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# 3D Geomechanical Modeling of Salt Creep Behavior on Wellbore Casing for Pre-Salt Reservoirs\*

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## Abstract

Exploration drilling is venturing out into deeper regions of water. While exploring these deeper water depths, large hydrocarbon deposits have been found below salt formations. These reservoirs are located in formations called “pre-salts,” which are located below the salt formations. Pre-salt reservoirs have been found in offshore Brazil, the Gulf of Mexico, West Africa, and the North Sea. Completions in salt formations can be difficult owing to the creep behavior that the salt formations exhibit. Creep behavior results from the instability of the salt formation, which causes a slow flow and permanent deformations. Creep deformation occurs over time and is initiated once the salt formation has been penetrated. Completion of the wellbore does not stop formation creep. The constant creep of the salt formation causes excess stress on the wellbore casing, which may eventually cause the casing to collapse. In this study, a 3D geomechanical model is developed, using data such as wellbore pressure and temperature, formation stress and temperature, rock, cement, and casing properties, to predict the effects of salt creep behavior on stress loading in the wellbore casing, which helps to assess the life expectancy of wells in pre-salt reservoirs. The simulation results of this model can provide quantitative results of casing stress and deformation as a function of time under various temperature, in-situ stress and operation conditions, that can be used as useful information for subsequent wellbore casing design and wellbore integrity analysis. In addition, possible methods that can mitigate the severity of salt mobility and reduce the risks of casing collapse are discussed.

**Keywords:** Salt creep; Pre-salt reservoir; Wellbore stability; Wellbore casing; Geomechanical modeling; Completion in salt

## 1. Introduction

Salt is one of the most effective agents in nature for trapping oil and gas: as a ductile material, it can move and deform surrounding sediments, creating traps; salt is also impermeable to hydrocarbons and acts as a seal. Most of the off-shore hydrocarbons in North America are trapped in salt-related structures (Farmer et al., 1996), as are significant amounts in other continents around the world. Many reservoirs in the North Sea are below salt, as are large fields in the Gulf of Suez (Western and Ball, 1992). In addition, because of the impermeability of salt rocks, cavities opened in these rocks can act as a strategic hydrocarbon reserve (Costa et al., 2012) to store large quantities of hydrocarbons, such as the Strategic Petroleum Reserve project (Sobolik and Lord, 2014).

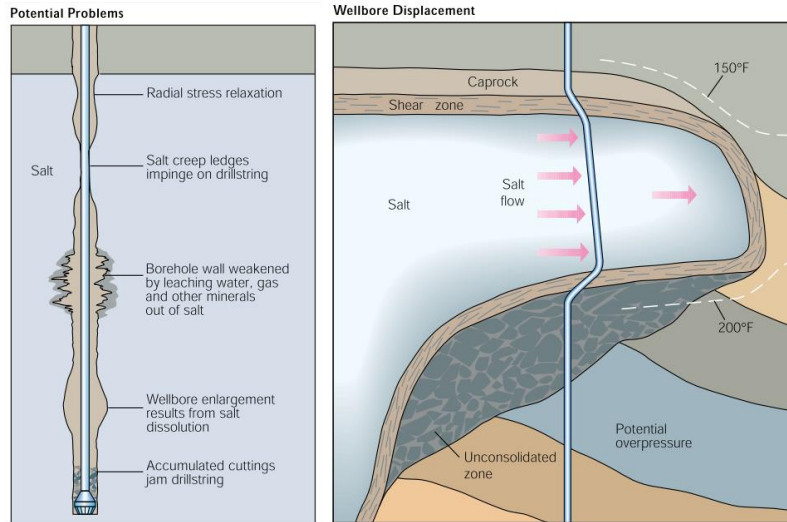
Salt can creep and/or deform. This ability is one of the unique and problematic characteristics of salt. If the overlying sediments offer little resistance, as is sometimes the case in the Gulf of Mexico, the salt rises, creating characteristic domes, pillows and wedges that truncate upturned sedimentary layers. If the overburden does resist, salt can still push through, creating faults in the process. If tectonic conditions are right, extensional faulting in the rigid overburden can open the way for salt ascent. So in the geological time frame, salt can move extensively within the subsurface creating diapirs and walls. While these structures generate significant traps for hydrocarbons they also present a number of drilling and completion problems. The rock salts behave in a visco-plastic manner, which will deform under pressure. This deformation is called creep and occurs over time once the salt has been disturbed. Creep begins the instant that drilling penetrates the salt formation and occurs as a result of instability and formation stresses. When drilling in salt sections, openhole instability and the accompanying problems can often arise, including borehole walls weakened by incompatible drilling fluids, restrictions and undergauge hole caused by salt creep, or enlargement because of dissolution (**Fig.1**, left). Completion of the well does not stop the creep process, during the life of a well, salt movement can displace wellbore tubular, possibly causing casing failure or restricted access to hydrocarbon flow (**Fig. 1**, right). In addition, a salt intrusion can locally distort the stress field making wellbore stability impossible to predict using conventional geomechanical models, because casing across salt zones is subjected to tension, compression, and hydrostatic loads combined with non-uniform forces, which must be included in design calculations to ensure the lifetime well integrity.

In recent years, with the development of new technology, the oil and gas industry is exploring deeper into waters. In areas, such as Brazil, the Gulf of Mexico, West Africa, and the North Sea, tremendous amount of hydrocarbon reservoirs were discovered under large, thick salt formations (Greenhalgh et al., 2012; Chitale et al., 2014), which are called pre-salt reservoirs. These pre-salt reservoirs differ significantly from the subsalt reservoirs found previously (Dribus et al., 2008). Pre-salt wells are drilled into formations that were deposited prior to the emplacement of a layer of autochthonous salt—salt that remains at its original stratigraphic level. This autochthonous salt lies above older rocks and is, in turn, overlain by

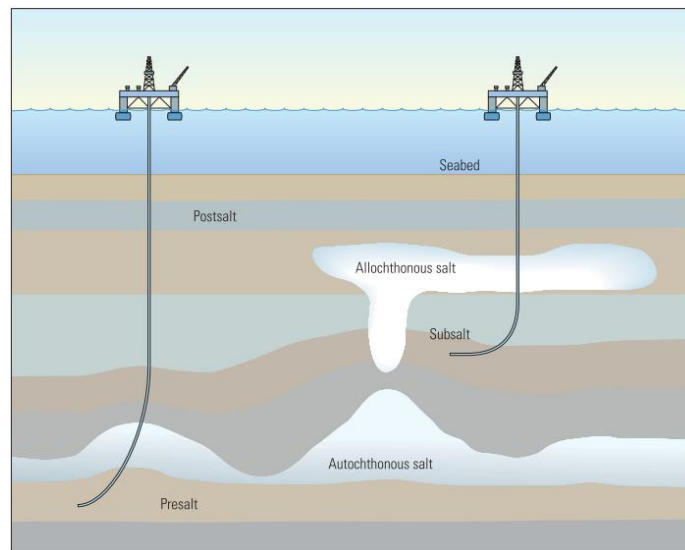
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younger strata. By contrast, subsalt wells are drilled into formations lying beneath mobile canopies of allochthonous salt—masses of salt, fed by the original autochthonous layer, that rise through overlying layers, and then spread laterally (**Fig. 2**). To reach the Pre-salt, carbonate reservoirs (Garland et al. 2012; Thompson et al. 2015), the well has to drill through the whole section of salt. In such cases, unlike drilling around a salt dome for subsalt reservoirs, it is not possible to design a well path that can circumvent the thick salt formation and reach the target reservoir below it (Dusseault et al., 2004).



**Fig.1** Challenges of drilling and completion in a salt formation (Farmer et al., 1996)



**Fig.2** Subsalt and pre-salt reservoirs under salt formations (Beasley et al., 2010)

Even though in many cases, the flow and deformation of a salt formation are slow and the associated wellbore closure process is also not noticeable enough to cause severe operational troubles. However, a poorly designed casing and cement job can increase the risk of collapse during production later on. Severe problems with casing failures in salt formations have been well documented in the literature (Cheatham Jr. and McEver, 1964; Pattillo and Rankin, 1981; Goodwin, 1984; Rike et al., 1986). Drilling and cementing operations in salt formations require careful planning to avoid undesired events, especially in deep water scenarios where cost and HSE are critical. Any failure and collapse of the wellbore can lead to tragic catastrophe, especially in an off-shore environment. In many reservoirs, pressure depletion after long-term production can lead to reservoir compaction, movement of overburden and subsidence of the surface above the reservoir. A compacting formation pulls the cemented casing along with it, compressing the axial dimension of the casing. Above the reservoir, the overlying material typically elongates, and the casing there stretches. In either situation, the casing may collapse owing to excessive stress within the compact zone or fail in tension in the overburden layers. However, in the context of salt formations, the excessive stress on casing is caused by the horizontal movement of salt that pushes the casing either along one horizontal direction or along the radial direction. So casing collapse is the main concern related to the development of the under salt reservoirs, which demands the construction of wells with preserved structural integrity for decades.

The deformation rate of salt (creep rate) is not only governed by the stress difference between the salt formation and the borehole hydrostatic pressure, but also strongly influenced by temperature. For example, in a deep water Gulf of Mexico well where the top of salt was at approximately a temperature of 118 °F, and the base salt was at a temperature of 200 °F. If the

differential stress between wellbore hydrostatic pressure and salt internal stress maintains the same level in the entire salt section, then the creep rate at the bottom of the hole would be expected to be one-hundred times faster caused by temperature effects alone (Dusseault et al., 2004).

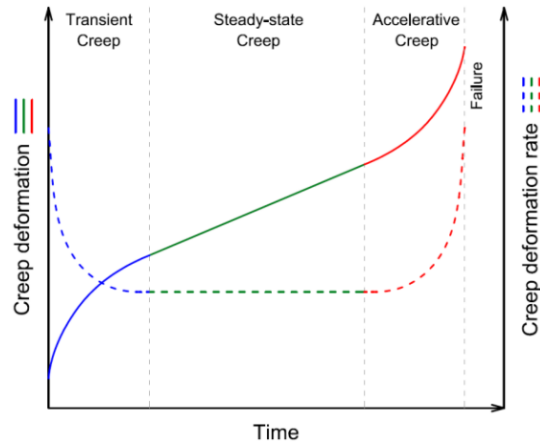
So it is crucial to be able to predict the creep behavior of salt formations and the stress loading in the casing, to ensure that the casing does not go beyond its mechanical strength during the life of production. Even though numerous efforts have been made to investigate geomechanical properties of salt rock and the associated challenges on drilling and wellbore stability (Chatar and Imler, 2010; Hansen, 2011; Lao et al., 2012; Mathur et al., 2010; Mackay et al. 2008), few literature is available to demonstrate a comprehensive model to predict the stress load on casing in salt formations under various conditions during the long-term production period in a rigorous way, by including the impact of temperature disturbance and considering salt formation, cement and wellbore casing as an integrated system.

