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Well Design for Drilling Through Thick Evaporite Layers in Santos Basin - Brazil

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Abstract

The presence of evaporite sections in prospects for oil or gas exploration is, in itself, a factor that increases the probabilities of success in the area due to favorable conditions for the hydrocarbons generation and trapping. However, many operational problems such as stuck pipe and casing collapse have been reported by the industry when drilling through those salt layers.

Historically, in the Campos Basin - Brazil, several deep wells have been drilled through thick salt intervals. Up to the 90's, the lack of reliable ways to predict salt behavior at high temperatures and high differential stresses led to very high drilling costs and even loss of wells.[1]

This paper presents a methodology for drilling fluid and casing design and drilling strategy for drilling at great depths through thick salt layers. The numerical simulation to evaluate the creep behavior of salt rocks (halite, carnallite and tachyhydrite) submitted to high differential stress and high temperature was done through the application of an in-house finite element code developed.

Results obtained by the numerical simulations in prospect with 2000 meters thickness of different evaporite rocks with high creep rate was used to predict the evolution of the well closure with time for various drilling fluid and analyze several technically feasible alternatives to drilling strategy. The casing design was accomplished with several failure scenarios of cement the casing/borehole annulus through the salt, and drilling fluid in annulus to determine the nonuniform loading and timing of salt loading on well casings deformation or ovalization. The casing was design to be capable of supporting high creep rate of carnallite and tachyhydrite.

Introduction

The Santos Basin, offshore southeast Brazil, is one of the Brazilian basins that are receiving considerably industry attention nowadays. Active drilling in the this area in recent years has not yet yielded discoveries comparable in size to fields in Campos Basin, the most prolific oil provinces in Brazil (Fig. 1). However, due to its size and for being relative under explored, it continue to attract interest.[2]

The object of this study is planning an exploratory deepwater well (WD = 2140 m) to a depth of 6000 meters TVD in Santos Basin. This prospect is expected to drill through almost 2000 m of salt rock - halite, carnallite and tachyhydrite (Fig. 2). This is the first of a toal of four wells to be drilled up to the end of 2006.

The presence of evaporite sections in prospects for oil or gas exploration is, in itself, a factor that increases the probabilities of success in the area due to favorable conditions for the hydrocarbons generation and trapping. However, many operational problems such as stuck pipe and casing collapse have been reported by the industry when drilling through those salt layers. Before planning to drill long salt sections, a through knowledge of salt and its properties is necessary.

Salt rocks belong to the group of sedimentary rocks, called evaporite, deposited by evaporation of saline water. Salt is an unusual geologic material for under sustained constant stress, significant deformation can be expected as a function of time, loading conditions and physical properties.[3] This behavior is called creep.

The rate salt will creep is dependent on some parameters: temperature, differential stress and salt type are of the paramount importance.

Thermal Gradient in Santos Basin

As stated before, one of the most important parameters for the creep rate is the temperature. To evaluate the temperature gradient in this exploratory prospect we used two methods. The first is through the extrapolation of the temperature of the offset wells. For that, we collect the 49 values of temperature of the 20 wells. [4] For the deepest section (1500/4500 meters of sediment thickness) the gradient was evaluated in 32 ºC/Km, with BHT reaching almost 160 ºC. The second, a thermal flow study was made to evaluate the same thing, that is, the temperature at the top and at the base of the salt section. That occurs for the salt presents a larger thermal conductivity than the near rock, influencing the thermal gradient of the adjacent formations.

The results showed on Fig. 3 presents some differences in the values of temperature. For the purpose of this study, we considered the most pessimistic situation, that is, the highest creep rate, assuming the temperature on the salt section obtained with the first method: top 31 ºC and base 101 ºC.

Constitutive Equation for Salt Behavior

Salt rocks exhibit time-dependent deformation when subjected to any level of shear stress due to its crystalline structure. This creep behavior, slow deformation under constant stress, is influenced sensibly by the thickness of the layer of salt, formation temperature, mineralogical composition, water content, presence of impurities, and the extent to which differential stresses are applied to the salt body. Chloride and sulphate salts containing water (bischofite, carnallite, kieserite, sylvite and tachyhydrite) are the most mobile. Halite is relatively slow-moving, and anhydrite and the carbonates (calcite, dolomite) are essentially immobile.[5]

The Brazilian Continental margin basins present, in general, high geothermal gradients, thick sediment column on top of salt layers, neo-tectonics inducing salt movement (wellbore breakouts measured) and evidences that salt diapirs are still moving, comproved by mapping of salt crestal faults in Campos and Santos basin. Information from wells drilled through deep salt sections shown that salt closure can reach high velocities (0.05 in/h).[6]

Starting from the beginning of the 90´s, creep constitutive laws based on deformation mechanisms, have been recommended by the international technical literature, to represent the intrinsic behavior of the material.[7-9]

The law that incorporates all the portions regarding the deformation mechanisms already isolated to the moment it was developed by Munson.[7,8] The constitutive equation due to Munson's creep law considers the following mechanisms: Dislocation Glide, Dislocation Climb and Undefined Mechanism. The largest contribution of one or other mechanism depends on the temperature conditions and differential stress that the salt is submitted.

The constitutive equation corresponding to the creep law of double mechanism of deformation is a simplification of the equation developed by Munson, and it considers the creep mechanisms Dislocation Glide and Undefined Mechanism. The latter effect was recently identified as being creep in the contacts of the halite grains, provoked by the dissolution of the salt in function of the increase of its solubility, under the high pressures that happen in the contacts among grains.

In this paper, salt rocks are analyzed according to the elasto/viscous-elastic behavior, adopting the Double Mechanism creep law, as shown in equation 1:

$$\varepsilon = \varepsilon_0 \left(\frac{\sigma_{ef}}{\sigma_0} \right)^n .exp^{\left(\frac{Q}{RT_0} - \frac{Q}{RT} \right)} \tag{1}$$

Salt Samples and Experimental tests

Until the last year just halite and anhydrite were present in the sub-salt prospects.[10,11] Nowadays the news challenges are drilling through very thick salt layers with differents salts, Fig.4, like carnallite ($KCl{\cdot}MgCl_2{\cdot}6H_2O$) and tachyhydrite ($CaCl_2{\cdot}2MgCl_2{\cdot}12H_2O$), that exhibit a high creep rate than halite (NaCl).

This motivated a new salt sampling, which was performed in wells located in the Northeast of Brazil (Sergipe State). [12,13] Special precedures were adopted to sampling, storage and tests the sample due to the high hygroscope of the salts. The creep tests were performed in specimens with a length/diameter ratio of 2 (ISRM Standards) in a Laboratory of Rock Mechanics and Rock Hydraulics from IPT - Institute for Technological Research of the State of São Paulo – Brazil. [14,15]

Experimental results

Three important stages of behavior that must be handled appropriately when material model parameters are evaluated in the laboratory characterize salt creep.

Two or three creep stages comprise a typical creep curve for salt. Following the application of the stress difference, the strain rate is very high. This rate then decreases monotonically with time until a constant rate of strain is observed. These two stages are called transient and steady state creep stages, respectively. A third stage called tertiary creep stage becomes evident. This is characterized by acceleration of the creep rates that cause dilation, an increase in volume through micro fracturing, leading to failure.

Fig. 5 shows a typical behavior of salt creep. In these tests, tachyhydrite, carnallite and halite are submitted to a 10MPa differential stress and 86 ºC temperature. Before 160h test, the specific axial strains are respectively 0.15, 0.055, 0.0014. With these test parameters, tachyhydrite is around 107 times most mobile then halite and around 2.7 times most mobile then carnallite.

Fig. 6 shows the strain rate results in steady state creep stage for different differential stress ranges (4-20 MPa) from tachyhydrite, carnallite and halite creep in 86 ºC temperature. The tachyhydrite´s behavior changes the stress expoent (n) from 2.4 to 7.12 after 7MPa differential stress and halite changes from 3.36 to 7.55 after 9.9MPa. Until now, no pottential behavior like was observed to carnallite, probability due to the tests didn´t finish at this temperature.

Finite element model of well closure

With the creep parameters validation, [14,15] it was applied the constitutive equation in the numerical simulation of the creep salt behavior to predict the evolution of well closure with time for various mud weights and analyze several technically feasible alternatives to drilling strategy through the salts intervals.

The prospect expected 1976m of salt rocks, to be drilled at the interval of 2984 to 4960m, (WD = 2140 m), Fig. 2.

For pre and post processing of the finite element model it is used the system SIGMA.[16] The numerical simulations have been done through the application of the finite element method being used the code ANVEC,[17] both PETROBRAS property. The program ANVEC, have an extensive application in the simulation of the behavior of underground excavations, [17-21] considers the non-linear physical elasto/visco-plastic phenomenon, with constitutive law of double mechanism of deformation for creep. The program demonstrated excellent stability and convergence to predict the creep phenomenon in conditions of high temperature levels and differential stresses and the procedure of simulating the behavior of the well with time as a function of the bit progress, through the technique of automatic mesh rezoning. This constituted in a differential advantage of the program providing valuable subsidies for the drilling operation. [10,11,14,15]

The axisymmetric model, according to the longitudinal axis of the well, comprises 1976m of salts interval and 200m of thick hard rock, below and above the salt layer to represent the boundary condition. We employed 78408 quadratic isoparametric elements (with 8 nodes) and 240043 nodal points in the finite element model, Fig. 7. To consider the temperature variation with depth, and the litology, different layers were built. As it was used the constants isolated in creep tests at the temperature of 86 ºC, it was necessary to correct the creep constants by the thermal activation factor ($\exp^{(Q/RT_0 - Q/RT)}$).

