A THERMOPOROELASTIC (T-P-E) MODEL DEVELOPED FOR CORE TRIPPING FAILURE ANALYSIS

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This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Vienna, Austria, 27 August – 1 September 2017

ABSTRACT

During tripping of cores to the surface, the core properties, in particular the mechanical properties, are adversely altered due to the drop of the confining pressure, pore pressure drop (i.e. hydraulic effect), and the temperature drop (i.e. the thermal effect) at the boundary of the core sample. This is while, depending on the core properties, the inner pore pressure and temperature may not change as quickly as at the outer boundary. This differential change of properties between the inner and outer part of the core sample may consequently cause the tensile failure of the core resulting in micro-fractures in the rock matrix. In this study, a safe core retrieval procedure is presented considering the hydraulic diffusivity using a thermoporoelastic (T-P-E) approach.

We developed a T-P-E model that incorporates the change of the confining pressure and temperature and the associated hydraulic and thermal effects in the core. The model calculates the pore pressure distribution and the tensile induced stresses within the core sample. Then, the induced stresses are summed-up to compare with the limits in the Griffith's tensile failure criterion to determine if the sample can be retrieved in a preserved manner. The T-P-E method will be applied to study the core retrieval of a very tight sample for different initial bottomhole depths.

The simulations show comparable results with another method developed in Fluent. The results indicated that the contribution of thermally induced stresses is much less significant than the hydraulically induced stresses for sample failure. We further show that the hydraulic diffusivity coefficient and the in-situ stress state conditions are the controlling parameters for safe tripping operations.

INTRODUCTION

A major challenge in coring during the oil and gas drilling operations is the potential for mechanical core damage which can occur during tripping [1–3]. This occurs due to tensile failures developed as a result of an extremely fast tripping rate. This phenomenon is more manifest in retrieving tight core samples. The resulting micro-fractures created in the sample due to this process alter the physical and mechanical rock properties such as porosity, permeability, Uniaxial Compressive Strength (UCS), Young's Modulus (E) and might lead to misinterpretation of subsequent core analysis. Therefore, the lab results may not represent the real rock properties, which will be used to characterize the reservoir.

To date, most of the core retrieval procedures and schedules have been generally based on generic methods and rules of thumb [4]. Most of these tripping-out schedules just indicate that the tripping should be conducted more slowly in an interval near the surface (e.g. 100-400 m). The recent research studies do not consider the changes in the mechanical and thermal properties of the core due to the tripping [5–7]. In the present study, we aim for a T-P-E model simulating the induced stresses and possible tensile failure during core tripping process.

TRIPPING INDUCED STRESSES AND FAILURE CRITERION

During tripping of the core to the surface, the pore pressure at the outer boundary of the core drops as it is in contact with the hydrostatic pressure exerted by the drilling fluid. This is while the change in pore pressure and temperature of the core does not equally distribute moving towards the center of the core.

During tripping, the induced stresses in the core body as a function of external stresses are the radial and tangential (hoop) stresses as depicted in Figure 1. The induced radial stresses (σ_{rr}) are created in radial direction of the sample. The induced hoop stresses ($\sigma_{\theta\theta}$) are the compressional stresses around the circumference of the sample.

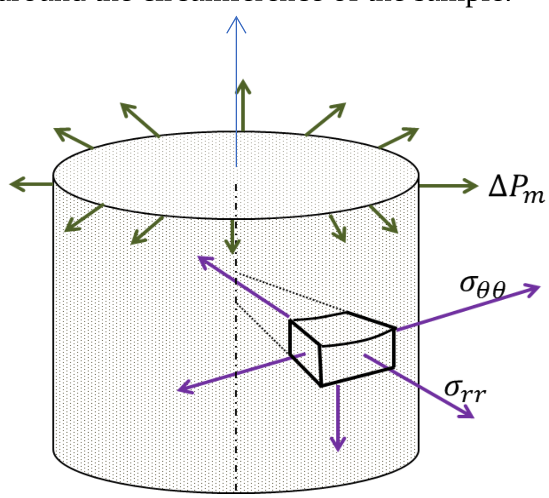

Figure 1: Two dimensional Induced Stresses in the Core during tripping out

If the tripping-induced stresses in the core exceed its tensile strength, the core may undergo tensile failure [5, 6, 8]. It has been noted that this tensile failure attributes the induced tensile stresses to the pore pressure and fluid flow/diffusion out of the core [1, 5, 6, 8] and the Griffith's failure criterion has been applied [9, 10]:

$$\Delta\sigma_3' - T_s \geq 0 \qquad \text{if} \quad (\Delta\sigma_1' + 3\Delta\sigma_3') > 0, \tag{1}$$

where for the case of core tripping, $\Delta\boldsymbol{\sigma}_1'$ and $\Delta\boldsymbol{\sigma}_3'$ are the induced effective maximum and minimum principal stresses, respectively. For the cylindrical sample, $\Delta\boldsymbol{\sigma}_3'$ can be either the differential effective radial $\Delta\boldsymbol{\sigma}_{\mathbf{rr}}'$ or the hoop stress difference $\Delta\boldsymbol{\sigma}_{\boldsymbol{\theta\theta}}'$ as depicted in Figure 2.

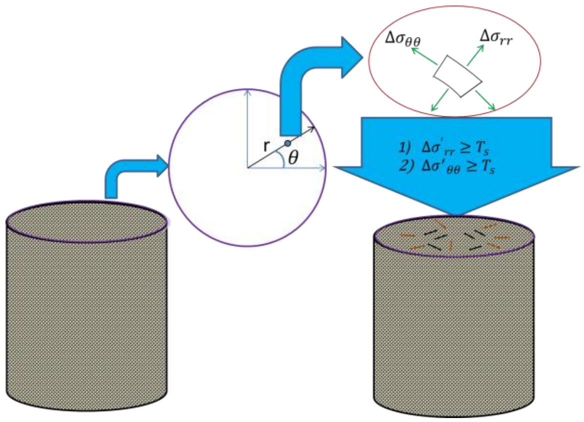

Figure 2: Griffith's Tensile Failure Criterion to Predict Failure during Core Tripping

THERMOPOROELASTICITY (T-P-E)

T-P-E is the study of rock mechanical behavior and how the rocks undergo deformation and failure in response to the effects of imposing a change or difference to confining stress, pore pressure, and also temperature [11–13]. In other words, it describes the interaction and coupling between the confining stress difference, the pore fluid pressure difference and the temperature difference.

Basically, in T-P-E the initial state constitutes the basis of the problem. Therefore, the T-P-E parameters are considered as their difference from their initial values. These parameters include the confining stress/pressure difference ΔP_c, the pore pressure difference ΔP_p, and the temperature difference ΔT. Therefore, the initial T-P-E parameters are considered zero. It is also assumed that these imposed changes occur immediately at the time of nearly zero (t=0$^+$). Then, the new conditions last for a certain period of time Δt (Figure 3). At the end of each time period, the effects of the changes in the conditions on the interested parameters can be analytically determined. The interesting parameters for each problem can be the induced pore pressures or the induced stresses. It is noted that the core tripping cannot be represented by the original T-P-E as the sample is not retrieved from the bottomhole immediately, but it is being tripped gradually during a time interval.

To use this method, first the T-P-E constitutive equations are considered. Then, the diffusivity equations, their initial and boundary conditions are taken into account. Next, the corresponding analytical solutions are found. Finally, using the constitutive equations, the equations for the induced radial and hoop stresses can be analytically derived.

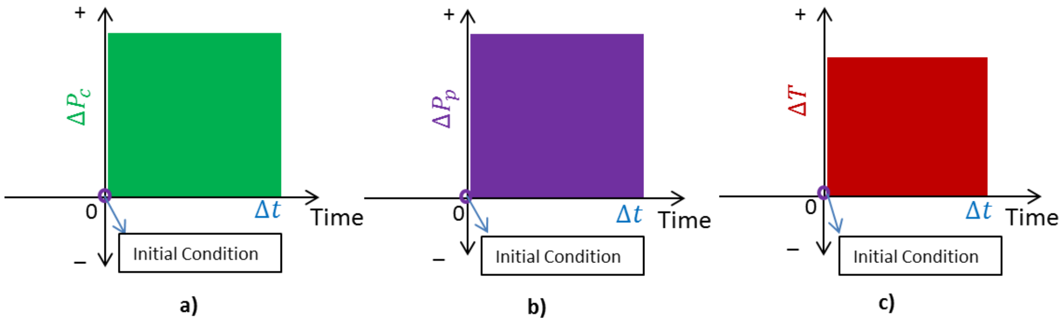

Figure 3: Initial and Boundary Conditions Using Original Thermoporoelasticity

CONSTITUTIVE EQUATIONS

The main constitutive equations used in T-P-E are [1, 11, 12, 14, 15]:

$$\Delta\sigma_{rr} = 2G\epsilon_{rr} + 2G\frac{\upsilon}{1-2\upsilon}(\epsilon_{rr} + \epsilon_{\theta\theta}) - a\Delta P_p \tag{2}$$

$$\Delta\sigma_{\theta\theta} = 2G\epsilon_{\theta\theta} + 2G\frac{\upsilon}{1-2\upsilon}(\epsilon_{rr} + \epsilon_{\theta\theta}) - a\Delta P_p \tag{3}$$

$$\Delta\sigma_T = K_{T(}\epsilon_T - \frac{\alpha_m}{3}\Delta T) \tag{4}$$

Where G is the shear modulus; υ is the Poisson's ratio; ϵ_{rr} is the radial strain; $\epsilon_{\theta\theta}$ is the tangential strain; ΔP_p is the differential induced pore pressure; $\Delta\sigma_T$ is the differential induced thermal stress; K_T is the isothermal bulk modulus*;* ϵ_T is the thermal strain; α_m is the bulk thermal expansion coefficient.

DIFFUSIVITY EQUATIONS

There are two hydraulic and thermal diffusivity equations. The coupled T-P-E diffusivity equation is expressed as [14–16]:

$$\frac{\partial\Delta P_p}{\partial t} = \eta\left(\frac{\partial^2\Delta P_p}{\partial r^2} + \frac{1}{r}\frac{\partial\Delta P_p}{\partial r}\right) + \eta'\frac{\partial\Delta T}{\partial t}, \tag{4}$$

where t is the time; η is the hydraulic diffusivity coefficient; η' is the corresponding coupling coefficient by the differential temperature on the pore pressure. The first and second terms on the right, respectively, pertain to the pressure diffusion and temperature gradient.

The thermoelastic equation is:

$$\frac{\partial\Delta T}{\partial t} = \eta_T\left(\frac{\partial^2\Delta T}{\partial r^2} + \frac{1}{r}\frac{\partial\Delta T}{\partial r}\right) + \eta'_T\left[\frac{\partial T}{\partial r}\frac{\partial\Delta P_p}{\partial r} + T\left(\frac{\partial^2\Delta P_p}{\partial r^2} + \frac{1}{r}\frac{\partial\Delta P_p}{\partial r}\right)\right], \tag{5}$$

where η_T is the thermal diffusivity coefficient; η'_T is the coupling coefficient by the pore pressure difference on the temperature. The first, second, and third terms on the right hand side of the above equation, respectively, indicate the heat conduction, the heat convection, and the pore pressure diffusion due to the temperature effect.

INITIAL CONDITIONS

In T-P-E, the initial state constitutes the basis of the problem. Therefore, prior to tripping, the initial conditions within the sample are:

- ✓ The confining pressure difference at t=0:

$$\Delta P_c(r,0) = 0 \tag{6}$$

- ✓ The pore pressure difference at t=0:

$$\Delta P_p(r,0) = 0 \tag{7}$$

- ✓ The temperature difference at t=0:

$$\Delta T(r,0) = 0 \tag{8}$$

BOUNDARY CONDITIONS:

Using the original T-P-E, there are three conditions at the boundary of the core sample as follows:

- ✓ The confining pressure difference at the boundary (for t>0):

$$\Delta P_c(R,t) = \Delta P_{c,0} \tag{9}$$

- ✓ The pore pressure difference at the boundary (for t>0):

$$\Delta P_p(R,t) = -\Delta P_0 \tag{10}$$

- ✓ The temperature difference at the outer boundary $(r = R)$, and the center (for t>0):

$$\Delta T(R,t) = -\Delta T_0, \tag{11}$$

- ✓ $$\frac{\partial}{\partial \mathrm{r}} \Delta \mathrm{T}(0,\mathrm{t}) = 0 \tag{12}$$

In the above equations, $-\Delta P_{c,0}$ indicates the induced confining pressure drop from bottomhole to the surface; $-\Delta P_0$ is the pore pressure drop from bottomhole to the surface; and $-\Delta T_0$ represents the temperature drop from bottomhole to the surface.