Khalaf and Cairo (1985) used a model derived from Lamé's elastic solution for a thick cylinder loaded with uniform internal and external pressure to evaluate the strength of concentric casings packed with cement. Their study shows that a string-in-string or thick walled casing provides better well integrity as compared to a higher grade single casing. Willson et al. (2003) investigated casing loading in uncemented hole sections using numerical simulation. The in-situ stresses are uniform with both, circular and noncircular, boreholes. Their research reflects a uniform casing load increasing with time, for the circular borehole. With the noncircular borehole, casing load changes from a point load to a uniform load. After an extended period of time, the casing load eventually equals the overburden pressure for both the circular and the noncircular boreholes. Zhao et al. (2011) developed a finite element model with rheological constitutive equations to investigate salt creep effects on casing. Their results indicate that in a non-creep formation, the maximum external pressure on the casing is the cement column pressure, but in a creeping salt bed, the in-situ stress is gradually applied to the cement after it is set. The pressure between the cement and the casing is uniform under idealistic cementing conditions. However, all these works are based on 2D models and assume plane strain conditions, which may not be valid in a time-dependent deformation such as with rock salt, where vertical strain cannot be zero or constant in the formation. And the effects of temperature disturbance during operations and productions are not included. Wang et al. (2014) developed a 2D finite element model to investigate how the variations in temperature around the wellbore, drawdown pressure during production, the shape of the wellbore, and formation anisotropic properties can impact long-term casing integrity. Their results indicate that many well-established factors that affect wellbore stability in a conventional and non-creep rock may not be valid in salt formations.

In this study, a 3D geomechanical model is developed, using data such as wellbore pressure and temperature, formation stress and temperature, rock, cement, and casing properties, to predict the effects of salt creep behavior on the stress loading in wellbore casing during drilling and production operations. The focus of this paper is to seek a better understanding of salt creep effects on wellbore casing in the context of a pre-salt environment and present a general approach/methodology to address this issue. The results from our numerical model can provide quantitative information on casing stress and deformation as a function of time under various operational conditions, which are crucial for subsequent suitable wellbore casing design and wellbore integrity analysis. In addition, possible methods that can mitigate the impacts of salt mobility and reduce the risks of casing collapse are discussed.

## 2. Salt Behavior

Salts belong to a group of sedimentary rocks called evaporates, resulting from sea water evaporation. Salt rock behaves as a visco-plastic material that has the tendency to creep when subject to stress. The creep strain rate is dependent on several factors, including (1) temperature, (2) differential stress, (3) confining pressure, (4) grain size, and (5) presence of inclusions of free water or free gas bubbles. Temperature and stress differentials are the main drivers for salt creep (Barker et al. 1994). For example, the rock tachyhydrite, which is a type of salt formation, is very weak in comparison to halite and can develop a creep strain rate that is two orders of magnitude faster than halite for the same state variables, temperature, and stress (Costa et al., 2010). From a geomechanical point of view, salt creep is the rock deformation caused by the dissipation of strain energy generated by the stress relief in an undisturbed salt rock mass. In the context of a wellbore, creep closure may also provoke stuck pipe and casing collapse, creating significant difficulties for well construction and operations. Even though the creep process is slow, well closure may still occur and eventually cause severe problems with casing failures in the salt formations (Rike et al. 1986), because of excessive stress that goes beyond the mechanic strength of the casing. A typical axial salt creep deformation curve is illustrated in **Fig. 3**.



**Fig. 3** Typical creep testing results from a salt rock specimen (Poiate, 2012)

A typical creep curve for salt rock consists of two or three creep stages. Following the application of the stress difference, the strain rate is initially significantly high. This high level of strain rate then decreases monotonically with time until a constant strain rate is observed. These two stages are called transient and steady-state creep stages, respectively. Depending on the level of temperature and the differential stress applied to the specimen, a third stage, called tertiary creep, may become evident. This is characterized by acceleration of the creep strain rate caused by the specimen structure damage induced by the creep strain accumulation with time. At the tertiary creep stage, the dilation phenomenon, an increase in volume through micro-fracturing develops, leading to failure of the specimen.

In the context of wellbore completions, the tertiary creep in the surrounding salt rock is not likely to occur because the deformations are constrained. Then the creep rate in salt formations can be defined by two components, as described above: one is known as the transient creep rate  $\bar{\epsilon}_t$ ; the second is known as the steady-state creep rate  $\bar{\epsilon}_s$ . The overall strain rate caused by creep is given by:

$$\bar{\epsilon} = \bar{\epsilon}_t + \bar{\epsilon}_s \dots \dots \dots (1)$$

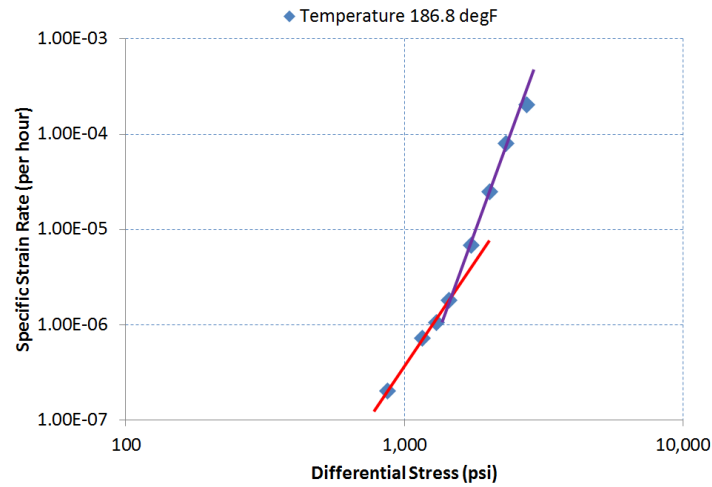
Because the transient creep occurs soon after excavation and only lasts for a short period of time (Jin and Cristescu 1998), transient creep is normally dissipated during drilling and cementing operations, which take days, if not weeks, to complete. So it is reasonable to assume that the steady-state creep primarily contributes to the overall strain rate owing to creep and the relationship of  $\bar{\epsilon} = \bar{\epsilon}_s$  is valid after the section of salt formation is cemented and cased.

To predict the salt creep behavior under various operational and in-situ subsurface conditions, a representative constitutive model for creep deformation in salt rocks is needed. Munson (2004) proposed a double mechanism creep law, which depicts that the largest contribution of creep behavior depends on the temperature conditions and differential stress to which the salt is submitted:

$$\bar{\epsilon}_s = \bar{\epsilon}_0 \left( \frac{\sigma_{eff}}{\sigma_0} \right)^n e^{\left( \frac{Q}{RT_0} - \frac{Q}{RT} \right)}, \dots \dots \dots (2)$$

where  $\bar{\epsilon}_0$  is strain rate owing to steady state creep at reference conditions;  $\sigma_{eff}$  is the creep effective stress;  $\sigma_0$  is the effective stress at reference conditions;  $n$  is the exponent constant determined from laboratory tests;  $Q$  is the activation energy ( 12 kcal/mol);  $R$  is the universal gas constant (0.003574 kcal/mol · °F);  $T_0$  is the temperature (°F) at reference conditions; and  $T$  is the rock temperature (°F). Creep tests can be performed on salt samples retrieved from cores in laboratory experiments (using simulated field conditions). The creep tests are used to determine the unknown parameter,  $n$ , in Eq. (2). **Fig. 4** shows a typical creep test experiment result of halite. From the extrapolation and curve fitting of experimental data at test temperature, the following parameters can be determined:

- Reference temperature  $T_0=186.8$  °F
- Reference effective stress  $\sigma_0=1,450$  psi
- If creep effective stress  $\sigma_{eff} <$  reference effective stress  $\sigma_0$ , then  $n=3.36$
- If creep effective stress  $\sigma_{eff} >$  reference effective stress  $\sigma_0$ , then  $n=7.55$



**Fig. 4** Steady-state Creep Strain Rate vs. Differential Stress for Halite (Modified from Costa et al., 2010)

With all this information provided by the experimental data, Eq. (2) then can be used to calculate the strain rate explicitly,  $\bar{\epsilon}_s$ , under various stress and temperature conditions. It is true that not all salts behave in the same way and so they have the same impact on wellbore stability. Simple salts, such as halite, remain relatively stable during drilling, but they can continue deforming for decades during the lifetime of a production well, thus should be taken into account when assessing long-term casing integrity. While complex salts, particularly tachyhydrite, can creep and close around a drill string very rapidly and cause drilling and cement problems, but have a negligible long-term impact. Since the focus of this article is to investigate the long-term effects of salt creep behavior on wellbore casing, the fast creep behavior that dissipates quickly after drilling operations will not be investigated in detail, but its overall impact on casing eccentricity and resulting consequence of non-uniform stress will be discussed in a later section.

### 3. Geomechanical Modeling

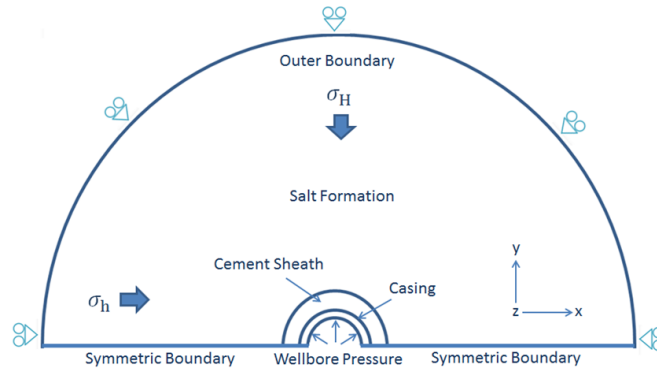
Geomechanical modeling of salt creep behavior is critical for optimum casing system design, risk management, and project economics because of the high costs of well-completion operations in regions where drilling through thick salt formations is necessary. Appropriate analysis and evaluation of deformations in salt and associated well-casing damage risks often includes: detailed near-wellbore modeling to investigate salt-cement-casing behavior, the use of available laboratory data to develop and validate appropriate constitutive models, and reservoir scale modeling to consider the range of loads and boundary conditions likely to be imposed on the near-wellbore system during long-term production.