The hard rocks with fragile behavior, above and below the salt, are analyzed according to a model elasto/plastic; being adopted the plastic flow criteria of Mohr-Coulomb for the multiaxial state of stress. During the plastic flow is considered the isotropic behavior, with associative law of plasticity. [17] For the lithostatic column the average specific weight of 22.56kN/m^3. The table 1 summarizes the elastic properties. [22]

Numerical prediction of well closure: drilling fluid design

The behavior of the well is simulated in the time domain, considering the viscous-plasticity of the salts using a computer P690 REGATTA IBM with logical partitions, 32 processors power 4 and 80 GByte RAM memory.

Numerical simulations were performed to predict the evolution of the well closure rate during drilling the salt zone, along its longitudinal axis, during the progress of the drilling column. Several drilling fluids weights were tested, but will be present just some importants results for drilling fluids weight.

To simulate the structural behavior of the well we adopted two strategies. On the first, it was considered that salt layers were drilled in 284 excavation steps, simulating the bit progress in 7m/h, in just on single stage. On the second it was considered that the salt layers was drilled in two stages.

Fig 8 shows the evolution of the wellbore closure with time being considered a single excavation stage (hole 14 ¾" x 17 ½"), when it was adopted an 11.0 ppg mud weight. Due to irregularities during the drilling, instead 2.5" drift, is considered an acceptable closure of 1.75in. The curves of wellbore closure with the time of each depth begin when the excavation, in the case the bit, reaches the respective depth. For example, notice that the curve of wellbore closure in the depth of -4292m begins around the instant t = 190h, instant in which the bit reaches the respective depth. The wellbore closure in that depth reaches the acceptable value around the instant t = 300h, about 110h after the bit has reached the respective depth and 36h after the excavation reaches the salt base. It is important observe that the largest closure of the well (of the 25 depths numerical monitored) occurs for the depth of -4292m, section located 668m above the base of the salt layer. As is expected, the tachyhydrite layers (-4292, -4208, -4083, -3819, -3632, -3529, -3446, -3363 and -3033m) have a very high closure rate, and the halite layers, a low closure rate. Is concluded that elapsed 300h after the beginning of drilling, at this drilling fluid weight 11.0 ppg could not be able to keep the wellbore open time enough for concluding the drilling operation without the risk of stuck pipe. At the same time, the wellbore would not be open enough time for the set the casing.

Based on that result, the mud weight was increase to 12.0, 13.0 and 14.0 ppg and redoes the simulation of the behavior of the well. Fig. 9a shows the summary results of the wellbore closure with the mud weights 11-12-13 and 14.0 ppg in the deepest tachyhydrite layer, -4292m. The Fig. 9b shows the results of the simulation of the salt layers in the numerical model with 14.0ppg. With the mud weight 14ppg, there are enough time for concluding the drilling operation and set the casing without the risk. To best visualize the results of the time to finish the well, included thickening time of cementation with various mud weights, are shows in the Fig. 10.

In the Fig. 11 is shows the evolution of the wellbore closure with time in function of the bit progress with 14.0 ppg mud weight, but the mud weight is reduce to 10.0 ppg when the excavation reaches the salt base (284h), to simulate the ruble zone.[23] The effects of the mud weight reduction in the wellbore closure are extremely dangerous to the drill string, in few hours the acceptable closure is reached. Based on this result, the drillings strategy changed.

The new strategy is drilling the well in two stages. The first (Plan A) is based on evaluation of salt creep rate with 14.0 ppg (Fig. 9 and 10) and no additional problem. The basic case well planning is to drill up to 200m above the base of the salt, to avoid the lost circulation in the rouble zone, set the casing and drilling the salt layers remain with 10.0 ppg. The second (Plan B), is based in run an intermediate casing in the middle of the salt section to cover to soluble salt layers. The Fig. 12 ilustrates the results of the Plan B, where a 14.0 ppg mud weight was simulate in the first stage drilling, and the Fig. 13 ilustrates the results in the second stage, where a 10.0 ppg mud weight was simulate. Elapsed 720h after the beginning of drilling, in each stage, the maximum wellbore closure is 1.25" and 1.50", respectively for the first and second stage.

The adoption of drilling strategy of two stages throught the thick salt layer with a mud weight of 14.0 ppg in the most part of the salt layer, specialy in tachyhydrite, and after set the casing of this stage, beginning the second stage drilling with a mud weight of 10.0 ppg in the layers less mobile (halite), provide a enough time for drilling the salt layer, running and setting the casing, avoidind the drill string to get stuck and lost of circulation. These numerical results will used during the drilling in order to guide the operations, so that well closure above the bit does not cause the drill string to get stuck.

Finite element model of the casing design

The casing design was accomplish with several cementation failure scenarios, from 5%–20% uncemented, in the annulus casing/borehole through the salt layer. The aim was determine the nonuniform loading and timing of salt loading on well casings deformation.[24]

For pre and post processing and the numerical simulations of the finite element model the softwares are the same used in the well closure simulation.

The plane strain model, perpendicular to the longitudinal axis of the well was built with 14506 quadratic isoparametric elements (with 8 nodes) and 43639 nodal points in the finite element model, Fig. 14. The depth analyzed was the deepest tachyhydrite layer (-4301m).

The model diameter was build with 100m, sufficient to avoid the bondary effects (borehole 17 ½"), with boundary anchored ends. The modeling consist in two steps, firstly, is applied the meshrezone (excavation) in a circular borehole with symmetrical closure. After a especific time the casing and ciment was introduce, with the rebuild process developed in ANVEC code.

Numerical simulation of casing design

Numerical simulations were performed to predict the salt loading on well casing induced by the salt creep. The casing was design to be capable of supporting high creep rate of tachyhydrite.

Fig. 15 shows the results in the numerical model with a 100% cemented annulus, after 500h in a concentric wellbore. The stress in the high colapse casing (14"x 0.722" – P110 - 9500psi - 1.5% maximum ovalization) is just 0.23 of SMYS, due to the uniform loading.

In deep-set casing through the salt layers, it is probable that the salt/casing annulus will have to remain uncemented. Simulations were done to evaluate 5%, 10%, 15% and 20% of cement channeling after 500h, Figs 16a-d respectively. From 15% cement channeling, the casing colapse is induced by the nonuniform loading.

To avoid the loading points in the casing caused by the ciment channeling, in this case, at least 90% cimentation is necessary. To guaratee this index, a short job cementation is recommended, and this way is possible a deep-set casing. However, the tachyhydrite layers will impige firstly the casing, and an initial nonuniform loading condition could develop by the differential stress along the casing (squeezing). To mimimize this, is simulated a dense mud (16,6 ppg) placed between the top of the cement shoe and the casing head, rebuild the drilling fluid instead the ciment in the simulation. This fluid redistributes the loads uniformely. The pressure increse in the shoe, created by the closure of the hole, is 818 psi in 490h and the radial casing deformation is 7E-3m and the stress in the casing is 0.57 of SMYS, Figs 17. The same analysis was accomplish, but the casing is considering non-concentric, Fig 18. The stress in the casing reaches 0.61 of SMYS, just 4% high then the concentric case.

Basic Well Planning – Plan "A"

Based on evaluation of salt movement and no additional problems, the basic case well planning (Fig. 19) is to drill a 36" hole, 70 meters bellow mudline, with sea water and set de 30" conductor; drill a 26" hole up to 60 meters inside the salt with sea water and change to salt saturated water base mud after reaching the salt, and set the 20" surface casing. After changing to synthetic base mud with 14 ppg, density necessary to control the salt creep according to the creep simulations, then drill the hole 14 3/4" x 17 1/2" with rhino reamer up to 200 meters above the base of the salt, to set the 14", intermediate casing.

Based in our experience in drilling salt in other wells in Campos Basin, it was decided to employ reamers instead of bi-center bits. Reamers are known to produce a more concentric borehole and allow backreaming, even though the bit has a potential of becoming stuck in the pilot hole, between the bit and the under reamer, since there is no hole enlargement in this interval.

Then reduce the mud weight to 10 ppg to drill the 12 ¼" x 14 ¾" hole through the remaining salt and the robble zone, that is expected just bellow the salt, up to the top of the first target. Then run the 10 ¾" 2nd intermediate casing.

The last interval of the well, through out the objectives, is planned to be drilled with 9" bit, up to TVD to run the 7 5/8" production liner if necessary. This is an optimistic well design, assuming that everything is going right.

Uncertainties Associated with Plan "A"

There are some uncertainties associated with the project before. The first is related to the LOT at the 20" casing, set 50 meters inside the salt. We know that the LOT in salt should be greater than in any other sedimentary rock at the same depth. However, we do not know if it will reach the minimum necessary value of 14.5 ppg, that is: MW 14.0 ppg plus 0.5 ppg (ECD + safety factor), in less than 1000 meters bellow mudline. There is no LOT date available in salt in nearby wells.

Assuming valid the Eaton's method to evaluate the Fracture Gradient (Fig. 20); the result is 11.7 ppg, which is not enough for what was planned, but we know that the method is not defined for this situation. Based on published data [3,4,5] and scout information from de Gulf of Mexico, we evaluated that the LOT at the 20" shoe should be greater than the overburden gradient between 10% and 20%, that is closer to the necessary value of 14.5 ppg. Since the mud operational window for this situation is so critical, we are analyzing the possibility to employ the Varcos' Continuous Circulation System (CCS), so as to keep the ECD continusly over the wall os the borehole, even during the conections.

