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A novel approach to quantify reservoir pressure along the horizontal section and to optimize multistage treatments and spacing between hydraulic fractures

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ABSTRACT

This work presents promising results for the application of a novel approach to estimate geopressure to optimize allocation of clusters in a horizontal wellbore in an unconventional shale play using information from logging while drilling (LWD) techniques. In previous publications on this subject, the usefulness of implementing the diffusivity equation in conjunction with information from well logs to estimate geopressure in conventional and complex unconventional geological scenarios was demonstrated. In this new study, a novel approach is applied to characterize reservoir and fracture pressures along the horizontal section of a well drilled in the Southwest part of the Eagle Ford unconventional shale play. To the best of the authors' knowledge, there is no report of estimation of pore pressure in a horizontal wellbore using theoretical principles, such as the diffusivity theory. The recorded rock properties from LWD along the horizontal section of the well serve multiple purposes. Firstly, they were introduced into the solution of the diffusivity equation as "normalized values" to obtain the pore pressure distribution. Secondly, they are employed to generate a synthetic acoustic log along the horizontal section of the wellbore to determine geomechanical properties of Eagle Ford formation.

The results documented in this work demonstrate that when using this novel methodology, horizontal wells can be characterized in great detail from the standpoint of reservoir pressure and brittleness. This novel approach is effective, reliable, and can help the completion engineer to decide where to allocate the clusters (perforations) to make more efficient the multistage hydraulic fracturing jobs and improve productivity. Furthermore, geoscientists, reservoir, and production engineers will benefit from knowing reservoir pressure distribution along the path of the horizontal section of the well in more detail. As a result, a more efficient reservoir characterization is obtained to improve horizontal wellbore performance.

1. Introduction

Two of the most important technologies that have contributed enormously to the success of developing unconventional shales in the last decade are horizontal drilling and hydraulic fracturing. Previous publications on this subject (Lopez and Sepehrnoori, 2015) demonstrated the usefulness of implementing the diffusivity equation in conjunction with information from well logs to estimate geopressure in conventional and complex unconventional geological scenarios. Because of the importance of horizontal wells and the hydraulic fractures requirement to improve production, we focused this new work on estimating geopressure along the horizontal section of a wellbore. The proposed novel technique proved to be effective and reliable in estimating formation pressures (Lopez and Sepehrnoori, 2015). It is important to remark that a transcendental part of the planning, design, and execution of a horizontal well and the induced fractures associated with it in a shale play is to position them in zones where hydrocarbons can be recovered. This task apparently seems to be satisfied when drilling within the producing zone is guaranteed. However, in real scenarios where heterogeneous formations are found, it is very important not only to assure drilling in the "pay zone," but also to identify those sections containing better hydrocarbon potential "sweet spots." These "sweet spots" are identified in this work as intervals with higher reservoir pressure and higher organic matter contents than others due to heterogeneities.

When using logging while drilling (LWD) techniques, recorded

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Nomenclature

A, B, C	Constants
BA	Brittleness average, dimensionless
C_f	fluid compressibility, 1/psi
C_r	pore volume compressibility, 1/psi
$E_{brittleness}$	normalized Young's modulus, dimensionless
E_{max}	maximum Young's modulus reading, psi
E_{min}	minimum Young's modulus reading, psi
$exp\ (e)$	base of natural logarithm
FPG	fracture pressure gradient
G	Lame's constant, psi
GR	gamma ray readings, API units
h	representative depth, m, (ft)
k	formation permeability, mDarcies
L	depth of investigation, m
OG	overburden gradient
PG	pore pressure gradient
P	Formation pore pressure, psi
P_{hyd}	Hydrostatic pressure, psi
r_{avg}	average resistivity, ohm m
r_o	observed resistivity, ohm m
S	Overburden total stress, psi
PI	Secondary Porosity Index, dimensionless
t	time, s (min)
TOC	Total Organic Contents, fraction
V_p	velocity of the compressional wave, ft/s
V_s	velocity of the shear wave, ft/s
z	depth of interest, m
β	thermal expansion coefficient, dimensionless
Δt_{avg}	Sonic Average Interval Travel Time, μsec/ft
Δt_n	Sonic ITT on normal trend line (μs/ft)
Δt_o	Sonic Interval Travel Time (ITT),μs/ft
Δt_p	compressional sonic Interval Travel Time (ITT) (μs/ft)
Δt_s	shear sonic Interval Travel Time (ITT) (μs/ft)
$\nabla^2 P$	Lapacian operator of P
ε_{kk}	Volumetric strain, dimensionless
ϕ	porosity, fraction
ϕ_D	density porosity, fraction
ϕ_N	neutron porosity, fraction
ϕ_{ND}	neutron-density cross plot porosity, fraction
ϕ_S	sonic porosity, fraction
η	Biot's modulus, psi
λ	eigenvalues
ρ	bulk density of rock, g/cm^3
μ	fluid viscosity, cp
σ_{eff}	rock matrix effective stress, psi
σ_m	mean effective stress, psi
υ	Poisson's ratio, dimensionless
$\upsilon_{brittleness}$	normalized Poisson's ratio, dimensionless
υ_{max}	maximum Poisson's ratio reading, dimensionless
υ_{min}	*minimum Poisson's ratio reading, dimensionless*