Caused by the complex nature of drilling and cementing operations, which includes strong drilling bit, salt rock and drilling/cement fluid interactions and associated rock damage mechanisms, it is extremely difficult, if not impossible, to directly model the excavation process from the state of initial reservoir conditions where rock is intact. Because a detailed investigation of fast salt creep behavior and its impact on drilling and cement operations is not the intention of this article, we only focus on the period that begins when the whole salt section has been cemented and cased, after which only slow, stable creep behavior impacts wellbore stability. Even after the cementing and casing of a wellbore in the salt formation, drilling operations still need to continue to drill deeper into the underlying pre-salt reservoirs and after the target reservoir is completed, the whole well is then ready for production.

During geological time history, when salt is under stress, it continues to compact, displacing brine, until the porosity is totally occluded. If the temperature and the stresses are high, the compaction will continue until only a brine filled low, residual porosity remains. The remaining porosity consists of thin, dendritic voids at the grain boundary. Flow through salt only occurs in non-salt lithologies or through introduced flaws, when viewed in an engineering time scale (< 100 years), fluid flow inside salt rocks is negligible, so salt rock can be viewed as a pure solid and pressure inside the wellbore completely acts on salt walls. Unlike allochthonous salt above subsalt reservoirs, most of the autochthonous salt above pre-salt reservoirs has equilibrated at a geological time scale because of its visco-plastic nature (Albertz et al. 2010); hence, the horizontal stress and overburden stress are equal in autochthonous salt formations. Because salt is also a barrier to basin fluids, if the outward flow is insufficient to achieve normal compaction, abnormally high pressure may develop below salt (O'Brien et al., 1994), so much higher drilling mud density may be needed to drill the pre-salt reservoir than to drill the salt section.

To investigate the effects of stable salt creep behavior on wellbore casing, a 3D geomechanical model is developed and applied to a synthetic field simulation case where a vertical wellbore is cemented and cased, and operation continues to drill a pre-salt reservoir with abnormally high pressure. The model includes salt formation, cement and casing as an integrated system, and a horizontal plane view of the simulation model is shown in **Fig. 5**. The inner and outer diameter of the casing is 7.921 inches and 8.625 inches, respectively. The outer diameter of cement is 12.25 inches and the casing is in concentric condition. The thickness and radius of the simulated formation section are 500 inches. A symmetric boundary condition is applied to the symmetric plane line (bottom of Fig.5) and non-displacement conditions are imposed at the outer boundary

along the radial direction (represented by triangles in Fig.5). Uniform horizontal stresses are applied to the x-y plane and vertical stress is applied on top of the formation along z direction. In addition, wellbore pressure is imposed on the internal surface of the casing to reflect the influence of wellbore pressure during drilling and production. It should be noted that the section of wellbore beneath the salt formation is excluded in the numerical model and the casing is unperforated within the entire salt formation.



**Fig. 5** Graphical representation of wellbore and stresses

For the purpose of simplification and easy interpretation of simulation results, gravitational effects on the simulated section are not considered. After applying the initial geo-stress conditions in the formation, three steps are developed to simulate the formation-cement-casing interactions during the drilling and production processes.

1. Drilling process—imposes a uniform wellbore pressure on the inner surface of the casing to reflect a high wellbore pressure to overcome abnormal high pore pressure in the underlying target reservoir. In addition, a low-temperature boundary condition is applied at the same time to account for effects of drilling fluid circulation. 100 days of the drilling process is simulated in this step.
2. Transitional process—a simplified process to reflect wellbore pressure alterations before the start of production where the wellbore pressure gradually declines to a low production pressure level. 50 days are assumed to complete the transitional process.
3. Production process— a low production wellbore pressure is maintained for a period of 500 days. And a high-temperature boundary condition is applied on the inner surface of the casing to account for the flow of high-temperature hydrocarbons from the deeper target reservoir.

For the transitional process, it is maybe more realistic to divide it into different subsections, where detailed operational wellbore pressure can be captured. However, a field case study with detailed procedure modeling is not the intention of this paper, which emphasizes on general approach and methodology. In addition, considering the extremely large volume of the formation rock and the small heat source along the wellbore, it can be assumed that the far field region remains at a constant temperature (under isothermal conditions) and the well temperature only affects the near wellbore region. Then we can apply a fixed temperature condition (initial in-situ temperature) at the outer boundary of the simulation domain. It should be noted that in realistic scenarios, heat can also transfer in the depth direction, because there exists a vertical temperature gradient within both wellbore and salt rock, and if the temperature gradient in the vertical direction is larger than that in the radial direction, vertical heat transfer will dominate temperature distribution in the near wellbore region. So the incorporation of a vertical heat transfer process requires detailed operation and thermal data on a much larger scale for different layers, which is out of the scope of this article. In our synthetic study, temperature only varies in the radial direction. Because short-term, fast creep behavior is not explicitly modeled, the impact of temperature transient behavior can be neglected and the steady-state temperature profile around the wellbore can be mapped with the provided boundary conditions and thermal properties.

The description and mathematical equation of each mechanism considered in the study are presented in the following. The heat transfer is based on an energy balance equation (Carslaw and Jaeger, 1959):

$$\rho C \frac{\partial T}{\partial t} + \nabla \cdot (-\lambda \nabla T) = q, \dots\dots\dots (3)$$

where  $\rho$  is the density of salt rock,  $C$  is the heat capacity of the salt rock,  $\lambda$  is thermal conductivity,  $T$  is temperature and  $q$  is the heat source.  $\nabla \cdot$  is the divergence operator. For steady-state problem, both of the terms,  $\rho C \frac{\partial T}{\partial t}$  and  $q$ , are zero.

Stress equilibrium is expressed by writing the principle of virtual work for the volume under consideration in its current configuration (Zienkiewicz and Taylor 2005).

$$\int_V \sigma : \delta \epsilon \, dV = \int_S \gamma \cdot \delta v \, dS + \int_V f \cdot \delta v \, dV, \dots\dots\dots (4)$$

where,  $\delta v$  is a virtual velocity field,  $\delta \varepsilon$  is the virtual rate of deformation,  $\gamma$  is the surface traction per unit area, and  $f$  is the body force per unit volume. This equation is then discretized using a Lagrangian formulation with displacements as the nodal variables.

The constitutive equation for the solid is expressed as (Hashiguchi 2014):

$$d\sigma = E d\varepsilon + \int_0^t (t - \tau) \frac{d\varepsilon}{d\tau} d\tau, \dots\dots\dots (5)$$

where  $\sigma$  is stress,  $\varepsilon$  is strain,  $E$  is the material stiffness and  $\tau$  is the relaxation time. The constitutive equation of salt behavior, which is based on the double-mechanism creep law, can be solved by the following iteration method:

1. At the end of the initial geo-static equilibrium, the displacement field  $[\delta_i]$  and stress field  $[\sigma_i]$  are solved, which are then passed to the production process as initial values.

$$[K][\delta_i] = [F] \dots\dots\dots (6)$$

$$[\sigma_i] = [D][B][\delta_i], \dots\dots\dots (7)$$

where,  $[K]$  is the stiffness matrix of the whole system,  $[F]$  is the equivalent nodal force,  $[D]$  is the elasticity matrix, and  $[B]$  is the geometric stiffness matrix.

2. Assume the stress field remains unchanged during each increment. Within the interval from  $t$  to  $t + \Delta t$ , the stress is  $[\sigma_t]$ . Calculate the creep strain increment  $[\Delta \varepsilon_t^c]$  during time interval  $\Delta t$ :

$$[\Delta \varepsilon_t^c]_{\Delta t} = \Delta t [\dot{\varepsilon}_t], \dots\dots\dots (8)$$

where  $[\dot{\varepsilon}_t]$  is the creep rate at time,  $t$ , and  $[\dot{\varepsilon}_t]^T = (\dot{\varepsilon}_1, \dot{\varepsilon}_2, \dot{\varepsilon}_3, \dots)$ . The components of  $[\dot{\varepsilon}_t]$  can be expressed as follows:

$$\dot{\varepsilon}_1 = \frac{\bar{\varepsilon}}{\sigma_{eff}} \left[ \sigma_1 - \frac{1}{2}(\sigma_2 + \sigma_3) \right] \dots\dots\dots (9)$$

$$\dot{\varepsilon}_2 = \frac{\bar{\varepsilon}}{\sigma_{eff}} \left[ \sigma_2 - \frac{1}{2}(\sigma_1 + \sigma_3) \right] \dots\dots\dots (10)$$

$$\dot{\varepsilon}_3 = \frac{\bar{\varepsilon}}{\sigma_{eff}} \left[ \sigma_3 - \frac{1}{2}(\sigma_1 + \sigma_2) \right]. \dots\dots\dots (11)$$

And according to Irgens (2008):

$$\sigma_{eff} = \frac{1}{\sqrt{2}} [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 + 6(\tau_{12}^2 + \tau_{23}^2 + \tau_{13}^2)]^{\frac{1}{2}}. \dots\dots\dots (12)$$

3. The increment of nodal force  $[\Delta F_c(t)]$  in each time interval can be expressed as:

$$[\Delta F_c(t)] = \int_{\Omega} [B]^T [D] [\Delta \varepsilon_t^c] d\Omega. \dots\dots\dots (13)$$

The equation above is applied to the entire salt formation domain.

4. Solve the following equilibrium equation.

$$[K][\Delta \delta^c]_t = [\Delta F_c(t)]. \dots\dots\dots (14)$$

Calculate the creep-induced increment of nodal displacement  $[\Delta \delta^c]_t$  during  $\Delta t$ . The stress increment during this time interval can then be expressed as:

$$[\Delta \sigma^c]_t = [D]([B][\Delta \delta^c]_t - [\Delta \varepsilon_t^c]). \dots\dots\dots (15)$$

5. Add  $[\Delta \delta^c]_t$  and  $[\Delta \sigma^c]_t$  to displacement field  $[\delta_t]$  and stress field  $[\sigma_t]$  of time  $t$ . We can then calculate stress  $[\sigma_{t+\Delta t}]$  and displacement  $[\delta_{t+\Delta t}]$  at the end of this time interval:

$$[\sigma_{t+\Delta t}] = [\sigma_t] + [\Delta \sigma^c]_t. \dots\dots\dots (16)$$



$$[\delta_{t+\Delta t}] = [\delta_t] + [\Delta\delta^c]_t \dots\dots\dots (17)$$

6. Check the total simulated time. If the total simulated time is equal to the specified value, then terminate the calculation; otherwise continue calculation from steps (2) to (5).