REPRESENTATIVE T-P-E FOR CORE TRIPPING

As it was discussed earlier, the original T-P-E formulation can only simulate the core retrieval corresponding to the immediate time of its transportation to the surface. To model the complete core retrieval process from the bottom of the hole to the surface, the T-P-E formulation needs to be modified to include the time evolvement during the core tripping process. Therefore, it is assumed that the core is being raised from the bottomhole in a number of discrete steps *n* and after implementation of each single step, the conditions of the sample are maintained for a specified duration until the next step is taken. This process continues until the core reaches the surface. The total number of steps, *N*, should be chosen large enough for exactness of the model. Depending on the chosen value *N*, each step carries specified three effects of reduction in confining mud pressure, pore pressure and the temperature at the boundary of the core, as shown in Figure 4. The impact of these three effects over the entire tripping period will be considered in the T-P-E modeling. The time intervals between the two successive steps is defined based on the selected tripping speed, bottomhole depth and *N*.

Therefore, when the core starts to be raised from bottomhole (during the first raising step from the bottomhole, *n=1*), the confining pressure, pore pressure, and temperature at the core boundary experience a specified difference or drop (this step is shown in Figure 4). The sample will continue experiencing these drops at its boundary until it reaches the surface. Therefore, the duration that the effects of the first step will last (that must be considered in T-P-E modeling) is equal to the whole tripping time. As the core is being raised for the second step (*n=2*), the same changes are induced to the sample and it will continue experiencing them until it reaches the surface. Obviously, the duration that the effects of the second step will last (that should be considered in the T-P-E modeling) is less than that of the first step. This process, shown in Figure 5, continues so forth until the core reaches the surface. It is noted that at each depth, the changes in the fluid properties such as viscosity and isothermal compressibility of gas have been considered.

