service suite for analysis behind well casing, DSI device can also provide, a measurement of the low propagation velocity behind the casing, using recently developed acquisition strategies and automatic seismic waveform processing.

APS logging (Accelerator Porosity Sonde) is a component part of the service suite for analysis behind well casing and uses an electronic pulsed neutron generator instead of a chemical source, delivering both epithermal and thermal neutron measurements. The relative intensity of the measurements to the borehole environment and formation characteristics, such as lithology and fluid salinity, provides accurate data for evaluating porosity, detecting gas zones, and correcting for borehole irregularity [3].

The use of a PNG instead of a conventional radioactive chemical source means that the APS sonde is ideal for wells with difficult conditions and a greater likelihood of sticking. Logistics are simplified and the concerns of deploying chemical sources are eliminated.

Measurements can be performed by the APS sonde in both open or cased holes.

For a complete image on the entire gas structure, it is necessary also the access of exploitation parameters, evaluation of well productivity and elaboration of some sensitivity analysis in the points of interest or problems, from the trail well – surface facility, in this way being detected the zones which are the best suitable for rehabilitation.

The newly identified reserves, from undrains or less drained zones, will be verified and revaluated through a working program, which objectives are the optimization and maximization of gas production, respectively increasing the recovery factor. The elaborated strategies will be subjected to economic analysis, and if this finds that they could develop under rentability conditions, the respective approaches will become viable.

3.1. RST logging (Reservoir Saturation Tool)

In case of the investigated gas wells from the reservoir, it was for the first time internationally, when this technology has been applied extensively, through the inside of two columns, tubing and casing. Traditionally, this kind of logging is performed in a singular tubular gasket, namely the casing.

The investigated wells were selected based on a cross section of the reservoir, in order to obtain a distribution of the properties of the reservoir, for evaluation. The majority of the investigated wells were selected regarding their location in the reservoir,

with reference to total vertical depth, position in the structure, pressure, equipping. The results of the investigations have been successful in identifying new areas, bypassed or insufficiently developed from the point of view of the exploitation process.

Obtaining evaluation data for the formations with the help of tubing and casing loggings, results in a three days operation (without installation) instead of a two weeks operation (with installation) and a cost reduction by up to 70%.

Logging data have identified sands with gas potential, remaining undrained. From the interpretation of the gas clues from loggings, have been identified gas bearing zones, forecasting their productivity. An example of petrophysical evaluation is presented in Figure 4.

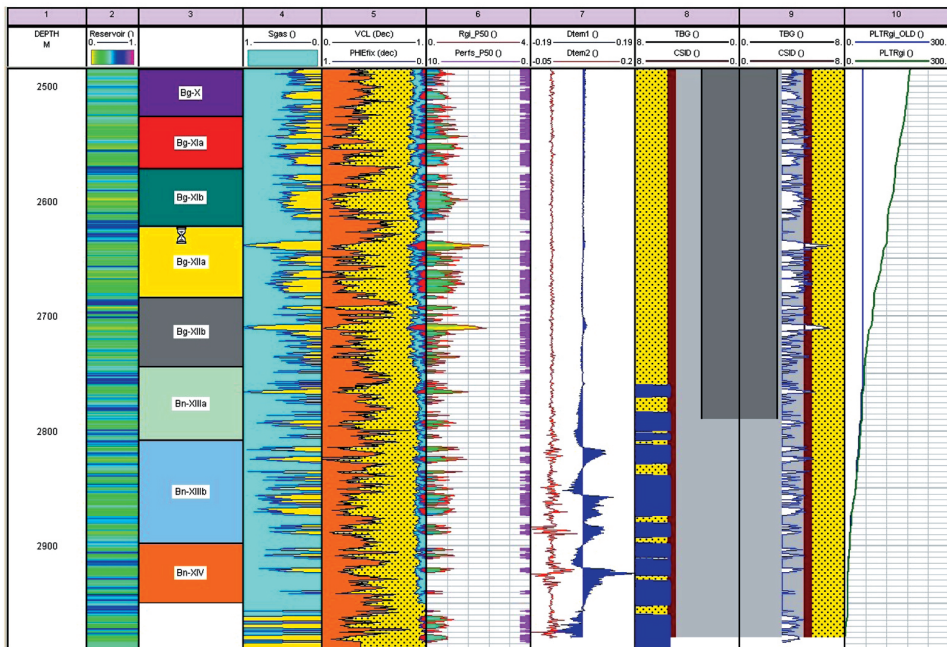


Fig. 4. Petrophysical evaluation of gas bearing sands evaluation, with RST logging

Figure 4 explanation:

Column 1: Well depth, measured in meters.