The coupled system of equations is solved by using the Newton-Raphson technique (Ypma, 1995), and a Jacobian matrix is generated for the entire system of equations. Incremental corrections are found by use of a linear solver that includes all the solution variables and all the variables are updated at the end of each time increment and input as initial values at the start of the next increment. The program for numerical calculations was developed using finite element code. All the input parameters, such as casing, cement and formation properties, as well as initial and boundary conditions, are shown in **Tables 1** and **Table 2**. It should be noted that the stresses have reached an equilibrium state in autochthonous salt rocks in geological time, so that the two principal horizontal stresses and overburden stress are the same.

**Table 1 - Property Parameters**

	Casing	Cement	Salt
Type	8 5/8 in. K-55	API Class G	halite
Young's Modulus	3E7 psi	2E6 psi	3E6 psi
Poisson's Ratio	0.3	0.2	0.36
Density	0.284 lb/ in <sup>3</sup>	0.0683 lb/in <sup>3</sup>	0.08 lb/ in <sup>3</sup>
Specific Heat	0.113 BTU/lb-°F	0.422 BTU/lb-°F	0.221 BTU/lb-°F
Thermal Conductivity	34.09 BTU/hr-ft-°F	0.8 BTU/hr-ft-°F	2.311 BTU/hr-ft-°F

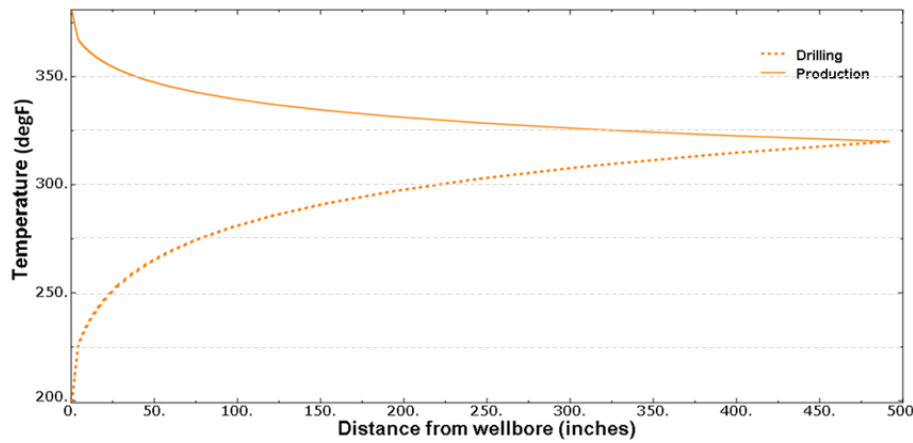
**Table 2 -Initial and Boundary Conditions**

Initial temperature	320 °F
Wellbore temperature during drilling and transition	200 °F
Wellbore temperature during production	380 °F
Wellbore pressure during drilling	3,500 psi
Wellbore pressure during production	1,500 psi
Total horizontal stress	2,300 psi
Overburden stress	2,300 psi

#### 4. Results and Analysis

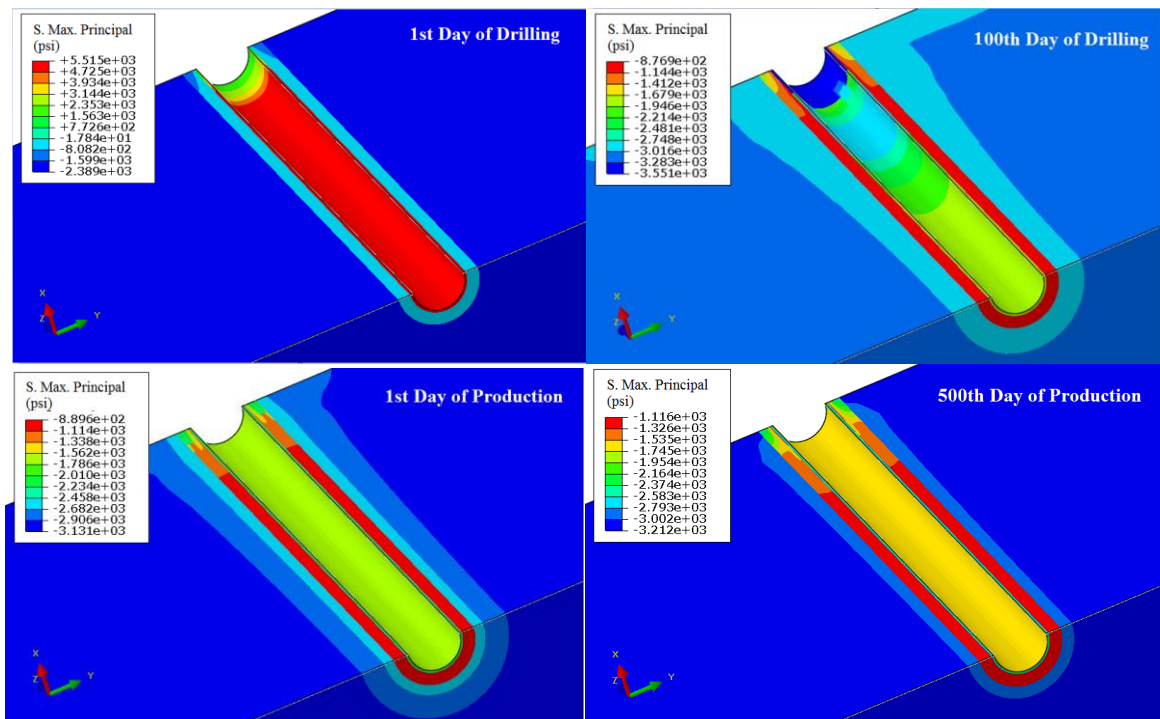
In this section, simulation results are presented to demonstrate the effects of salt creep behavior on wellbore casing during drilling and production under various conditions. And to demonstrate the impact of vertical deformations resulting from overburden stress and salt plastic flow, the simulated results generated from 3D and 2D, plane strain models are compared. Even though the fast salt creep behavior during drilling and cementing operations is not explicitly modeled, its impact on casing eccentricity and resulting non-uniform stress is discussed. In addition, based on the simulation results, possible methods and techniques that can mitigate the severity of salt creep impact and reduce the risks of casing collapse are discussed.

**Fig.6** shows the steady-state temperature distribution along the radial direction of the simulated region during drilling and production. It can be noticed that the temperature is lower during drilling because of drilling fluid circulation and higher during production because of the flow of hydrocarbons from deeper formations. We can also observe that the wellbore temperature impacts mostly the near wellbore region, and as the distance away from the wellbore increases, the wellbore temperature converges in the far field region, where it remains constant. These temperature profiles are discretized and applied in the constitutive equation for the salt formation (Eq. 2) in all the following simulation cases.



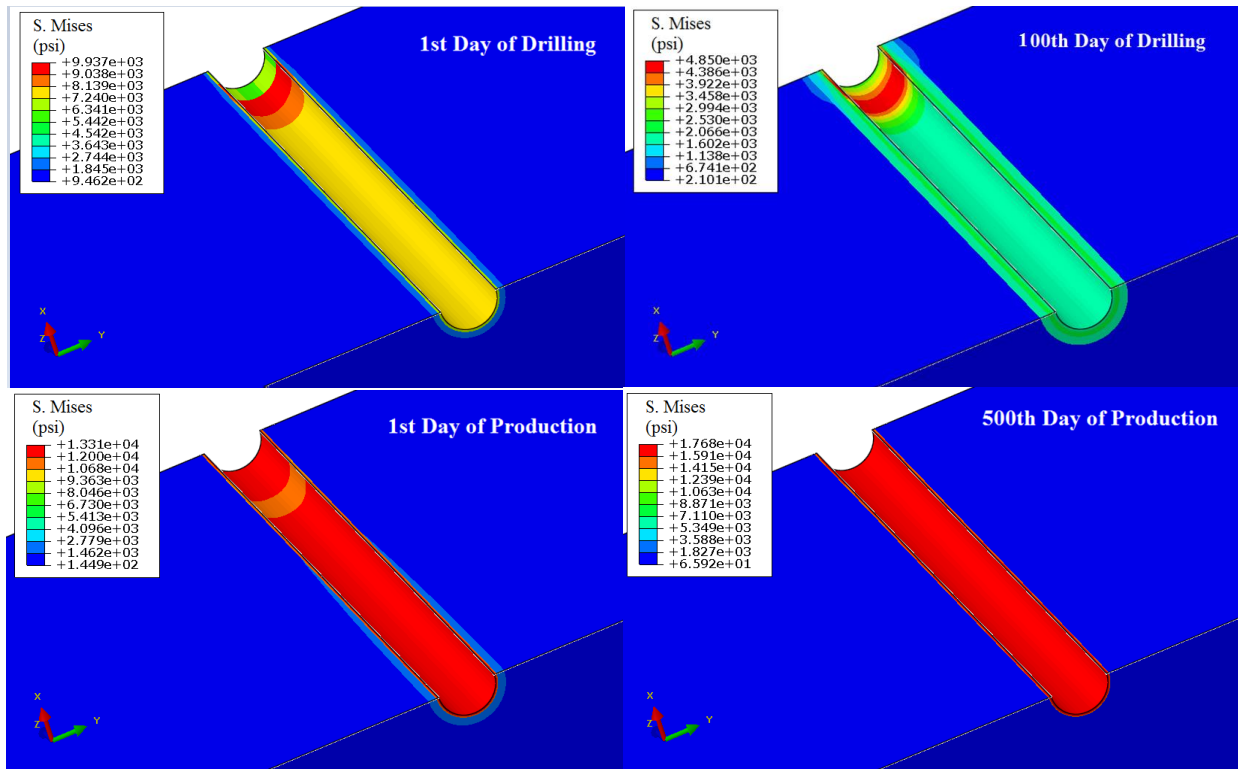
**Fig. 6** Temperature profile along the radius of the simulation model

**Fig.7** shows the distribution of the value of maximum principal stress during simulation. It can be observed that at the beginning of the drilling process, the largest value of maximum principal stress occurs within the casing in the form of tension (positive value). However, as salt starts to deform slowly and exerts extra stress around the wellbore, the largest value of maximum principal stress starts to occur within the cement in the form of compression (negative value). It can also be observed that the absolute value of the maximum principal stress (maximum compression stress) in the cement becomes larger and larger as time goes on, in both drilling and production processes. It should be mentioned that the region around the top end of the casing is interfered by the imposed boundary conditions, so it is excluded in all the analyses presented in this article.