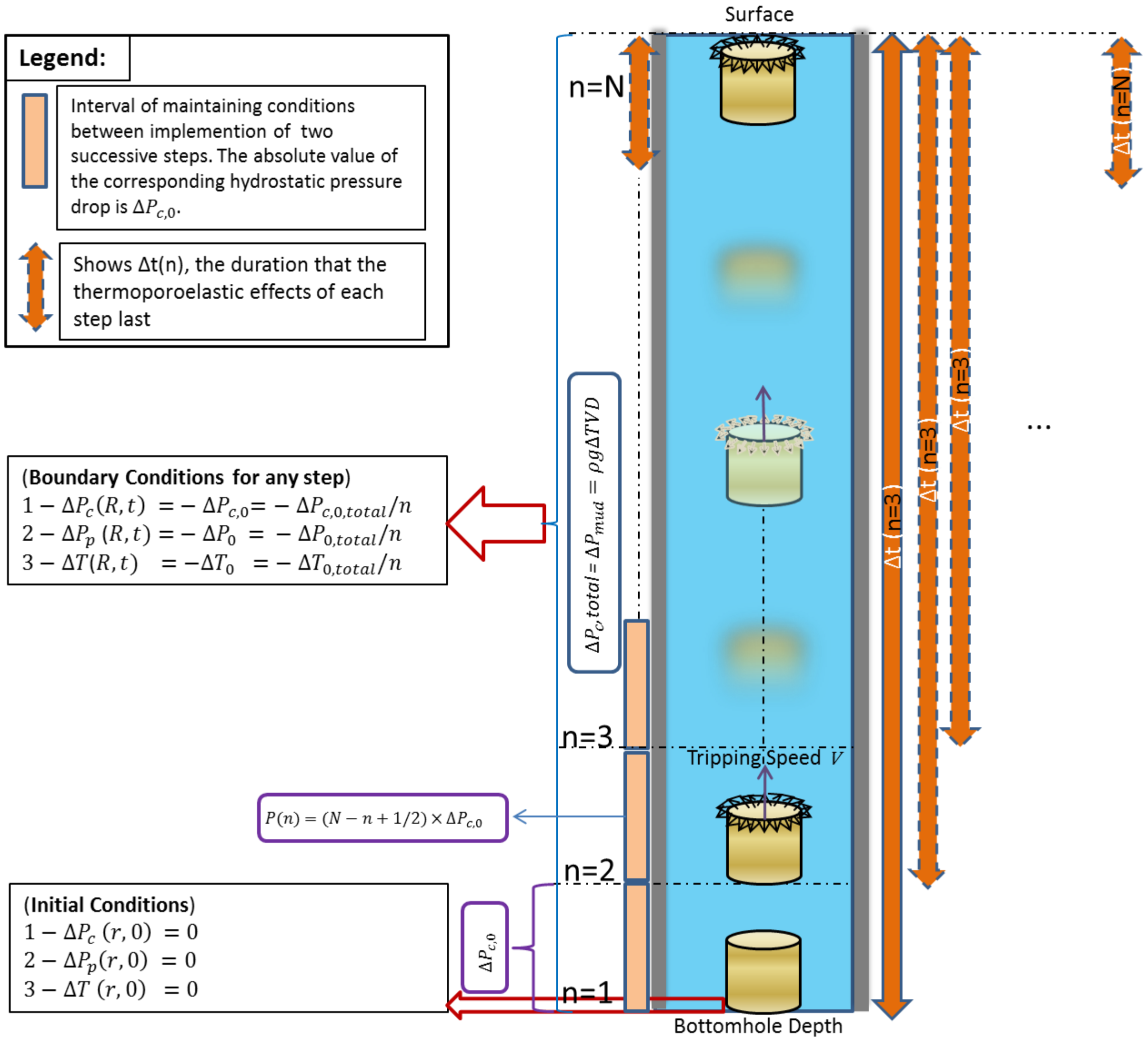

Figure 4: Step-wise progression of the core during its Trip from the bottomhole to the surface.

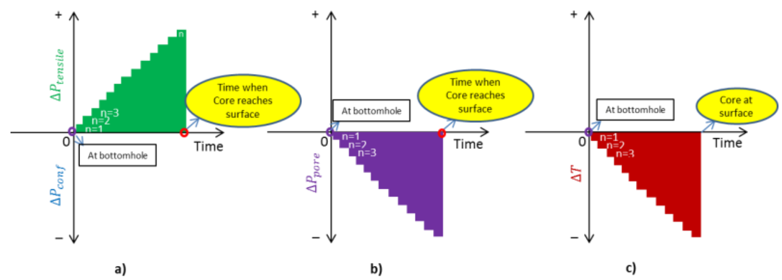

Figure 5: Initial and boundary conditions considering step-wise core decompression from bottomhole to the surface, simulating the real gradual core tripping using thermoporoelasticity

DEVELOPED MODEL

The diffusivity equations were used to develop the boundary and initial conditions corresponding to the pore pressure and temperature distribution within the sample. This requires intensive math exercises including Laplace transformation of the Partial Differential Equations, derivations, integrations, rearrangements, and taking inverse Laplace transformation. This allows calculation of the induced radial and hoop stresses as well as pore pressures based on the T-P-E model for each time step. Using the superposition principle, the total induced stresses and pore pressure corresponding to the sample when brought to the surface is found as the summation of the values for all steps. Then, the effective induced tensile stresses are calculated by including the effect of pore pressure. The final step is to apply the failure criterion to determine if the sample can reach the surface under preserved condition and if so, what the optimum safe tripping speed is to avoid any type of failure. The proposed model was fully developed in Matlab-2015.

RESULTS AND DISCUSSION

Before the implementation of the developed model, it is important to compare its results with some published work to determine if the new model provides more realistic results. For this purpose, the published data in the literature which was conducted using *Ansys-Fluent* software was utilized. The results are presented in this section, followed by analysis of a typical core tripping case.

Benchmarking

In this section, the results of the developed T-P-E model are compared with the Ansys-Fluent simulations performed [5]. They assumed a core sample of 4-inch (10.16 cm) with 2% porosity, and permeability of 2×10^{-4}mD, and gas viscosity 0.02 cp, is retrieved from the depth of 1502.46 m to the surface. The drilling mud weight in the wellbore was 12.5 ppg (1259 Kg/m^3) equivalent to 18.65 MPa as the initial bottomhole pressure. The initial sample pore pressure is assumed to be equal to the initial mud hydrostatic pressure. The surface and bottomhole temperatures are 10˚C and 34˚C respectively. Based on the tripping schedule mentioned in their paper, the core is raised from 1502.46 m to 914.5 m at 0.31 m/s; from 914.5 to 198 m at 0.065 m/s; and from 198 m to the surface at 0.05 m/s tripping speed. Using this data, the hydraulic diffusivity coefficient η of $4\times10^{6}\,\frac{\mathrm{m}^2}{\mathrm{s}}$ was obtained. This value will be used in the T-P-E model.

Similar to other studies, *Zubizarreta et al.* (2013) ignored the impact of the mechanical and thermal effects on the induced pore pressured and stresses. However, in the T-P-E model presented in this work, the contribution of the mechanical and thermal properties of the sample in its response during the tripping are considered. In order to perform the analysis based on the T-P-E model, further input data is required, which was assumed based on the best correspondence to the rock description in the published work. The data used for this purpose include Poisson's ratio $\upsilon = 0.18$, Undrained Poisson's ratio $\upsilon_u = 0.28$, Biot's coefficient $a = 0.7$, Young's modulus E=10 GPa), thermal expansion coefficient $10^{-5}\ \frac{1}{°\mathrm{C}}$, and thermal diffusivity coefficient of $8\times10^{-7}\,\frac{\mathrm{m}^2}{\mathrm{s}}$.