Column 2: Reservoir identification based on gamma logging, lighter colors highlights more clean sands.

Column 3: Formation layers.

Column 4: Gas qualitative saturation from RST logging evaluation.

Column 5: Lithology and fluid analysis from RST logging evaluation (clay, sand, total water volumes, total gas volumes).

Column 6: RST gas clues on the left side of the column, perforation potential intervals on the right side of the column

Column 7: Differential temperature curves, used for identification of production intervals.

Column 8: Tubing – Casing schematization, left side (blue color highlights the existent perforations).

Column 9: Tubing – Casing schematization, right side (white color underneath the blue curves highlights RST clues for gas potential sands).

Column 10: Synthetic flow profiles, blue curve represents the flow profile from the existent perforations, green curve represents the probable flow profile for all gas potential sands.

This kind of investigation, of high resolution managed to identify the thin gas saturated layers, unperforated, which were not included into the effective thickness zones. The productive potential of these thin layers was proved by the success of an addition campaign, which was triggered later.

3.2. DSI logging (Dipole Shear Sonic Imager)

The interpretations of this kind of investigation includes porosity estimation, pore pressure and fracturing pressure gradient calculation (Fig. 5).

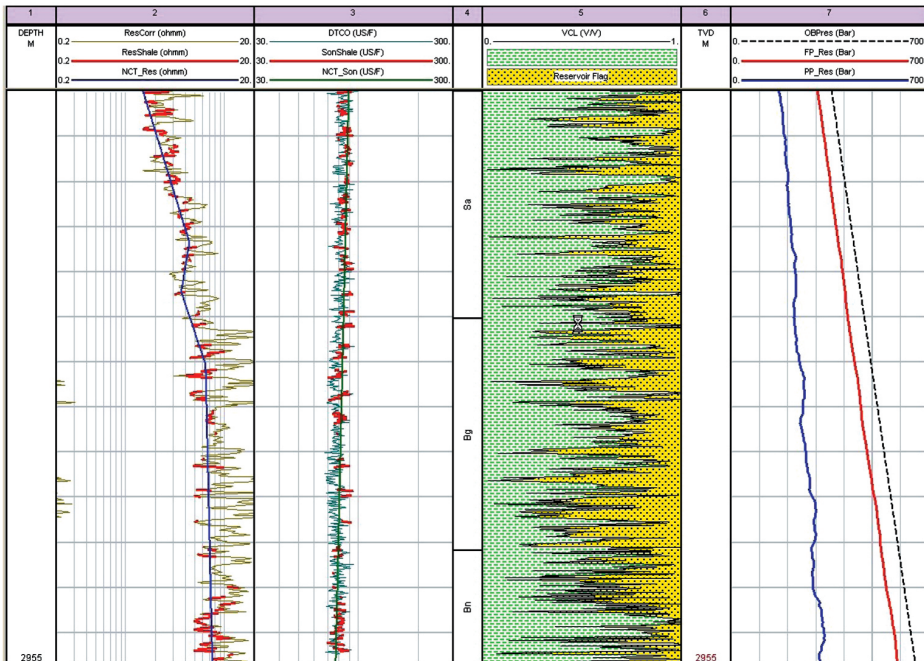


Fig. 5. Pore pressure and fracturing pressure gradient from DSI logging

Figure 5 explanation:

Column 1: Well depth, measured in meters.

Column 2: Clay rock compaction tendency from resistivity.

Column 3: Clay rock compaction tendency from sonic.

Column 4: Formation ages.

Column 5: Lithology: clay and sand.

Column 6: True vertical depth, measured in meters.

Column 7: Lithostatic pressure gradient (black dotted curve), fracturing pressure gradient (red curve), pore pressure gradient (blue curve).

3.3. APS logging (Accelerator Porosity Sonde)

Five detectors provides information for porosity evaluation, gas detection, clay rock evaluation, vertical resolution enhancement and wellbore correction. This kind of investigation shows a higher vertical resolution, than conventional neutron loggings (Fig. 6).