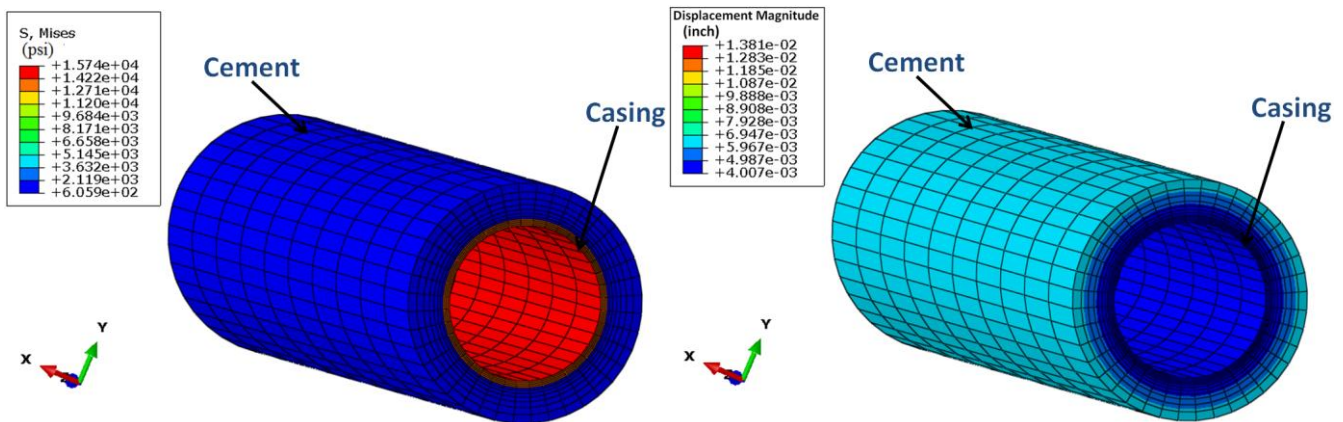
**Fig. 7** Maximum principal stress distribution

One of the most commonly used criteria in determining whether an isotropic and ductile metal will yield when subjected to a complex loading condition is the von Mises Yield criterion. This is accomplished by calculating the von Mises stress and comparing it to the material's yield stress. The concept of von Mises was first introduced by Huber (1904) and von Mises (1913) and then it was recognized that it can be related to deviatoric strain energy. Taylor and Quinney (1931) published results of tests on copper, aluminum, and steel demonstrating that the von Mises stress is a more accurate predictor of the onset of metal yielding than the maximum shear stress criterion. And this criterion became the most widely used predictor of metal yielding to date (Corona and Reedlunn 2013). In the scenarios of wellbore casing failure in salt formation, the most likely failure is metal plastic yield caused by salt flow, rather than the onset of the development of cracks. So von Mises stress is a key quantitative reference value to assess the risk of casing failure. **Fig.8** shows the distribution of von Mises stress within the simulated region. It can be noticed that the maximum von Mises stress always occurs in the casing, but its value declines in the drilling process while it increases during the production phase.



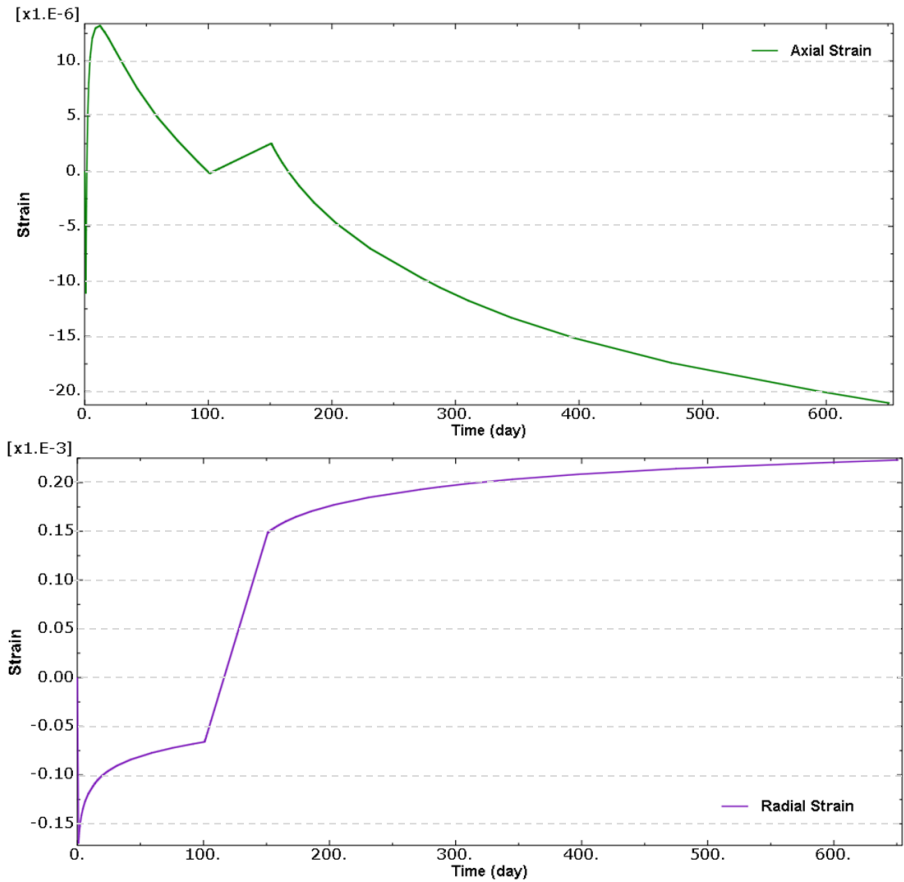
**Fig. 8** Von Mises stress distribution

**Fig.9** shows Von Mises stress and displacement in cement and casing, along with element meshes, after 500 days of production. It clearly indicates that the highest stress concentrates in the casing, even though larger deformation occurs in the cement.



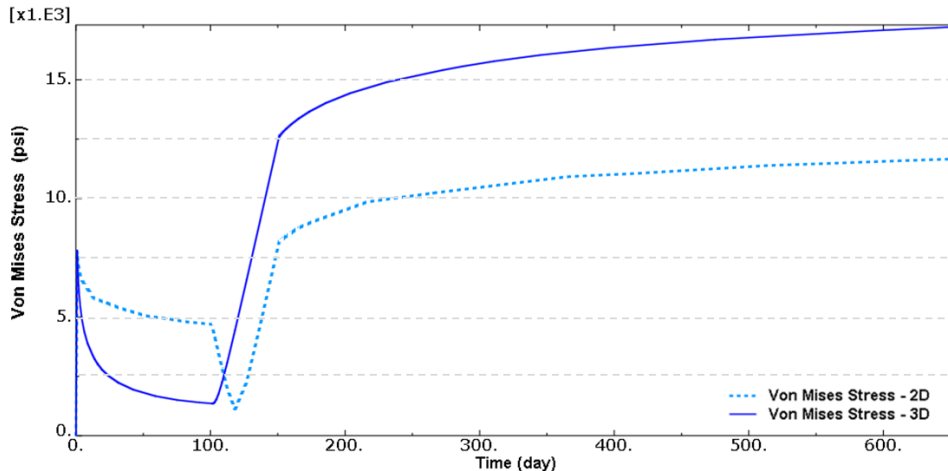
**Fig. 9** Von Mises stress and displacement in cement and casing after 500 days of production.

**Fig.10** shows axial and radial strain in the casing during drilling and production operations. The results indicate that the salt creep behavior pushes the wellbore casing, which leads to the increase of axial and radial strain in both drilling and production phase, and strain in the radial direction is much larger than that in the axial direction. The straight line interval in the figure represents the transitional period, when the wellbore pressure gradually declines from drilling phase (3,500 psi) to production phase (1,500 psi).

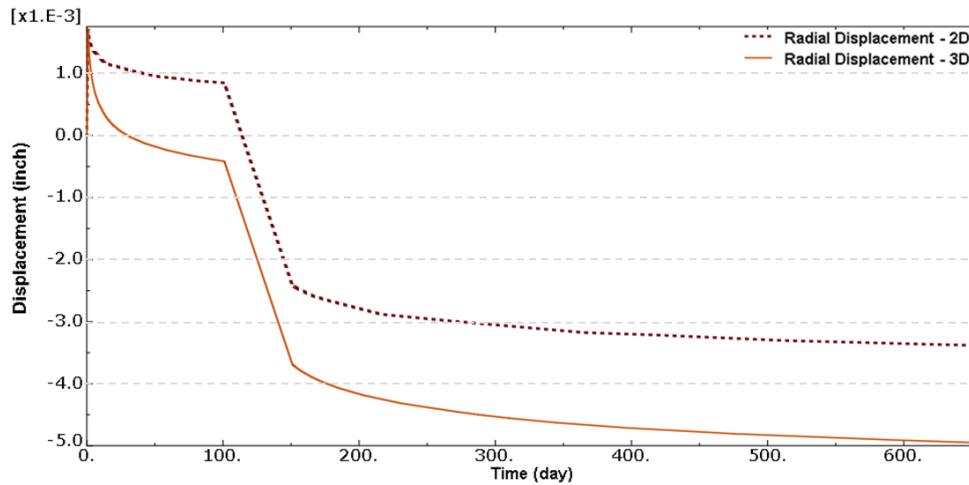


**Fig. 10** Simulated axial and radial strain in the casing

Previous studies investigated the salt creep behavior by using 2D models, either analytically or numerically, under the assumption of plane strain conditions. To compare the results of 2D and 3D models and demonstrate the importance of including vertical deformation in the salt formation, a 2D plane strain model was also developed based on our 3D geomechanical model, and both models are applied to our synthetic simulation case with the same input parameters and boundary conditions. The predicted von Mises stress and radial displacement from both models during drilling, transition, production phases are shown in **Fig.11** and **Fig.12**. The results demonstrate that the general trends predicted by 2D and 3D models are similar: during drilling when the wellbore pressure is higher than the horizontal stress, the von Mises stress in the casing declines gradually and salt creep behavior has a relaxation effect, while during the production phase when the wellbore pressure is lower than the horizontal stress, the von Mises stress increases over time. In both phases, the radius of the casing shrinks as time goes on. However, it can be observed that the difference in the prediction by 2D and 3D models is quite apparent. It seems that the 2D model tends to underestimate the effects of salt creep behavior caused by its negligence of vertical strain during transient salt creep behavior, even though it predicts the same initial values as the 3D model at the beginning of simulation at static conditions.