The analysis was conducted based on the T-P-E model and the results were compared against those published by a literature work [5]. Figure 6 shows a good agreement between the results of the two models. However, the T-P-E model presents a larger induced pore pressure which is due to the fact that the Fluent model has not included the mechanical and thermal properties of the sample in its analysis. The black curve in Figure 6 (left) represents the induced radial stress in the center of the core, which the difference between the value of the pore pressure inside the core (blue) and the mud pressure in its boundary (red). The critical core internal pressure (shown in green color) is found as the summation of the outside mud pressure and the equivalent tensile strength.

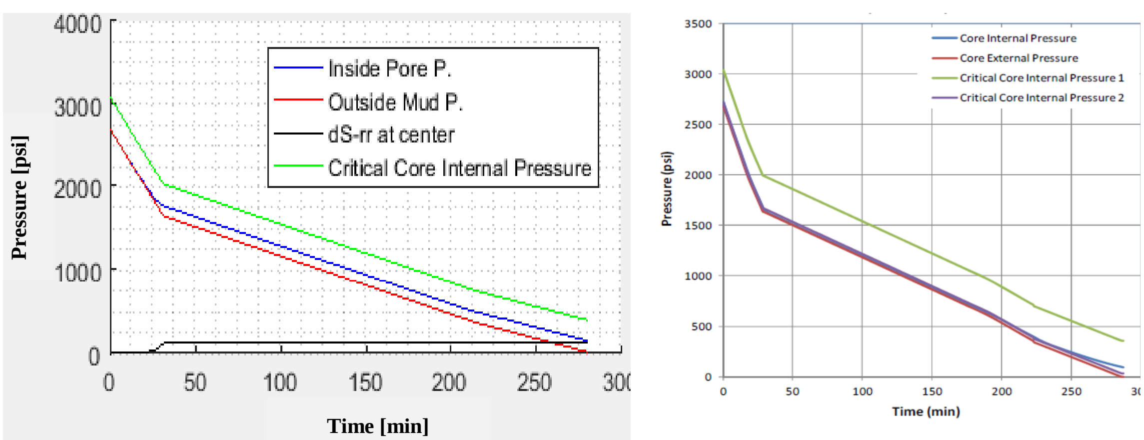

Figure 6: Comparison of the Results of the T-P-E model developed here (a) and model of *Zubizarreta et al.* (2013). (b)

A Typical Core Tripping Case

A set of input data representing the properties of a typical gas-bearing tight core sample is shown in Table 2. For single phase fluids, gas is the worst case because of its compressible nature. The data of Table 2 is taken from *Chen and Ewy (2005)* and *Hettema et al. (2002),* in addition to the data from the industry core analysis results. The T-P-E model was run and the potential failure of the core sample was investigated.

Running the T-P-E model, the induced stresses were evaluated for two scenarios: 1) considering both the hydraulic and thermal effects, and 2) ignoring the thermal effect. Comparing the results of the two cases allows evaluating the extent of the impact of the thermal effect on the induced stresses. Next, to investigate the possible failure within the sample when it reaches the surface, the Griffith' failure criterion was applied for three cases of the induced radial and hoop stresses and the induced radial stress in the center of the sample, evaluated by subtracting the mud pressure from the pore pressure in the center of the core.

Table 1: Input data corresponding to a typical tight gas-bearing Core sample used for T-P-E core tripping analysis