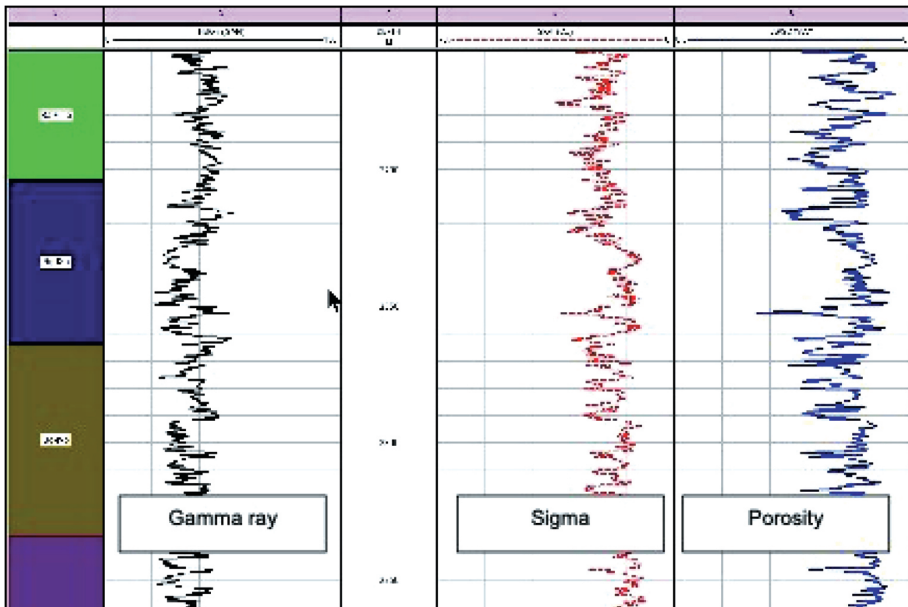


Fig. 6. Accelerator Neutron Porosity Sonde (APS) logging

Figure 6 explanation:

Column 1: Formation layers.

Column 2: Gamma rays.

Column 3: Well depth, measured in meters.

Column 4: Sigma, catch section of the formation.

Column 5: Epithermal neutron porosity.

Due to the laminar nature of the sand-rock clay sequence, high resolution loggings are needed, for a good definition of reservoir properties from thin layers. The investigation types mentioned before, are loggings of this kind, used for petrophysical properties analysis of thin sands.

Reservoir saturation loggings, purchased through tubing and casing investigations, in gas wells belonging to the reservoir, were used for identification of gas potential sands. This information represented a significant contribution to the selection process of gas wells candidate for re-equipping. Through the respective interventions supplementary sands were opened, from other layers. Production loggings (PLT) performed after the interventions in the respective gas wells, identify the perforated sands, as those who, following the investigations, presented a high potential.

In Figure 7 an example referring to this aspect will be presented.

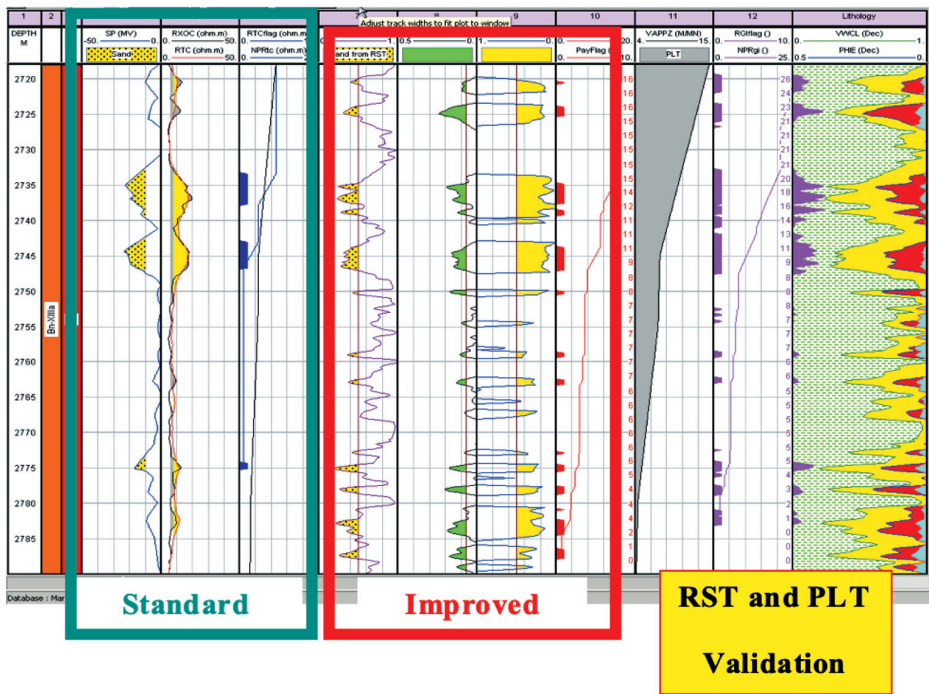


Fig. 7. Comparison between standard and high resolution loggings

It is noticeable that in the improved version with the information from the special investigations, there are a few layers with high potential, which in the standard version are not indicated as gas bearing layers. In the petrophysical evaluation of standard logging, the clay volume was based on the invaded zone resistivity (RXOC) and spontaneous potential (SP). Gas volumes from these so-called non-gas areas, seem to be coming