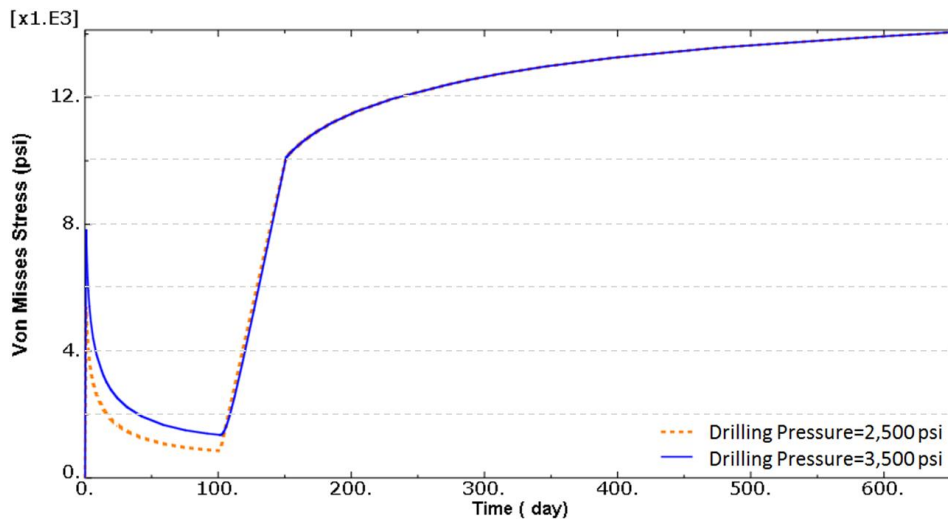


**Fig. 11** Von Mises stress in the casing predicted by 2D and 3D models



**Fig. 12** Radial displacement predicted by 2D and 3D models

As mentioned earlier, our model assumes that the salt section has already been completed and the well is drilling through a target formation that may be thousands of feet below. The 2,300 psi stresses in the salt rock are not necessarily close to the higher in-situ stresses within the underling carbonate reservoir. To differentiate the influence of drilling pressure, a new case with 2,500 psi drilling pressure is simulated and the results are shown in **Fig. 13**. The results suggest that the drilling pressure only impacts stress before production: with lower wellbore pressure, lower von Mises stress is expected. And drilling pressure has a negligible impact for the production phase when wellbore pressure gradually declines to a stable production pressure.



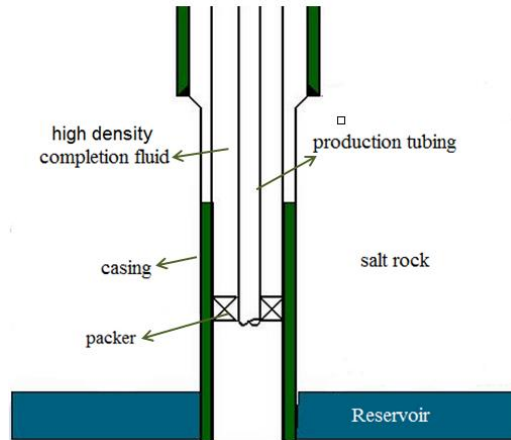
**Fig. 13** Von Mises stress in the casing with different wellbore pressure during drilling

The above simulations are under a steady-state heat transfer assumption. In reality, a transient heat transfer process within the near wellbore region, because of various operation procedures, may affect salt creep behavior around the wellbore. However, in the long term, when temperature does reach steady-state, the impact of creep effects on casing stress under different temperatures tends to converge, because changes in temperature only affect early time stress evolution in the casing, and the long-term creep behavior is mostly controlled by salt properties, shape of wellbore and stress state (Wang et al., 2014). So if our objective is to design a casing system that can ensure long-term well integrity, then a steady-state heat transfer process can still be considered a valid assumption.

## 5. Considerations for Completion Design

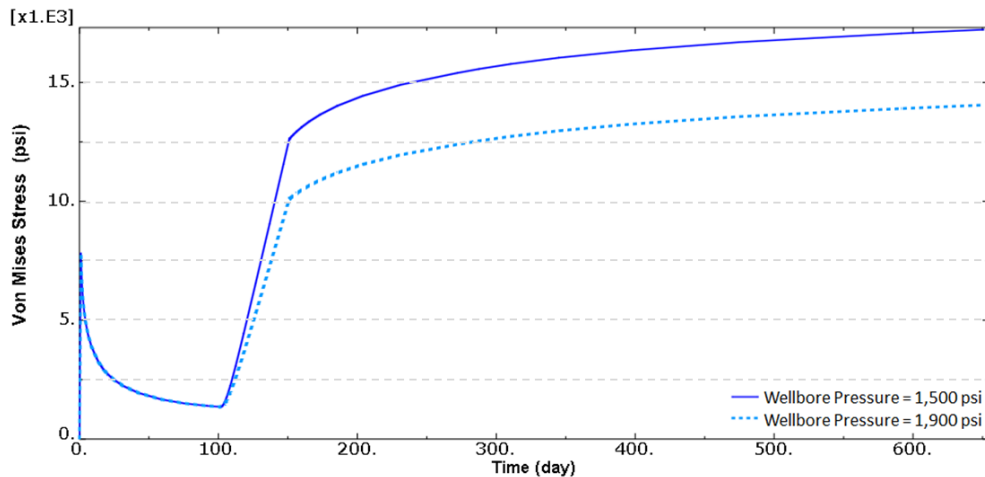
To avoid casing collapse during production, we can either increase the casing strength using string-in-string or thick walled casing (Khalaf and Cairo 1985) or reduce the excessive stress induced by salt creep behavior. For a certain type of salt rock, the severity of creep behavior is primarily controlled by temperature and the differential stress between the pressure acting on the internal surface of the casing and in-situ stresses in the salt formation. Because formation temperature is normally out of engineering control, it is difficult to ease the effects of salt creep behavior by altering the temperature for the entire salt section. However, as discussed in the previous section, if the differential stress can be reduced with certain completion designs, then the salt creep behavior can be possibly alleviated. Here, we propose a method that can significantly reduce the

differential stress, even with a single casing, as shown in **Fig.14**. After the salt formation is cased and cemented, and the well has drilled into the target reservoir, the wellbore can be completed with a production tubing extended down to the bottom of the salt formation and sealed with a packer, so the produced hydrocarbon from the underlying reservoir can flow directly through the production tubing to the surface facility. Fill the annulus between tubing and casing with high-density completion fluid to increase the pressure acting on the internal surface of casing, and leave some empty volume on top of the annulus (e.g., run the completion string into a partially filled well) to account for volume changes from casing deformation. With such a completion design, the section of the wellbore that is below the packer can maintain low pressure to meet production rate demand, while the pressure inside the annulus between casing and production tubing can be elevated to the desired level, by adding high-density completion fluid, to reduce differential stress and mitigate salt creep behavior.



**Fig. 14** Graphic presentation of suggested method to reduce differential stress with tubing-packer completion design

To illustrate the effects of reducing differential stress by our proposed method, the pressure acting on the internal surface of casing is increased from 1,500 psi to 1,900 psi, to reflect the increased hydrostatic pressure from completion fluid. The simulation results are shown in **Fig. 15** and show that the von Mises stress in the casing can be reduced significantly if we can lower the differential pressure between the pressure acting on the internal surface of the casing and in-situ stresses in salt formation.

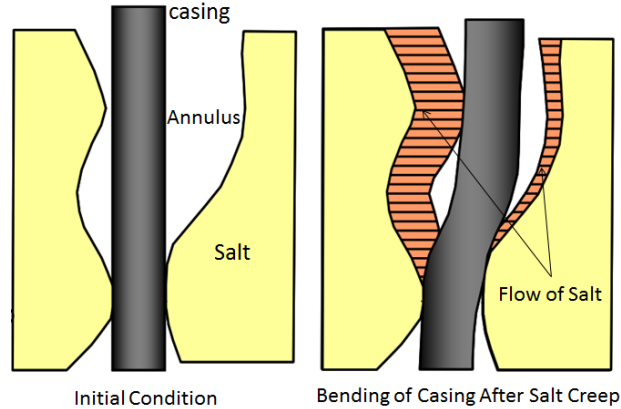


**Fig. 15** Von Mises stress in the casing with different wellbore pressure

For the salt section investigated in this study, we assume that the stresses do not vary according to depth. However, in field case applications, the stress profile can be very different at different depth, especially when the salt formation is thick. For autochthonous salt studied in this article, the deeper the salt formation, the higher the stresses. This also applies to the wellbore pressure profile along the depth, where higher hydrostatic pressure is expected at deeper depth. Detailed investigation of the impact of differential stress along the vertical direction is beyond the scope of this article, but from Fig.15, we can still get a good sense of how stress difference between wellbore pressure and salt in-situ stresses affects long term salt creep behavior on casing stress. A more comprehensive study on the effects of varying differential stress has been done by using plane strain models (Wang et al., 2014).

## 6. The Effects of Casing Eccentricity

Casing eccentricity has always been considered as a problem during the design and operations of drilling and primary cementing in salt formations, because of an irregular and tortuous shape of the wellbore, caused by fast salt creep behavior, as shown in **Fig.16**. It is necessary to use enough centralizers on the casing to maintain the casing at the center of the wellbore. If the hole is tortuous and there are not enough centralizers placed on the casing, casing eccentricity is inevitable (Matsuzawa et al. 2006; Cheatham Jr. and McEver, 1964).

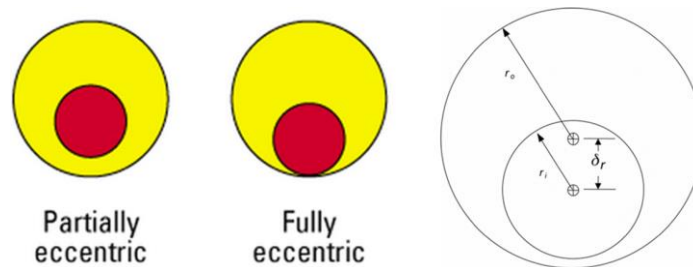


**Fig.16** Tortuous wellbore caused by salt mobility

As mentioned in the previous section, to model fast salt creep behavior during drilling and cementing operations explicitly is beyond the scope of this study, but its adverse impact and the resulting consequence of casing eccentricity should be carefully examined. Because casing design and safety factor estimation based on stress calculations that are under the assumption of concentric casing placement may lead to erroneous or, at least, inaccurate results. **Fig. 17** shows the graphical representation of casing eccentricity. The casing eccentricity  $\epsilon$  is a dimensionless indicator that is directly related to the deflection of the casing in the borehole through the following equation:

$$\epsilon = \frac{\delta_r}{r_0 - r_i} \quad (18)$$

$\delta_r$  is the deflection of the casing from the center of the borehole (distance between the center of the hole and center of the casing),  $r_0$  is the radius of the borehole, and  $r_i$  is the outside radius of the casing).