The second possible source of problems is related to the amount and thickness of layers of carnallite and tachyhydrite (with high creep rate) expected for this salt section by the geophysicist through the analysis of the seismic line. If during drilling we find more layers than employed in the creep rate simulation, maybe we could not keep the hole long enough to fully penetrate the salt section and run the intermediate casing.

If any of the two situations happen, it will be necessary to run an intermediate casing in the middle of the salt section to cover to soluble salt layers. Since the chance that this happen is high, we included a contingency in Plan "A", as explained in the next section.

Well Planning with Contingencies – Plan "B"

The Plan "B" for this well (Fig. 19), considering the situation before, is to drill a 36" hole, 60 meters bellow mudline, and set de 30" conductor; drill a 26" hole up to 60 meters inside the salt with salt saturated water base mud and set the 20" surface casing. After changing to synthetic base mud with 14 ppg, as before, drill the hole 14 ¾" x 17 ½" with rhino reamer up to half way of the salt column, where is expect to reach the base of the soluble salt (carnallite and tachyhydrite), to set the 14" intermediate casing.

The next interval of rock salt is planned to be drilled with 12 ¼" x 14 ¾" with rhino reamer up to 30 meters above the base of the salt, with the same mud weight 14 ppg, to avoid the rubble zone that is expected bellow the base of the salt. To detect the base of the salt during drilling we are planning to use the Seismic While Drilling. The 10 ¾", 2nd intermediate, should be set 40 meters above the top of the salt.

After setting and cementing the 10 ¾", the mud weight will be reduced to 10 ppg to avoid lost circulation in the rubble zone. Then drill with 9" bit, up to the top of the first target and set the 7 5/8" liner.

The objectives will be drilled with 6 ½" bit up to TVD, at 6014 meters.

Uncertainties Associated with Plan "B"

Other critical point for this well design is that in the event we have to use Plan "B", that is, the creep rate is too high for drilling and casing the whole salt section, it will be necessary to run the 14" intermediate casing. According to the simulation results to determine the magnitude and timing of salt loading on well casing, this casing does not have enough collapse resistance to keep the hole opened, that is, the strongest 14" casing available will suffer collapse in front of the salt during the drilling of the next phase (12 ¼" x 14 3/4") after sometime of exposure.

It is not advisable to cement the whole annular, since it is possible to create some cement channeling. This would be worse for generating punctual or nonuniform loads on the casing provided by salt movement, resulting in casing collapse.

To avoid this situation we are planning to displace a very dense mud (16,6 ppg) in front of the cement slurry. That mud will be placed between the top of the cement and the casing head. This fluid is expected to redistribute the loads created by the closure of the hole.

It is important to point out that the 14" casing is a temporary solution to sustain the salt creep that is, just to work during the drilling o f the next phase. The definitive solution will be reached after setting the 10 ¾" - 133 #/ft - high collapse - that is designed to support the salt movement.

Nomenclature

E =Young's Modulus (MPa)
ECD = Equivalente Circulation Density
h = hour
in = inch
ISRM = International Society for Rock Mechanics
K = thermal conductivity (BTU/(°F.ft.h))
LOT = Leak Off Test
n = Stress expoent of salt rocks
Q = activation energy = 12 kcal/mol
R = Universal gas constant = 1.9858 E-03 kcal/mol.K
SMYS = Minimum yield stress = 758MPa
T = Temperature of rock (K)
T_0 = Reference temperature (K)
ε = Strain rate due to creep at the steady state condition
ε_0 = Reference strain rate due to creep (in steady state)
ρ = density (lbm/gal)
ν = Poisson's Ratio
σ_{ef} =Creep effective stress
σ_0 = Reference effective stress

Conclusions and Recommendations

- In this work we presented a methodology developed by Petrobras R&D for mud weight and casing design and also to define the strategy to drilling sub salt prospects.
- Computer modeling to evaluate the creep behavior of salt rocks submitted to high differential stress and high temperature and casing loads due to salt creep was applied.
- The numerical simulations have been done through the application of an in-house developed computer code based on the finite element method.
- The mud weight through the salt layers is: 14.0 ppg and 10.0 ppg, respectively in two drilling stages.
- Maximum failure of cementation in the annular space between well and 14"casing is 10 %.
- Minimum drilling fluid between casing and well placed between the top of the cement shoe and the casing head is 16.6ppg.
- Perform the LOT up to fracture. Up to know the LOT in salt has been with limited pressure to support at maximum the (MW+ECD) planned for the salt section. For going through thick salt layers, through knowledge of the fracture gradient in salt is necessary.
- The Continuous Circulations System (CSS) was proposed to be employed in this prospect, at least on the first well, while we calibrate some of the parameters, such as temperature, and get a more reliable creep rate, since with this equipment could be incorporated to the mud weight and, therefore, the LOT at the 20" casing shoe would became less critic.
- Employ the Seismic While Drilling to determine the base of the salt, to set the casing just above the expected rubble zone, and therefore, to avoid lost of circulation.
- The lessons learned on this exploratory well will allow us to optimize the well design for the next three wells proposed for this area.

References

1. Oliveira, J. E.; Idagawa, L. S.; Nogueira, E. C.: *"Evaporite in Campos Basin: Geological Aspects and Drilling Problems",*

Report CENPES-475 (1985), PETROBRAS, Rio de Janeiro, Brazil (in Portuguese).

2. Modica, C. F. and Brus, R. H.: *Postrift Sequence Stratigraphy, Paleogeography, and Fill History of the Deepwater Santos Basin, Offshore Southeast Brazil*, AAPG Bulletin, v. 88, No 7 (July 2004), pp. 923-945
3. Barker, J.W. and Meeks W. R.: *Estimating Fracture Gradients in Gulf of Mexico Deepwater, Shallow, Massive Salt Sections*, paper SPE 84552, presented at the 2003 SPE Annual Technical Conference and Exhibition, held in Denver, Colorado, October 5-8
4. Falcao, J.L.: *Drilling in High-Temperature Areas in Brazil: A Wellbore Stability Approach*, paper SPE 69516, presented at the 2001 SPE Latin American and Caribbean Petroleum Engineering Conference held in Buenos Aires, Argentina, 25–28 March
5. Barker, J.W. Feland, K.W. and Tsao, Y. H.: *Drilling Long Salt Sections Along the U.S. Gulf Coast*, paper SPE 24605, presented at the 1992 SPE Annual Technical Conference and Exhibition, held in Washington, DC, October 4-7
6. Amaral, C. S.; Costa, A.M.;Gonçalves, C. J. de Castro;Fonseca, C. F.: *"Reavaliação do Comportamento do Poço 1-RJS-480 por ocasião do Fechamento do Revestimento de $9^5/_8$"* no Trecho de Travessia da Zona de Sal", Report CENPES/DIPREX/SEDEM-013 (1999), PETROBRAS, Rio de Janeiro, Brazil.
7. Munson, D.E., Fossum, A.F., Senseny, P.E. (1990) Approach to First Principles Model Prediction of Measured WIPP (Waste Isolation Pilot Plant) In-Situ Room Closure in Salt. *Tunneling and Underground Space Technology*, 5, 135.
8. Munson, D. E.; Devries, K. L.: "Development and Validation of a Predictive Technology for Creep Closure of Underground Rooms in Salt, paper presented at the 1991 Seventh International Congress on Rock Mechanics, Aachen/Deutschland.
9. Frayne, M. A.; Mraz, D. Z.: "Calibration of a Numerical Model for Different Potash Ores", paper presented at the 1991 Seventh International Congress on Rock Mechanics, Aachen/Deutschland.
10. Costa A. M., Poiate E. J., Falcão, J. L., Cardoso C. O., Rocha, R. S.: "*Previsão numérica do comportamento do poço 1-RJS-602 durante a travessia da zona de sal e dimensionamento do fluido de perfuração*", Report RT/MC-040 (2003), PETROBRAS, Rio de Janeiro, Brazil.
11. Costa A. M., Poiate E. J.: "*Previsão numérica do comportamento do poço lua norte 1-RJS-601 durante a travessia da zona de sal e dimensionamento do fluido de perfuração*", Report RT/MC-179 (2003), PETROBRAS, Rio de Janeiro, Brazil.
12. Poiate E. J., Costa A. M., Garske R. B. : "*Acompanhamento de testemunhagens de carnalita do poço 7-CP-1498-SE*", Report RT/MC-034 (2004), PETROBRAS, Rio de Janeiro, Brazil.
13. Poiate E. J., Costa A. M., Garske R. B. "*Äcompanhamento de testemunhagens de taquidrita do poço 7-SZ-433-SE*", Report RT/MC-035 (2004), PETROBRAS, Rio de Janeiro, Brazil.
14. Costa A. M., Poiate E. J. : "*Acompanhamento dos ensaios de fluência sobre amostras de rocha halita – Projeto 600102 - período de julho a outubro de 2002*", Report RT/MC-009 (2003), PETROBRAS, Rio de Janeiro, Brazil.
15. Costa A. M., Poiate E. J., Falcão, J. L.: *Triaxial Creep Tests in Salt Applied in Drilling Through Thick Salt Layers in Campos Basin-Brazil*, paper SPE 92629, presented at the 2005 SPE Annual Drilling Conference, held in Amsterdam, The Netherlands, February 23-25
16. Amaral C. S., Costa, A. M., Carvalho, M.T.M. & Lira, W.W.M, "*Descrição do Sistema SIGMA – Sistema Integrado em Geotecnia para Múltiplas Análises*", Agreement TeCGraf/PUC-Rio – CENPES/PETROBRAS, (1996), Rio de Janeiro, Brazil.
17. Costa, A. M.: "*Uma Aplicação de Métodos Computacionais e Princípios de Mecânica das Rochas no Projeto e Análise de Escavações Subterrâneas Destinadas à Mineração Subterrânea*", Tese de Doutorado, COPPE/UFRJ, 1984.
18. Costa, A. M.; D'Elia, P. D. ;Moreira, L. F. R.; Coelho, L. C. : "*Estudo de Mecânica das Rochas e Dimensionamento dos Painéis de Lavra da Camada Inferior de Silvinita da Mina de Sergipe*", Report CENPES/DIPREX/SEDEM RE-013 (1990), PETROBRAS, Rio de Janeiro, Brazil.
19. Costa, A. M.: "*Análise da Influência da Espessura de Laje de Silvinita e Carnalita Sobrejacente à Taquidrita em Inibir a Fluência da Taquidrita*", Technical Report to Vale do Rio Doce Company RT-CVRD003 (1995), Rio de Janeiro, Brazil
20. Costa, A. M.: "*Simulação do Comportamento de Fluência do Painel D1 e Câmara Experimental C1D1, Dimensionamento do Painel de Lavra para a Camada Inferior de Silvinita da Mina de Potássio de Taquari-Vassouras-Sergipe*", Technical Report to Vale do Rio Doce Company RT-CVRD002 and RT-CVRD004 (1995), Rio de Janeiro, Brazil.
21. Costa, A . M.: "*Reavaliação do Comportamento do Painel de lavra I4a da Mina de Potássio de Taquari-Vassouras*", Technical Report to Vale do Rio Doce Company RT-CVRD 01 (2000), Rio de Janeiro, Brazil.
22. Filho, V. M.;Costa, A. M. :"A técnica de Sísmica de Transmissão Direta na Obtenção de Parâmetros Elásticos de Maciços Rochosos com Aplicação em Projetos de Escavações Subterrâneas", paper presented at the 1985 Second Underground Meeting, Rio de Janeiro/Brazil.
23. Fredrich, J. T.; Coblentz, D.; Fossum, A. F.; Thorne, B. J. *Stress Perturbations Adjacent to Salt Bodies in the Deepwater Gulf of México*, paper SPE 84554, presented at the 2003 SPE Annual Technical Conference and Exhibition, held in Denver, Colorado, October 5-8
24. Willson S. M., Fossum A.F., Fredrich J. T. *Assessment of Salt Loading on Well Casings*, paper SPE 74562, presented at the 2002 SPE Annual Drilling Conference, held in Dallas, Texas, February 26-28