Parameter	Value	Evaluation Method
Depth at bottomhole [m]	Mostly 500	
Diameter of core [in]	2 (≈5 cm)	
Porosity, ϕ [%]	40	Estimated/Measurable
Permeability of core, K [mD]	10^{-3}	Estimated/Measurable
Viscosity of gas, μ_g [cp]	0.02-0.04 (surface)	Measured
Viscosity of water, μ_g [cp]	1	
Molecular Weight of gas, M_g	16 (Methane)	Depending on the gas
Specific Gravity of gas (Surface)	0.65	Depending on the gas
Compressibility of rock, C_r [1/pa]	5×10^{-10}	Estimated/Measurable
Compressibility of gas (surface), C_g [1/Pa]	9.869×10^{-6}	Estimated/Measurable
Compressibility of water, C_w [1/pa]	5×10^{-10}	Estimated/Measurable
Interstitial Water Saturation, $S_{w,i}$	20%	Estimated/Measurable
Total Compressibility, $C_{t,g}$ [1/Pa] (gas-bearing core)	7.89×10^{-6}	$C_t = C_r + S_w C_w + S_g C_g$ [Ahmed & McKinney, 2005]
Hydraulic-Diffusivity, η [m^2/s] (Gas-bearing at surface)	10^{-8}	$\eta = 9.869\times10^{-13}\dfrac{K}{\varphi\mu_g C_{t,g}}$ [Ahmed & McKinney, 2005]
Thermal Expansion Coefficient, α_m [1/˚C]	10^{-5}	Estimated/Measurable [Timoshenko, 1934)]
Thermal Diffusivity, η_T [m^2/s]	8×10^{-7}	Estimated
Geothermal Gradient [˚C/m]	0.044	Estimated/Measurable
Uniaxial Compressive Strength, UCS [Mpa]	20	Measurable/Estimated
Young's Modulus [GPa]	4.2	Calculated/Estimated
Tensile-Strength, T.S. [Mpa]	1.7–2	$T.S. = UCS/m$, m=7–15 [Jaeger et al., 2007]
Biot's coefficient, α	0.7	0.6-0.7 (for shales)
Poisson's Ratio, ν	0.3	Estimated/Measurable
Undrained Poisson's Ratio, ν	0.4	Estimated/Measurable

Mud Weight, ρ_m [kg/m3]	1078	$MW[ppg]\times 119.826 = MW\left[\frac{kg}{m3}\right]$
Mud Cake Pressure Drop		Zero
Coupling Coefficient, η' and η'_T	0.17–0.3	Estimated
Initial Bottomhole Pressure [Mpa]	5.4	
Initial Pore Pressure		Equal to initial hydrostatic pressure

Figure 7 a and b show the induced radial and hoop stresses within the sample. The constant values of the tensile strength of the sample, 2MPa is shown in red color. Figure 7-c displays the induced radial stresses in the center of the core as well as the core's tensile strength, versus time. Comparing the effective induced stresses with the tensile strength of the sample determines whether failure and microfracturing can occur or not.

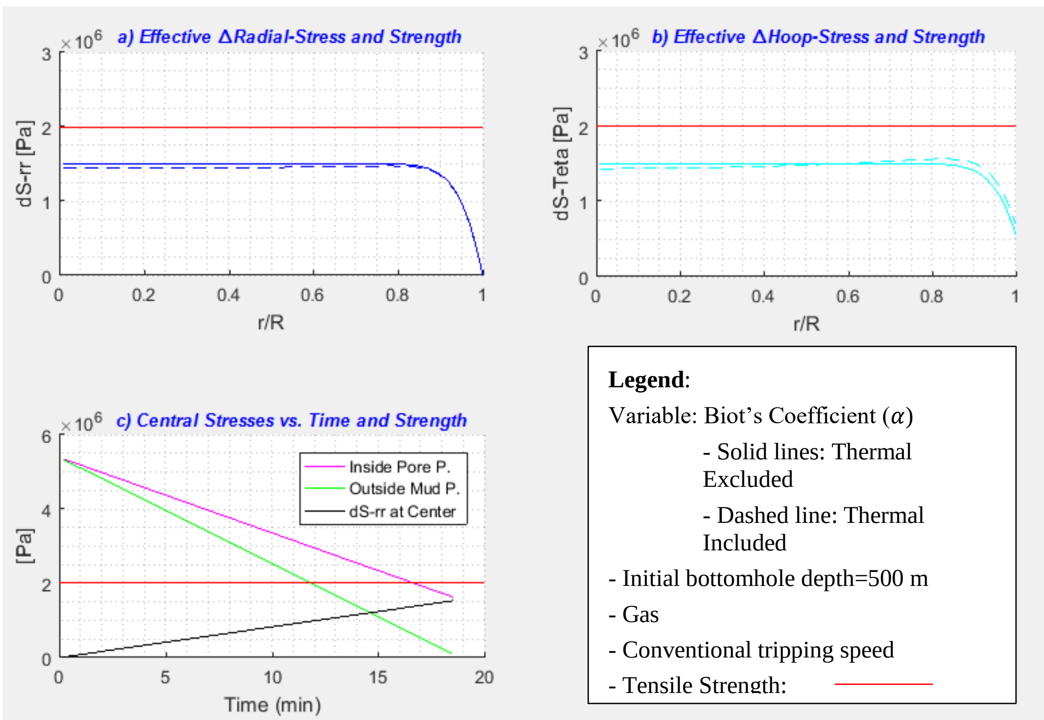

Figure 7: Thermal Effect Excluded and Included during Tripping

The results of Figure 7 show that the tight core sample located at 500 m, can be tripped in a preserved manner to the surface. In addition, the thermal effect corresponds to only ≈6% of the total induced stresses.