formation property values along the horizontal section of the well are introduced into the solution of the diffusivity equation to obtain the real reservoir pore pressure distribution. Quantifying properly reservoir pressure along the horizontal section of the wellbore should be without doubt a critical part of the planning and design of completion of the well; particularly, when hydraulic fracturing jobs are required to improve production. Because of low permeability of producing formations in unconventional shale plays, it is a well-recognized practice to hydraulically fracture these formations to reach production or to increase it. In current days, multistage hydraulic fracturing jobs are typical in these scenarios. However, in current conditions, quantifying reservoir pressure along the horizontal wellbores is not a practice. Typically, the reservoir pressure is obtained from implementing well-known reservoir engineering techniques and a unique value is computed, not considering the heterogeneity of producing formations.

Although not an objective of this work to elaborate on hydraulic fracturing design, we do consider it convenient to refer to material related to this subject. Jacobs (2014) discussed briefly the evolution of hydraulic fracturing jobs in shales, highlighting zipper fracture as a methodology to improve production compared with other hydraulic fracturing methods in a multi-well completion. Jacobs remarks that relatively tight spacing between horizontal wells and configuration of the fracture stages on the horizontal sections are the main aspects to have success when applying novel fracturing techniques. The success of this technique is partially explained by the stress shadow effect occurring when hydraulically fractures are closely spaced and developed in a short period of time. In addition, Yu and Sepehrnoori (2013), when studying optimization of multiple hydraulically fractured horizontal wells in unconventional gas reservoirs, concluded that "The economic success of shale gas reservoirs depends on optimization of the number of treatment stages and number of fractures and horizontal wells." It is in this regard where our approach becomes important. In order to optimize the number of treatment stages with optimizing spacing between fractures, we obtained detailed reservoir pressure distribution and characterized geomechanically the producing formation along the complete horizontal section of a well drilled in the Southwest portion Eagle Ford Shale. The methodology is described in detail, and the results are validated with available completion and production information. This validation provides a better insight on the benefits of using this novel proposed technique for the purpose of optimizing completion and reservoir management.

2. The proposed model

Charlez (1991, 1997) describes that diffusivity comes from three different sources: hydraulic, mass, and thermal sources. An expression of diffusivity is obtained when Darcy's law is introduced to mass balance. Assuming the system is under equilibrium and mass diffusion through a porous medium and temperature remaining at equilibrium allow simplifying the diffusivity equation to the following partial differential equation:

$$\frac{1}{\eta}\frac{\partial P}{\partial t} - \beta\frac{\partial \varepsilon_{kk}}{\partial t} = \frac{k}{\mu}\nabla^2 P. \tag{1}$$

Specific loading paths allow rearranging Eq. (1) to other expressions more commonly used in reservoir engineering applications such as

$$\mu\frac{\partial P}{\partial t} = \frac{k}{\phi(C_f + C_r)}\nabla^2 P, \tag{2}$$

where $\nabla^2 P$ is the Laplacian operator on P.

In one-dimension, the diffusivity equation can be expressed as follows:

$$\frac{\partial P}{\partial t} = \lambda\frac{\partial^2 P}{\partial z^2}. \tag{3}$$

Solving Eq. (3) by separation of variables allows a special solution that can be written as a linear combination of the product of functions of the individual variables. The general solution of Eq. (3) is expressed as follows:

$$P(z,\ t) = C_n e^{-\lambda t}(A\cos(z\sqrt{\lambda\mu/c^2}) + B sin(z\sqrt{\lambda\mu/c^2})), \tag{4}$$

(Solution found is in Kreyszig (1999) and Olver (2013)) where $z\sqrt{\lambda\mu/c^2} = n\pi$ and $\lambda = (n\pi c/z)^2/\mu$.