SI Metric Conversion Factors

ft x 3.048	E-01 = m
ppg x 1.298264	E+02 = kg/m^3
psi x 6.894757	E+00 = kPa
in x 2.54	E-02 = m

Table 1: Elastic Properties.

Material	E(kPa)x 10^7	ν
Halite	2.04	0.36
Carnallite	0.420	0.36
Tachyhydrite	0.492	0.33
Fine Limestone	3.10	0.30
Ciment	2.10	0.25
Casing	21.0	0.28

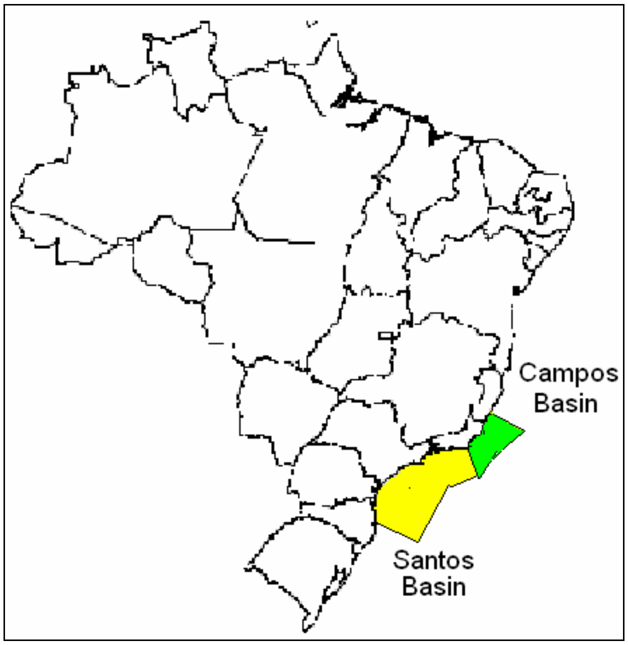


Figure 1 – Campos and Santos Basin Localization

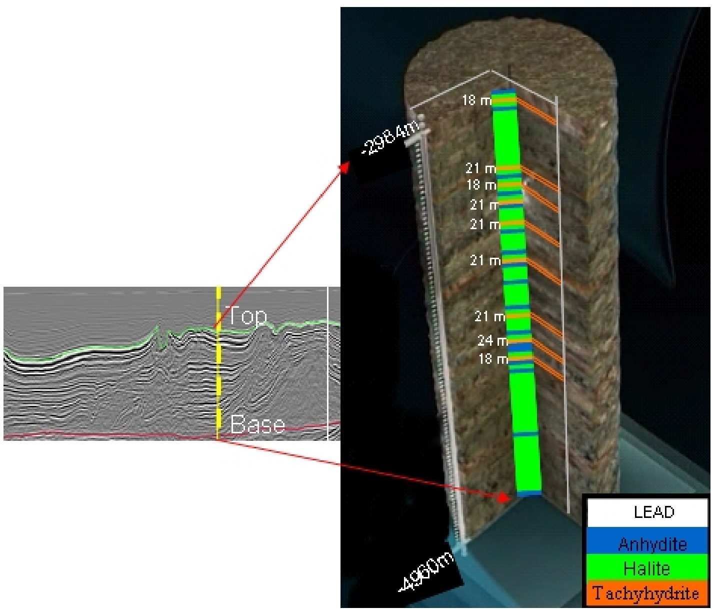


Figure 2 – Salt Section and Location of Well # 1

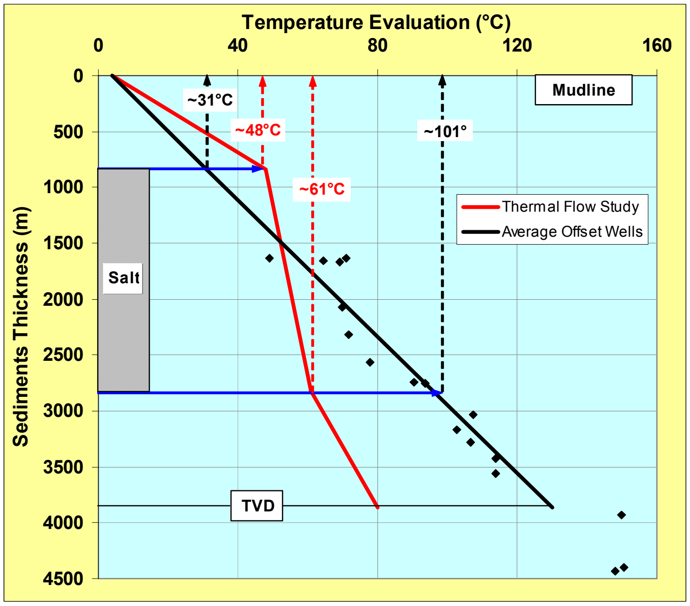


Figure 3 - Extrapolated Temperature- Santos Basin

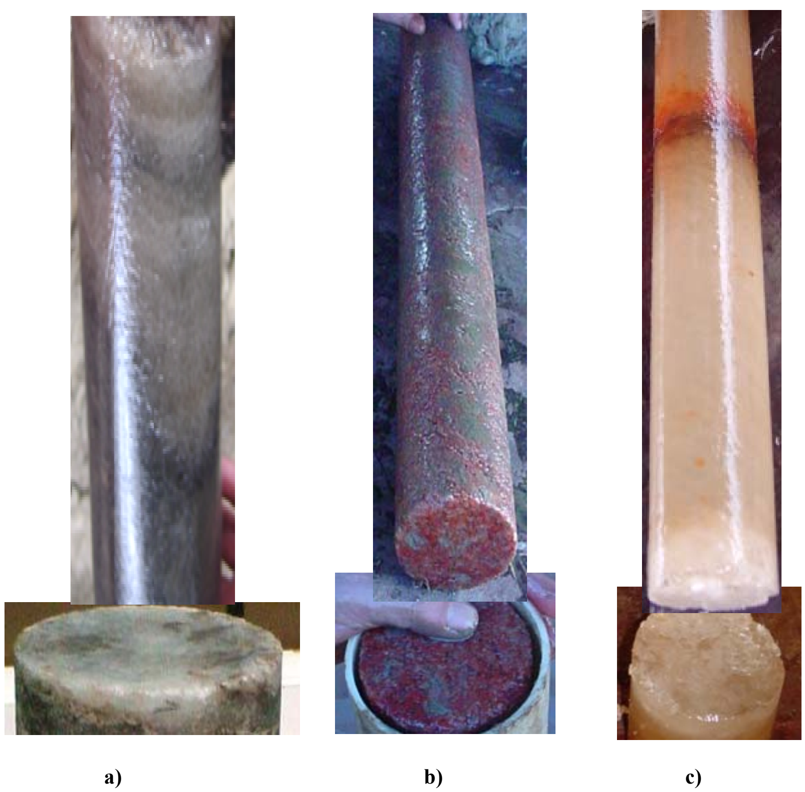


Figure 4 – a)Halite, b)Carnallite e c) Tachyhydrite.