The initial bottomhole depth of the core sample is also an important parameter affecting the sample's T-P-E behavior during tripping. To simulate this effect using the T-P-E model, the data of Table 2 was used. The industry suggestion for conventional coring in very tight formations is to use a tripping speed of 0.45 *m/s*.

Figure 8 shows that failure occurs for all the in-situ bottomhole depths, except for bottomhole depth of 500 *m*, as only at this depth the induced radial and hoop stresses are less than the sample tensile strength. This indicates that the suggested 0.45 *m/s* tripping speed is not a proper value to use. The results of Figure 8 show the greater the depth, the greater the initial bottomhole confining pressure of the mud and the initial pore pressure of the sample will be. Therefore, the total differential confining and pore pressure that the sample will experience during tripping longer distances, would be larger. In short, tripping from deeper bottomhole corresponds to larger induced stresses being applied to the sample while its tensile strength remains constant. This means that the possibility of the failure increases with greater bottomhole depths.

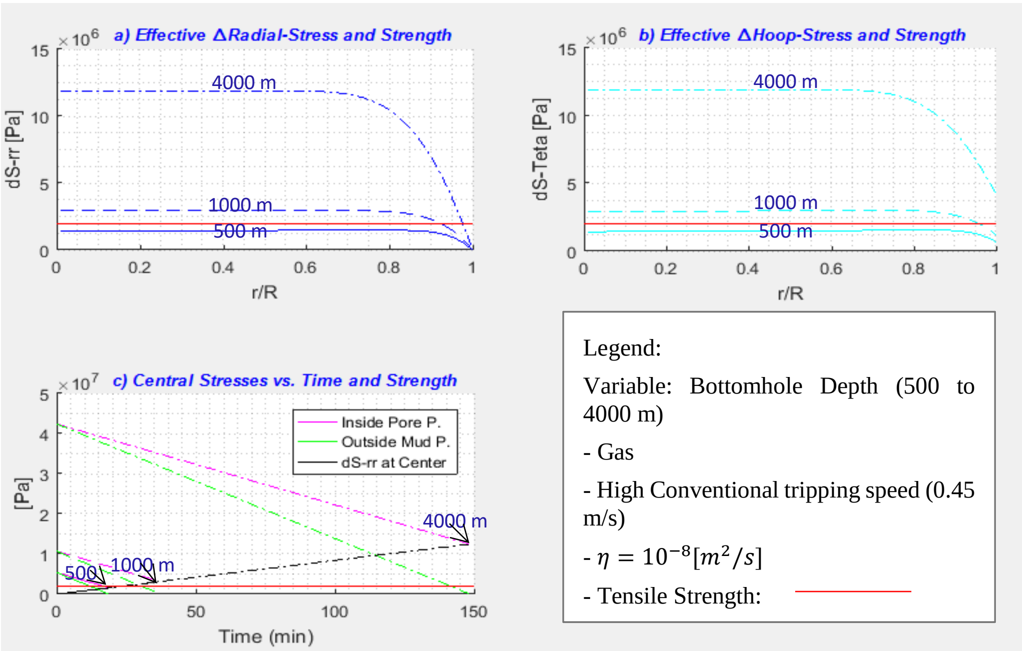

Figure 8: The effect of tripping from deeper bottomhole on the induced T-P-E stresses and sample failure

SUMMARY AND CONCLUSIONS

A thermoporoelastic (T-P-E) model was developed to investigate the magnitudes of stresses applied to a core sample and its potential failure when it is tripped from bottomhole to the surface. The model considers the effect of differential confining mud pressure, pore pressure and the temperature drop at the core boundary during tripping. The improvement yielded from this model were shown by comparing its results against the published data in the literature. The model provides enhanced performance as it also considers the mechanical and thermal effects. Also, analyzing the data corresponding to a typical tight core sample indicated that the contribution of thermally induced stresses is much less significant than the hydraulically induced stresses. We also have shown that very tight core samples with hydraulic diffusivity coefficient of $10^{-8} m^2/s$ cannot be retrieved in a preserved manner to the surface unless its initial bottomhole depth is shallower than 500 m.

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