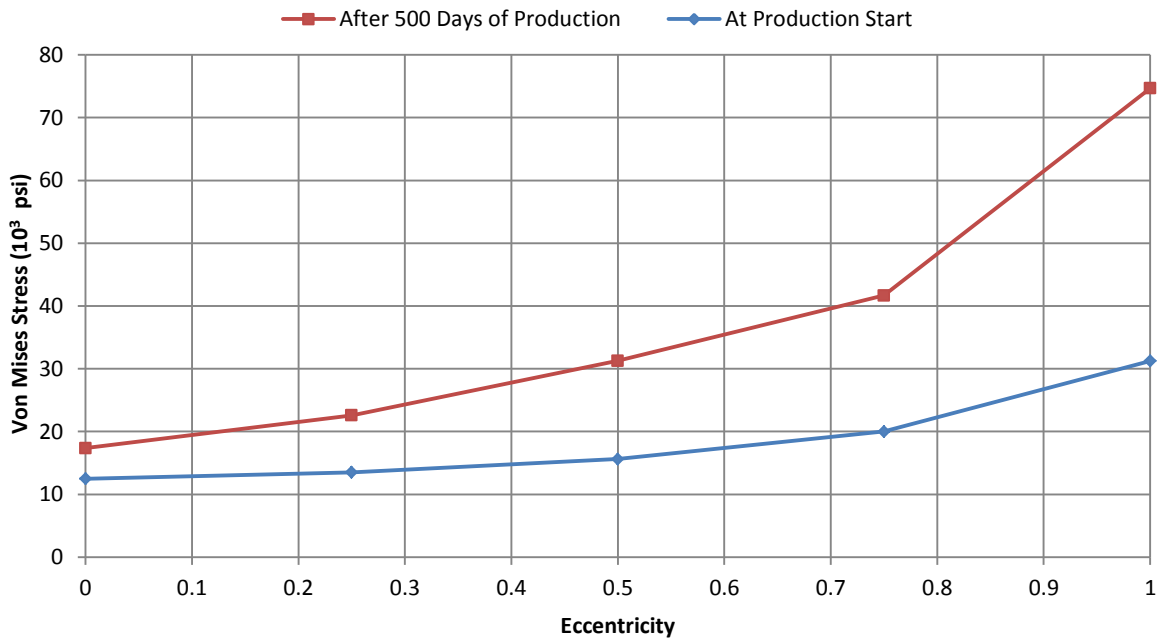


**Fig.17** Graphical representation of casing eccentricity

To investigate the effects of eccentricity on the casing stress loading in a salt formation, four scenarios ( $\epsilon=0.25, 0.5, 0.75,$  and  $1$ ) are simulated to reflect the increased severity of fast salt creep. Because the maximum von Mises stress in the casing always occurs during production, here we only analyze the stress in the casing at the end of 500 days of production. It should be kept in mind that in a specific case, the predicted von Mises stress should be selected at a much longer desired production time to match against the casing yield strength.

**Fig. 18** summarizes the maximum von Mises stress in the casing with different eccentricity after 500 days of production. To differentiate the two mechanisms that both contribute to a higher stress in the casing with increasing eccentricity, the simulation results at the beginning of production are also included. As it can be seen, the maximum von Mises stress increases as eccentricity increases, even at the beginning of production. This is caused by the non-uniform stress loading on the casing because of eccentric casing-cement geometry, the higher the eccentricity, the severer the non-uniform stress distribution. The results also indicate clearly that the eccentricity has a large influence on casing stress over time, and the ratio maximum von Mises stress in the casing after 500 days of production to that at the beginning of production increases approximately from 1.4 to 2.1 as eccentricity increases, which reveals that the eccentricity can substantially amplify the effects of salt creep behavior on casing stress. It can be also observed that the combined effects of both salt creep behavior

and non-concentric geometry can lead the maximum von Mises stress in the casing to increase more than 4 times after 500 days of production. So casing eccentricity resulting from poor drilling and cementing operations can significantly increase the risks of casing failure during the long term production life in a salt formation.



**Fig. 18** Maximum von Mises stress in the casing with different eccentricity

It can be seen that even though fast salt creep dissipates quickly and only impacts drilling and cementing operations, its adverse consequences on casing eccentricity can significantly intensify the effects of slow, stable salt creep behavior on the long term casing stress loading, because of the associated non-uniform stress concentrated in the near wellbore region. So it is imperative to have a strong quality control on drilling and cementing fluids to prevent salt dissolution and ensure enough centralizers are placed during operations to minimize the occurrence of casing eccentricity.

## 7. Conclusions and Discussion

As the industry ventures out into deeper regions of water and large hydrocarbon deposits that have been found below salt formations, it is essential to understand the geomechanical aspects of the impact of salt rock and associated challenges when planning drilling and completion operations. Wellbore failure can lead to catastrophic consequences, especially in deep water scenarios. In this paper, a 3D geomechanical model is presented to predict the effects of salt creep behavior on the stress loading in the wellbore casing, by considering salt formation, cement and wellbore casing as an integrated system. Example cases are simulated with this presented model, which not only accounts for the fact that the pressure and temperature conditions around the well will vary greatly during drilling and production, but also examines the long-term effect of salt creep behavior by simulating the entire life of the well. From this study, it has been observed that:

1. 2D plane strain model is not applicable to salt deformation problems because it ignores the vertical strain imposed by overburden stress, so it underestimates of the effects of salt rock mobility on the stress loading and deformation of wellbore casing.
2. The differential stress between pressure acting on the internal surface of casing and stress in the salt formation determines the evolution of the von Mises stress in the casing. When the wellbore pressure is higher than the formation stress, the von Mises stress decreases over time, while when the wellbore pressure is lower than the formation stress, the von Mises stress increases over time.
3. It is possible to mitigate the excessive casing stress exerted by salt creep during production using high density completion fluid with a tubing-packer completion design (using the production tubing to transport hydrocarbons and filling the annulus with completion fluid of the desired density), to increase the pressure acting on the internal surface of casing and reduce the differential stress.
4. The casing eccentricity induced by fast salt creep behavior can have a large impact on casing bearing stress, because it exacerbates both the non-uniform stress loading and salt creep impact. So besides selecting a casing with the appropriate yield strength for completion, improving the quality of drilling and cement in a salt formation can



substantially reduce the risks of casing collapse, e.g., centralizers should be used more frequently when expecting high differential stress during operations.

In summary, fast salt creep effects can be reduced by planning drilling and cementing operations properly to minimize casing eccentricity, and stable, long-term salt creep effects can be mitigated by using a suitable completion design. It should be emphasized that the detailed process of drilling and cementing operations in a salt formation is not explicitly modeled in this article, but the effects of fast salt creep behavior during these processes are represented by casing eccentricity implicitly. Nevertheless, the idea of unifying drilling, cementing and production phases and to model salt rock damage and associated fluid/flow interactions explicitly is certainly worth pursuing in future research efforts, and this requires a better understanding of the fully coupled physical process and the use of an adaptive mesh to represent the continuously changing geometry and boundary conditions of the well during these various stages.

## Nomenclature

$B$	= Geometric stiffness matrix, 1/in.
$C$	= Heat capacity, BTU/lb- $^{\circ}$ F
$D$	= Elasticity matrix, psi
$E$	= Material stiffness, psi
$F$	= Nodal force, lbf
$K$	= Stiffness matrix, lbf/in.
$Q$	= Activation energy, $Q=12$ kcal/mol
$R$	= Universal gas constant, $R=0.003574$ kcal/mol $\cdot$ $^{\circ}$ F
$S$	= Surface area, $in.^2$
$T$	= Formation temperature, $^{\circ}$ F
$T_0$	= Reference temperature, $^{\circ}$ F
$V$	= Generic volume, $in.^3$
$f$	= Body force per unit volume, lbf/ $in.^3$
$n$	= Exponent dependent on creep mechanism
$q$	= Heat source term, BTU/ $in.^3 \cdot hr$
$r_0$	= Radius of the borehole, in.
$r_i$	= Outside radius of the casing, in.
$t$	= Generic time, hr.
$\Delta t$	= Time interval for incremental steps, hr.
$\gamma$	= Surface traction per unit area, lbf/ $in.^2$
$\delta$	= Displacement, in.
$\delta_i$	= Initial displacement, in.
$\delta_r$	= Deflection of the casing from the center of the borehole, in.
$\varepsilon$	= Strain
$\bar{\varepsilon}_0$	= Steady state creep rate at reference conditions, 1/hr
$\bar{\varepsilon}_s$	= Steady state creep rate, 1/hr
$\bar{\varepsilon}_t$	= Transient creep rate, 1/hr
$\bar{\varepsilon}$	= Strain rate owing to creep, 1/hr
$\epsilon$	= Casing eccentricity
$\lambda$	= Thermal conductivity, BTU/hr-ft- $^{\circ}$ F
$\rho$	= Density, $lb/in.^3$
$\sigma$	= Stress, psi
$\sigma_i$	= Initial stress, psi
$\sigma_{eff}$	= Creep effective stress, psi
$\sigma_o$	= Reference effective stress, psi
$\tau$	= Relaxation time, hr.
$v$	= Velocity, in/hr.
$\Omega$	= Simulation domain, $in.^3$
$\nabla \cdot$	= Divergence operator

## References

- Albertz, M., Beaumont, C., Shimeld, J.W., Ings, S.J. and Gradmann, S., 2010. An investigation of salt tectonic structural styles in the Scotian Basin, offshore Atlantic Canada: 1. Comparison of observations with geometrically simple numerical models. *Tectonics*, 29(4). <http://dx.doi.org/10.1029/2009TC002539>
- Barker, J.W., Feland, K.W., and Tsao, Y.H. 1994. Drilling long salt sections along the U.S. Gulf Coast. *SPEDC*, 9(3): 185–188. <http://dx.doi.org/10.2118/24605-PA>
- Beasley, C., Fiduk, J., Bize, E., Boyd, A., Frydman, M., Zerilli, A., Dribus, J., Moreira, J., and Pinto, A. 2010. Brazil's Presalt Play. *Oilfield*

Review. 22(3),28-37. [https://www.slb.com/~media/Files/resources/oilfield\\_review/ors10/aut10/03\\_presalt.pdf](https://www.slb.com/~media/Files/resources/oilfield_review/ors10/aut10/03_presalt.pdf)

Beltrao, R. L. C., Sombra, C. L., Lage, A. C. V. M., Netto, J. R. F., and Henriques, C. C. D. 2009. SS: Pre-salt Santos basin - Challenges and New Technologies for the Development of the Pre-salt Cluster, Santos Basin, Brazil. Offshore Technology Conference, Houston, Texas, 4-7 May. <http://dx.doi.org/10.4043/19880-MS>

Carslaw, H.S., and Jaeger, J.C. 1959, Conduction of Heat in Solids, 2<sup>nd</sup> edition, Oxford University Press.