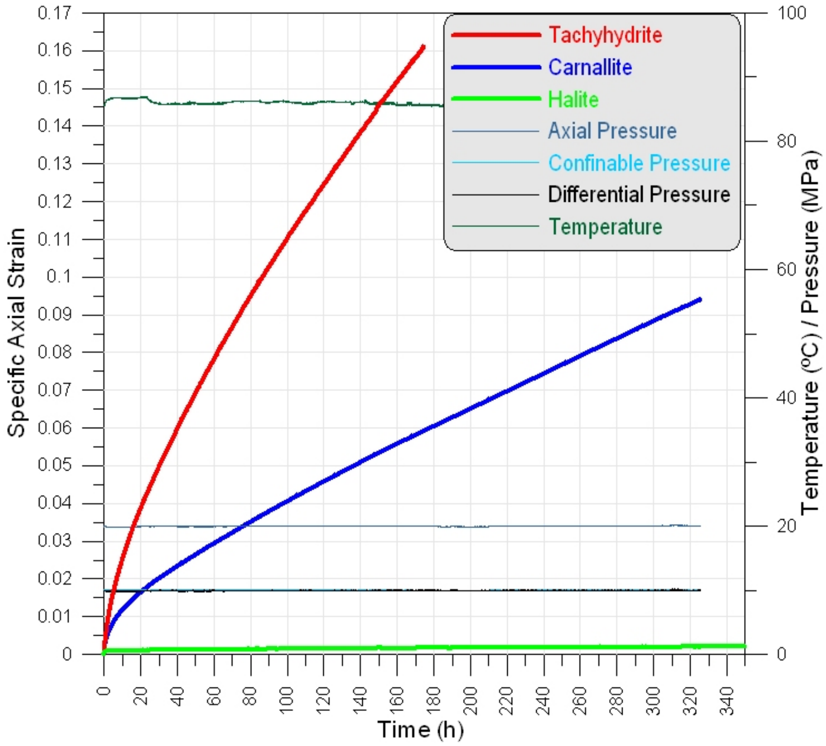


Figure 5 - Salts creep test, 86ºC, Δσ=10MPa

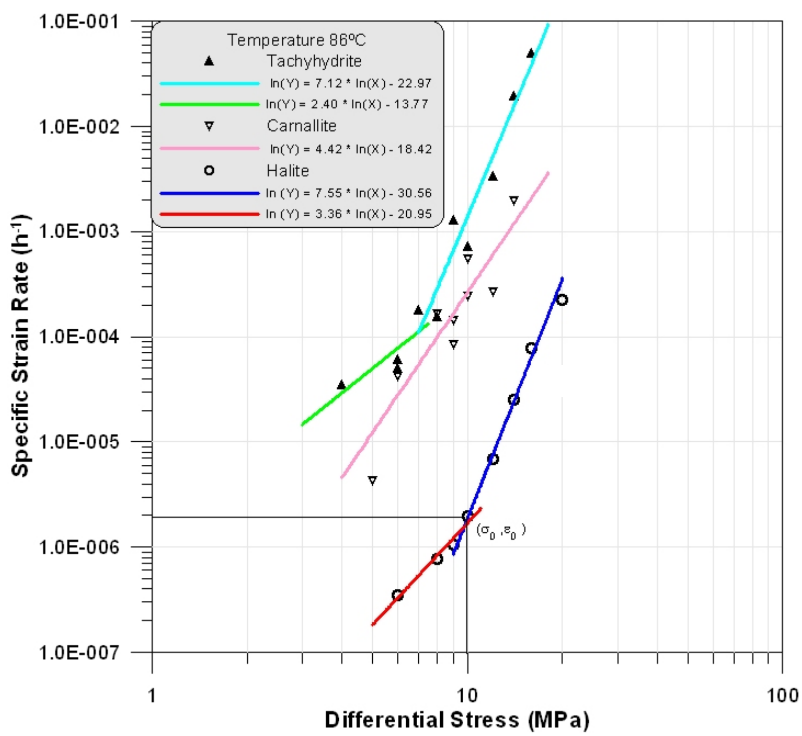


Figure 6 – Strain rates results from salt creep test in the stead state condition.

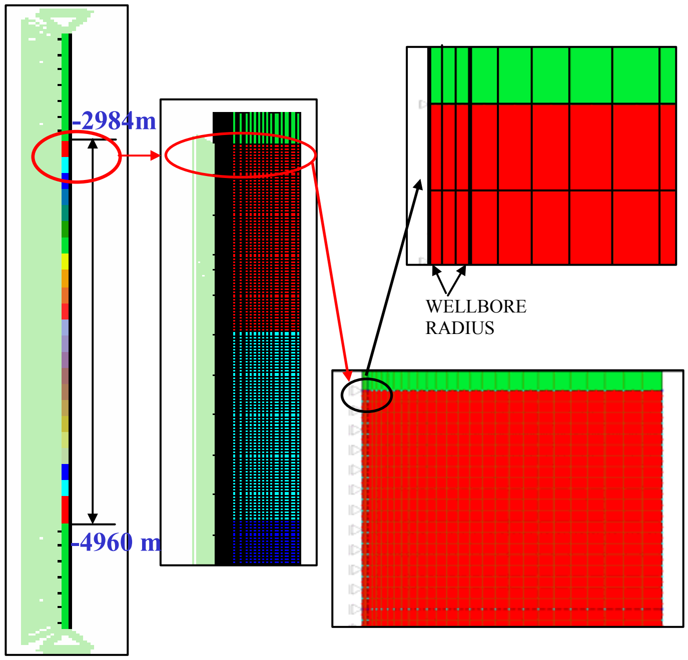


Figure 7 – Finite element model - axisymmetric model.

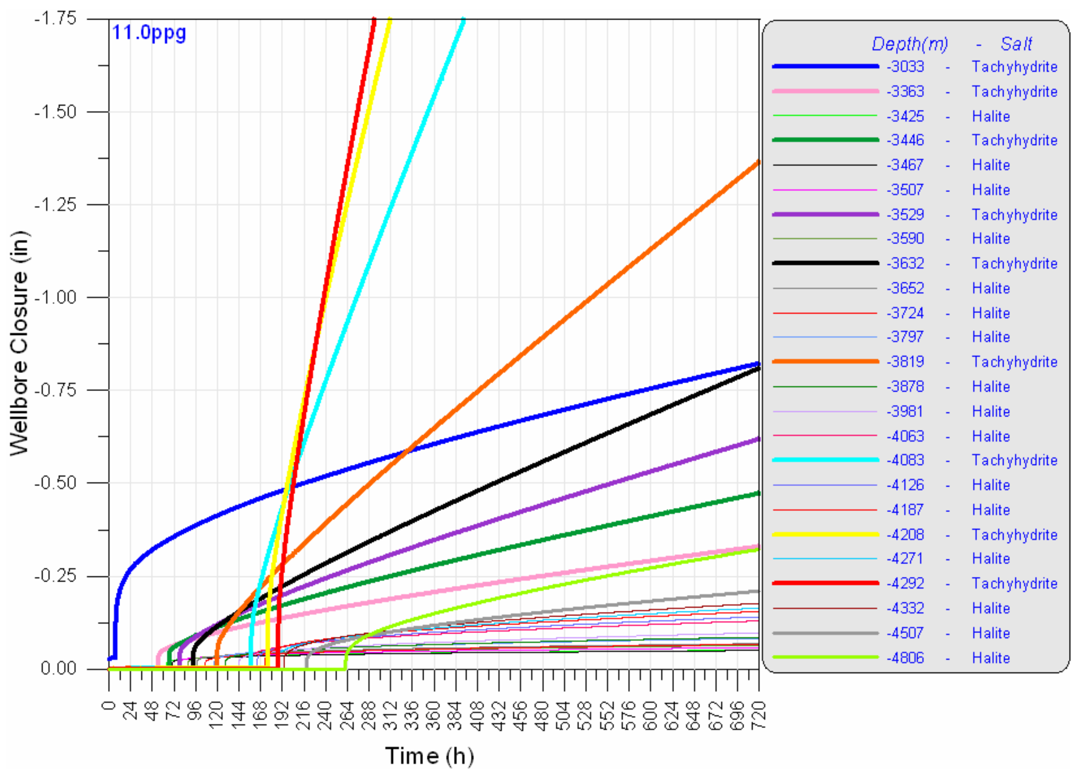
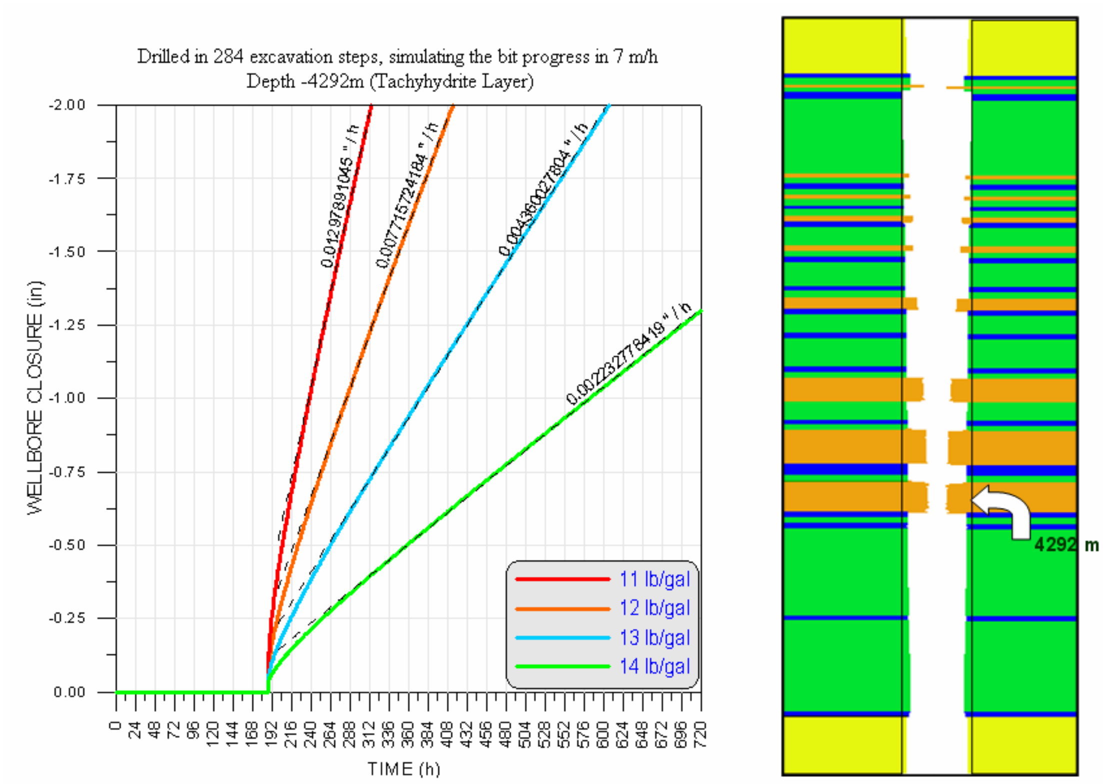