from thin layers, which are too small to be detected with standard electrical logging. The record provided by the RST device, with a much better resolution, permitted the detection of some new layers, which were not included into the effective thickness of the objective.

The RST informations have been validated in practice, in the sense that perforating those thin layers have confirmed the indications of the investigations. The ulterior effectuation of a production logging (PLT) came to strengthen the obtained results.

For example, in Figure 8 it is observed that after perforating the gas saturated layers, detected through RST investigation, the gas well flow-rate grew from 19.000 m³/day up to 89.000 m³/day, so the new gas identified areas, represents a gas reserve increase.

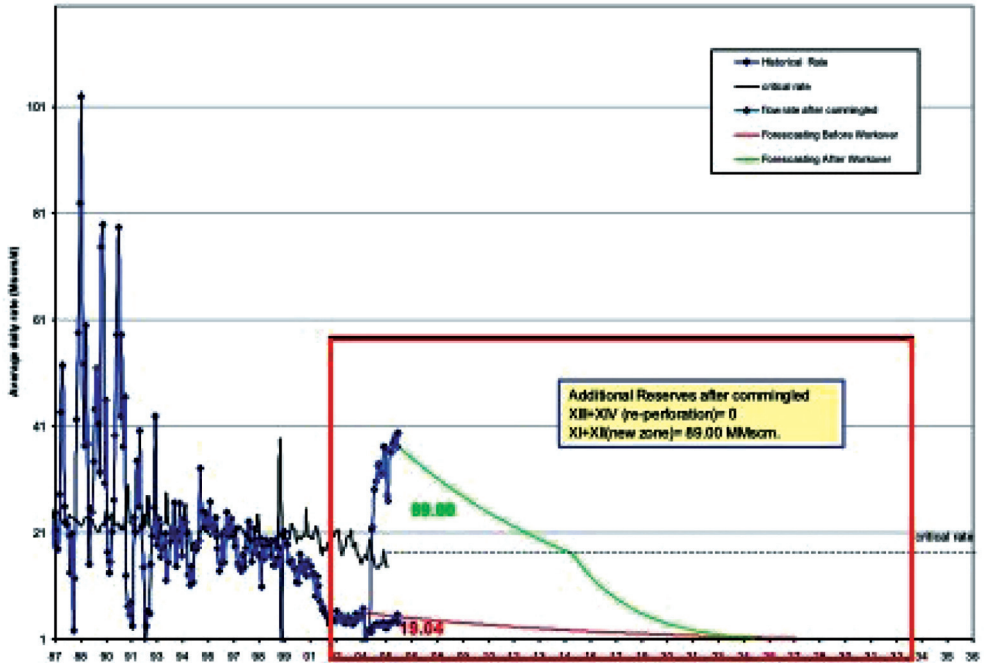


Fig. 8. Results for well #2

Identifying the thinnest gas saturated layers, causes the changing of gas resources and reserves values. The estimated volume increase results from larger surfaces, larger effective thicknesses and larger porosities attributed to the respective zones.

4. CONCLUSIONS

Even though the art of reservoir simulation has evolved through more than four decades, there is still a substantial research activity that aims toward faster, more robust, and more accurate reservoir simulators.

The informations regarding the reservoir type, fluid distribution and reservoir rock characteristics, allows the geological modeling and subsequent evaluation of the gas resources.

Maximizing the reservoir view using advanced seismic interpretations, based on complex technologies for viewing new volumes of resources, permits a reevaluation, sometimes spectacular of the geological model.

The new investigation technologies for wells, capable to highlight the thinnest natural layers saturated with gas, offers a new chance for mature reservoirs, representing the foundation for a reevaluation of gas resources and reserves.

The newly identified reserves, from undrains or less drained zones, will be verified and reevaluated through a working program, which objectives are the optimization and maximization of gas production, respectively increasing the recovery factor.

For mature gas reservoirs, this kind of approach offers new perspectives.

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