Chatar, C. and M.D. Imler. 2010. Overcoming a Difficult Salt Drilling Environment in the Gulf of Mexico: A Case Study. Paper SPE 128192 presented at the IADC/SPE Drilling Conference and Exhibition, New Orleans, Louisiana, 2-4 February. <http://dx.doi.org/10.2118/128192-MS>

Cheatham Jr., J.B., and McEver, J.W.1964. Behavior of Casing Subjected to Salt Loading. Journal of Petroleum Technology:1069-75. <http://dx.doi.org/10.2118/828-PA>

Chitale, V., Alabi, G., Kasten, R., Taylor, A., and Hoenmans, P. 2014. Learning From Deployment of a Variety of Modern Petrophysical Formation Evaluation Technologies and Techniques for Characterization of a Pre-Salt Carbonate Reservoir: Case Study From Campos Basin, Brazil. SPWLA 55th Annual Logging Symposium, Abu Dhabi, United Arab Emirates, 18-22 May.

Corona, E. and Reedlunn, B.. 2013. A review of macroscopic ductile failure criteria. Sandia Report SAND2013-7989, Sandia National Laboratories.

Costa, A. M., Poiate, E., Amaral, C. S., Goncalves, C. J, Falcao, J. L., & Pereira, A. 2010. Geomechanics Applied to the Well Design Through Salt Layers In Brazil:A History of Success. Paper presented at the 44th U.S. Rock Mechanics Symposium and 5th U.S.-Canada Rock Mechanics Symposium, Salt Lake City, Utah, 27-30 June.

Costa, A.M., C.S. Amaral, E. Poiate Jr, A.M.B. Pereira, L.F. Martha, M. Gattass and D. Roehl. 2012. Underground Storage of Natural Gas and CO2 in Salt Caverns in Deep and Ultra-deep Water Offshore Brazil. Harmonising Rock Engineering and the Environment: 1659-1664.

Dribus JR, Jackson MPA, Kapoor J and Smith MF: "The Prize Beneath the Salt," Oilfield Review 20, no. 3 (Autumn 2008): 4-17. [http://www.slb.com/~media/Files/resources/oilfield\\_review/ors08/aut08/the\\_prize\\_beneath\\_the\\_salt.pdf](http://www.slb.com/~media/Files/resources/oilfield_review/ors08/aut08/the_prize_beneath_the_salt.pdf)

Dusseault, M. B., Maury, V., Sanfilippo, F., and Santarelli, F. J. 2004. Drilling Around Salt: Risks, Stresses, And Uncertainties. The 6th North America Rock Mechanics Symposium (NARMS), Houston, Texas, 5-9 June

Farmer,P., Miller,D., Pieprzak,A., Rutledge,J., and Woods,R. 1996. Exploring the Subsalt. Oilfield Review. 8(1), 50-64. [https://www.slb.com/~media/Files/resources/oilfield\\_review/ors96/spr96/ors96\\_salt\\_p50\\_64.pdf](https://www.slb.com/~media/Files/resources/oilfield_review/ors96/spr96/ors96_salt_p50_64.pdf)

Garland, J., Neilson, J., Laubach, S.E. and Whidden, K.J., 2012. Advances in carbonate exploration and reservoir analysis. Geological Society, London, Special Publications, 370(1), pp.1-15. <http://dx.doi.org/10.1016/10.1144/SP370.15>

Goodwin, K.J. 1984. Salt-Free Cement – An Alternative to Collapsed Casing in Plastic Salts. Journal of Petroleum Technology:320-4. <http://dx.doi.org/10.2118/10885-PA>

Greenhalgh, J., Borsato, R., Mathew, F., Duncan-Jones, G., Primenta, I., da Silva, J. M., and da Silva, L. N. 2012. Pre-Salt Hydrocarbon Prospectivity in the Kwanza and Benguela Basins of Offshore Angola. The SEG Annual Meeting, Las Vegas, Nevada, 4-9 November.

Hansen, F. D. 2011. Salt Repository Geomechanics Research Agenda. The 45th U.S. Rock Mechanics and Geomechanics Symposium, San Francisco, California, 26-29 June.

Hashiguchi, K. 2014. Viscoplastic Constitutive Equations. Lecture Notes in Applied and Computational Mechanics, 69:307-316. [http://dx.doi.org/10.1007/978-3-642-35849-4\\_12](http://dx.doi.org/10.1007/978-3-642-35849-4_12)

Hencky, H.Z.1924. Zur Theorie plastischer Deformationen und der hierdurch im Material hervorgerufenen Nachspannungen. Journal of Applied Mathematics and Mechanics, Vol. 4, pp. 323. (in German). <http://dx.doi.org/10.1002/zamm.19240040405>

Huber, M.T. 1904. Wlasciwa praca odkształcenia jako miara wyteżenia material. Czasopismo Techniczne, Lemberg, Austria, Vol. 22, pp. 181. (in Polish)

Irgens Fridtjov. 2008. Continuum Mechanics. Berlin, Germany : Springer

Jin, J. and Cristescu, N.D., 1998. An elastic/viscoplastic model for transient creep of rock salt. International Journal of Plasticity, 14(1), pp.85-107. [http://dx.doi.org/10.1016/S0749-6419\(97\)00042-9](http://dx.doi.org/10.1016/S0749-6419(97)00042-9)

Khalaf F and Cairo U. 1985. Increasing casing collapse resistance against salt-induced loads. Middle East Oil Technical Conference and Exhibition, Bahrain, 11-14 March. <http://dx.doi.org/10.2118/13712-MS>

Lao, K., Bruno, M. S., and Serajian, V. 2012. Analysis of Salt Creep and Well Casing Damage in High Pressure and High Temperature Environments. Offshore Technology Conference, Houston, Texas, USA, 30 April-3 May.

Mackay, F., Inoue, N., da Fontoura, S. A. B., and Botelho, F. 2008. Analyzing Geomechanical Effects While Drilling Sub Salt Wells Through Numerical Modeling. SPE Indian Oil and Gas Technical Conference and Exhibition, Mumbai, India, 4-6 March. <http://dx.doi.org/10.2118/113216-MS>

Mathur, R., Seiler, N., Srinivasan, A., and Pardo, N. O. 2010. Opportunities and Challenges of Deepwater Subsalt Drilling. IADC/SPE Drilling Conference and Exhibition, New Orleans, Louisiana, USA, 2-4 February. <http://dx.doi.org/10.2118/127687-MS>

Matsuzawa, M., Umezu, S., Yamamoto, K. 2006. Natural Hydrate Exploration Campaign in the Nankai-Trough Offshore Japan. IADC/SPE Drilling Conference, Miami, Florida, USA, 21-23 February. <http://dx.doi.org/10.2118/98960-MS>

- Munson, D.E. 2004. M-D Constitutive Model Parameters Defined For Gulf Coast Salt Domes And Structures. The 6th North America Rock Mechanics Symposium, Houston, Texas, 5–9, June.
- O'Brien J and Lerche I. 1994. Understanding Subsalt Overpressure May Reduce Drilling Risks. *Oil & Gas Journal* 92:28–34.
- Pattillo, P.D. and Rankin, T.E. 1981. How Amoco Solved Design Problems in the Gulf of Suez. *Petroleum Engineer International*, 86-112.
- Poiate Jr, E. 2012. Mecânica das Rochas e Mecânica Computacional para Projeto de Poços de Petróleo em Zonas de Sal. DSc. Thesis. Rio de Janeiro, Departamento de Engenharia Civil, Pontifícia Universidade Católica do Rio de Janeiro (in Portuguese).
- Rike, E.A., Bryant, G.A., and Williams, S.D. 1986. Success in Prevention of Casing Failures Opposite Salts, Little Knife Field, North Dakota. *SPE Drilling Engineering*, 131–40. <http://dx.doi.org/10.2118/12903-PA>
- Salehabadi, M. 2009. Finite Element Modeling of Casing in Gas-Hydrate-Bearing Sediments. *SPEDC*, 24(4): 545–552. <http://dx.doi.org/10.2118/113819-PA>
- Sobolik, S. R., and Lord, A. S. 2014. Case Study of the Impact of Prior Cavern Abandonment on Long-Term Oil Storage at a Strategic Petroleum Reserve Site. The 48th U.S. Rock Mechanics and Geomechanics Symposium, Minneapolis, Minnesota, 1-4 June.
- Taylor, G.I., and Quinney, H. 1931. The Plastic Distortion of Metals. *Phil. Trans. R. Soc., London*, Vol. A230, pp. 323. <http://dx.doi.org/10.1098/rsta.1932.0009>
- Thompson, D.L., Stilwell, J.D. and Hall, M., 2015. Lacustrine carbonate reservoirs from Early Cretaceous rift lakes of Western Gondwana: Pre-salt coquinas of Brazil and West Africa. *Gondwana Research*, 28(1), pp.26-51. <http://dx.doi.org/10.1016/j.gr.2014.12.005>.
- Von Mises, R. 1913. *Mechanik der Festen Körper im Plastisch Deformablen Zustand*, *Nachr. Ges. Wiss. Göttingen*, pp. 582. (in German). <http://eudml.org/doc/58894>
- Wang, H., Kumar, A., & Samuel, R. 2014. Geomechanical Modeling of Wellbore Stability in Anisotropic Salt Formation. Paper SPE 169458 presented at the SPE Latin America and Caribbean Petroleum Engineering Conference, Maracaibo, Venezuela, 21-23 May. <http://dx.doi.org/10.2118/169458-MS>
- Western P and Ball G. 1992. 3D Prestack Depth Migration in the Gulf of Suez: A Case Study. *Geophysical Prospecting*. 40: 379-402. <http://dx.doi.org/10.1111/j.1365-2478.1992.tb00533.x>
- Willson SM., Fossum AF., and Fredrich JT. 2003. Assessment of salt loading on well casing. *SPE Drill and Completion*, 18:13–21. <http://dx.doi.org/10.2118/74562-MS>
- Ypma, T.J. 1995 Historical development of the Newton-Raphson method, *SIAM Review*, 37(4), 531–551. <http://www.jstor.org/stable/2132904>
- Zhao, H., Chen, M., and Wang, J. 2011. Salt loading on casing in cased wellbore sections. *International Journal of Rock Mechanics & Mining Sciences*, 48:501–505. <http://dx.doi.org/10.1016/j.ijrmms.2011.02.011>
- Zienkiewicz, O.C., and Taylor, R.L. 2005. *The Finite Element Method*, 5th edition, London: Elsevier Pte Ltd.