Figure 8 – Closure curve in 25 differents depths drilled with in a drilled in 198 excavation steps, 11.0 mud weight, in just on single stage.



a) b)

Figure 9 – a)Summary results of the wellbore closure with the mud weights 11-12-13 and 14.0 ppg in -4292m depth and b)The model result with 14ppg.

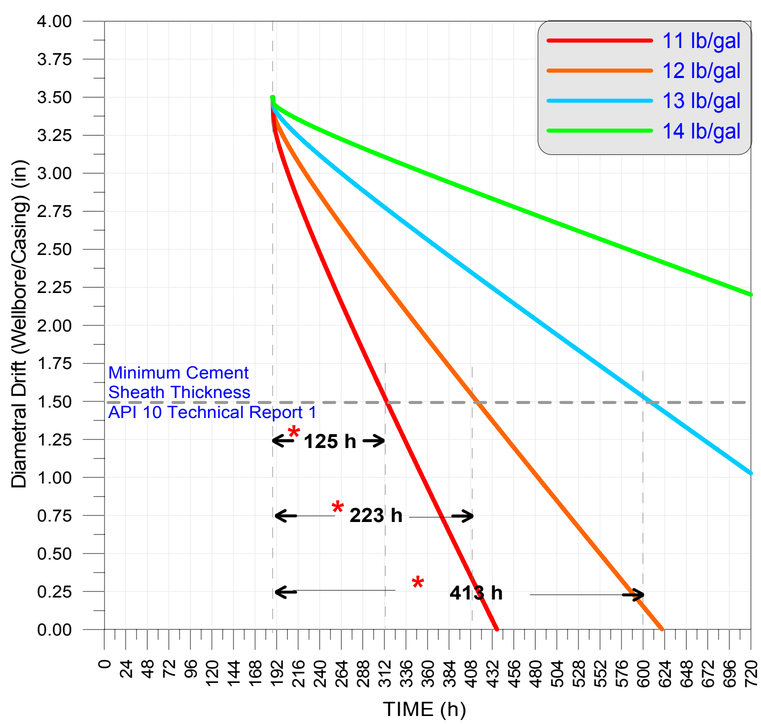


Figure 10 – Summary results of the time to finish the well, included thickening time of cementation with different mud weights.

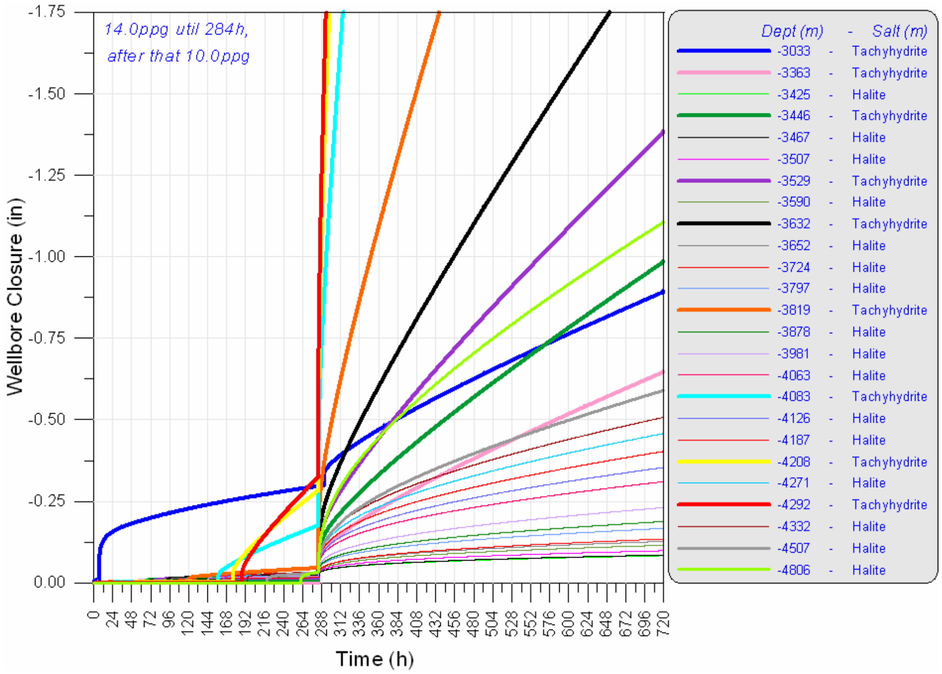


Figure 11 – Wellbore closure with 14.0 mud weight until 284h, after that 10ppg.

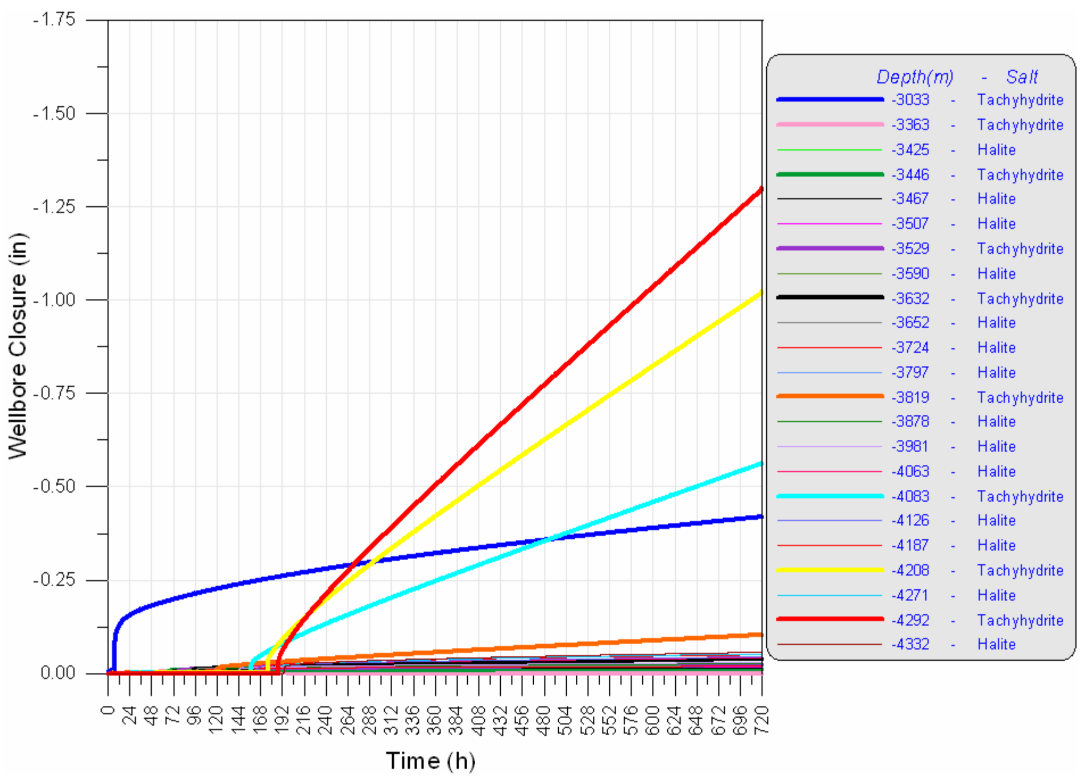


Figure 12 – Closure curve with 14.0ppg mud weight, first stage.

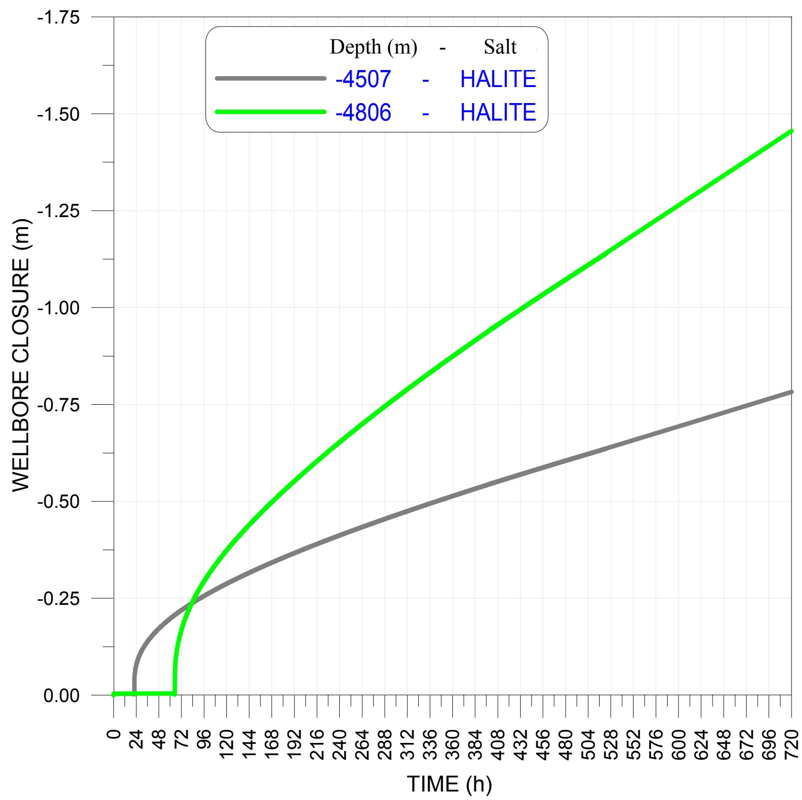


Figure 13 – Closure curve with 10.0ppg mud weight, second stage.

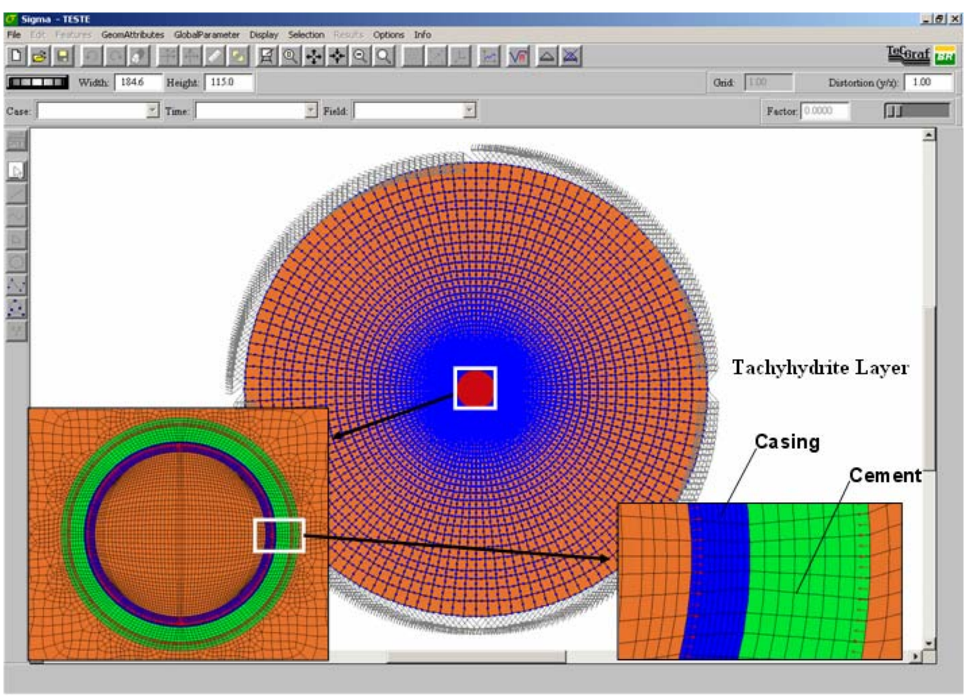


Figure 14 – Finite element model – plane strain model.

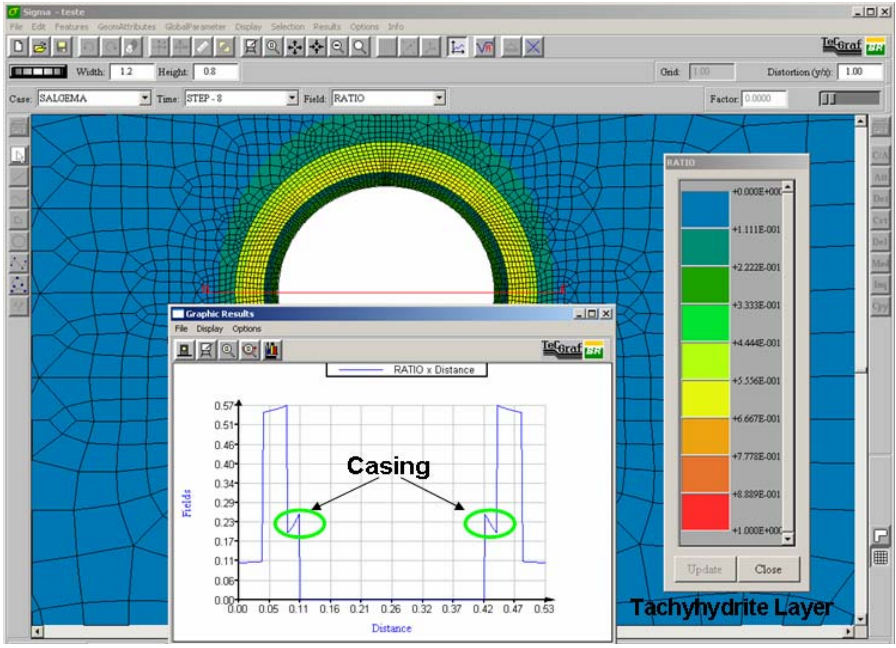


Figure 15 – 100% cemented annulus, after 500h in a concentric wellbore.

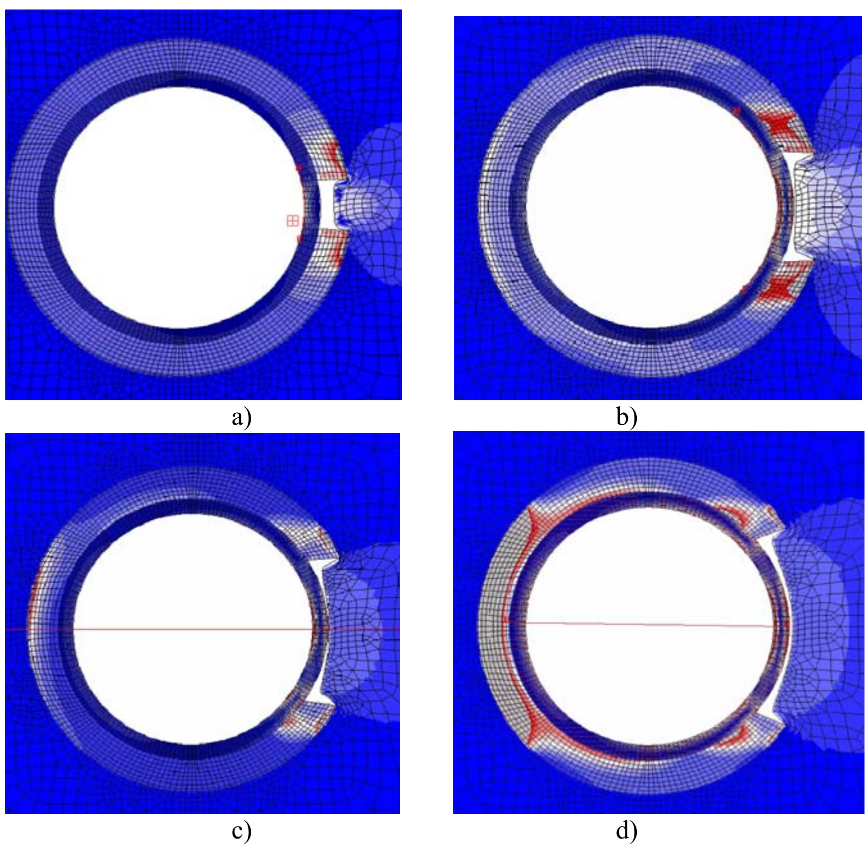


Figure 16 – Cement channeling a)5%, b)10%, c)15% and d)20%.

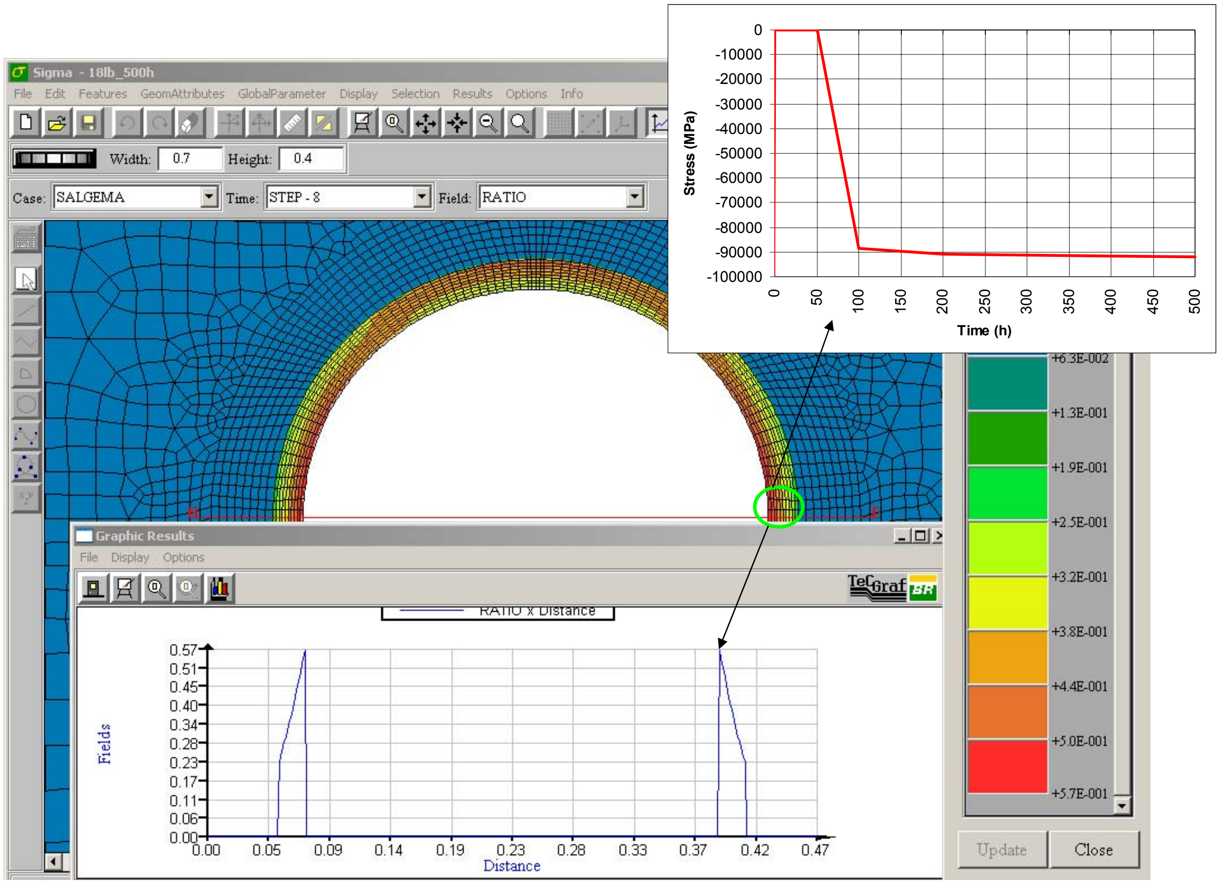


Figure 17 – Dense mud (16,6ppg) placed in annulus salt/casing concentric

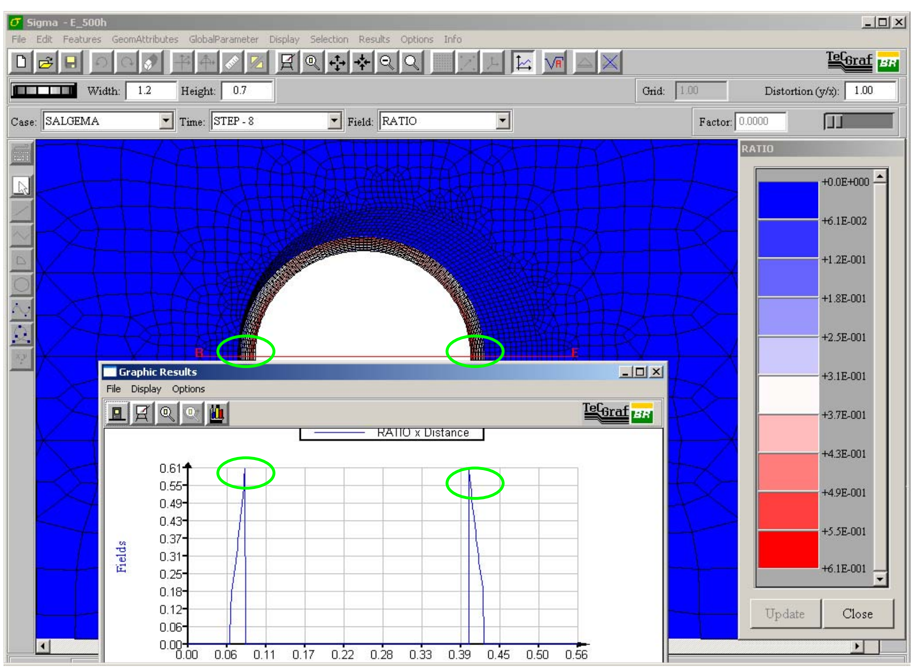


Figure 18 – Dense mud (16,6ppg) placed in annulus salt/casing non-concentric

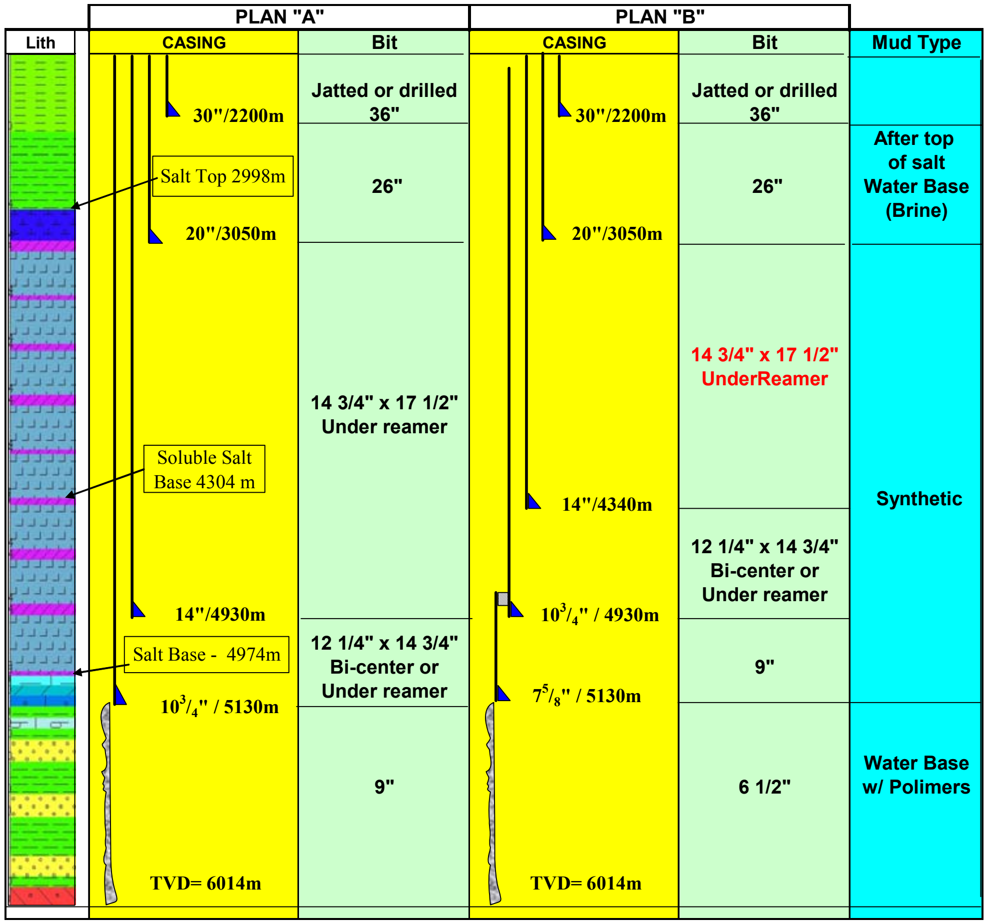


Figure 19 – Proposed Casing Program – Plan "A" and Plan "B"

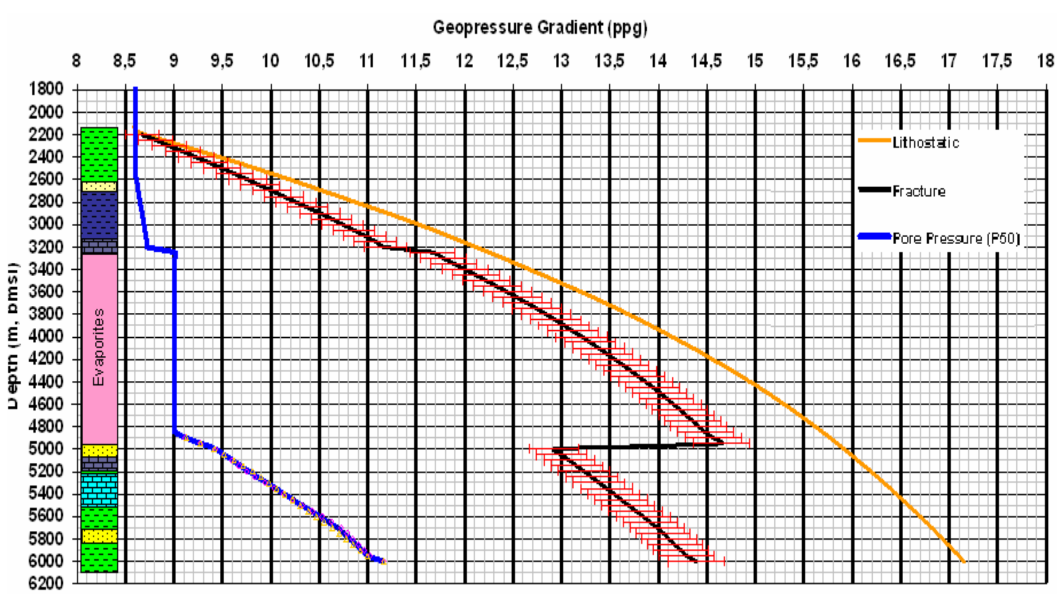


Figure 20 – Well # 1- Geopressure Evaluation – Eaton's Method