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A new approaching method to estimate fracture gradient by correcting Matthew–Kelly and Eaton's stress ratio

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A B S T R A C T

Fracture pressure is one of the most important parameters in wellbore stability. Fracture pressure shows the ability of rock to hold vertical stress before starts to fracture. The application of fracture gradient (FG) affects the well design, such as mud weight profile, casing setting depth, and cementing operation. Fracture gradient could be determined directly by using leak-off test (LOT) and formation integrity test (FIT), and calculation from logging data. There have been a lot of studies in predicting fracture gradient after the fundamental theory of fracture pressure was developed by Hubbert and Willis in 1957. However, most of those studies were performed without considering the geological characteristic, such as precipitation environment, geology structure, and stratigraphy. A new methodology to predict fracture pressure from former calculations, Matthew–Kelly and Eaton, is proposed. The methodology characterized the formation lithology from Poisson's ratio and stress ratio value which is corrected and analyzed by two correcting constants, *a* and *b*. As the result, a new value of Poisson's and stress ratio of the formation was generated and the accuracy of fracture gradient was improved. In addition, the flexibility of this methodology indicates that this methodology could be applied in various drilling area.

1. Introduction

Fracture gradient is a crucial parameter for developing a successful drilling program, especially in wellbore stability. An initial objective of this study is to develop a modification of previously fracture gradient prediction, Matthew–Kelly and Eaton, especially by correcting the stress ratio constants.

This study shows improper fracture gradient estimation in three exploration wells drilled in field X and drilling problem take place. It is necessary to address this concern by further investigating the effect of vary lithology type in selected study area. However, several obstacles are encountered during this study, especially in experimental data availability including logging data, leak-off test (LOT), or formation integrity test (FIT). Solving this problem, this study proposed a new study methodology due to obtain the preferable results approaching the actual fracture gradient.

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1.1. The tectonic stress field

Prior to drilling, rocks are in near-balanced state and the mechanical stresses in the formation are less than the strength of rocks. Near-balanced state provides a naturally occurs stress in place which called the in-situ stress. There are three principal in-situ stress magnitudes, the vertical stress, S_v, equal to total weight of rocks and fluid above that depth; the maximum principal horizontal stress, S_H; and the minimum principal horizontal stress, S_h (Amoco, 1996).

The magnitudes of each stress influence the fault regime in earth crust. Anderson (1951) classifies an area as being characterized by normal, strike-slip or reverse faulting depend on whether (i) the crust is extending and steeply dipping normal faults accommodate movement of the hanging wall (the block of rock above the fault), (ii) block or crust are sliding horizontally past one another along nearly vertical strike-slip faults, or (iii) the crust is in compression and relatively shallow-dipping reverse faults are associated with the hanging wall block moving upward with respect to the footwall block (Zooback, 2007).

1.2. Fracture gradient theory

1.2.1. Fracture gradient estimation methods

Methods to determine formation fracture gradient consist of

Nomenclature

a, b	Matthew Kelly and Eaton's fracture pressure correction constants
D	Depth, ft
K_i	Matthew–Kelly stress ratio
p_f	Pore pressure, psi
p_{ff}	Fracture pressure, psi
p_n	Normal pressure, psi
S_h	Minimum horizontal stress, psi
S_H	Maximum horizontal stress, psi
ε_1	Longitudinal contraction, ft
ε_2	Lateral expansion, ft
ν	Poisson's ratio
σ_{min}	Effective minimum stress, psi
σ_z	Effective vertical stress, psi
S_v	Vertical stress, psi
FG	Fracture gradient, ppg
PR	Poisson's Ratio
OBG	Overburden gradient, ppg
ECD	Equivalent Circulating Density
FIT	Formation Integrity Test
LOT	Leak Off Test
LOP	Leak Off Pressure

Unit conversion

1 ft	0.3048 m
1 psi	6994.75729 Pa
1 g/cm^3	8.33 ppg=0.0001 kg/m^3
1 µs	1×10^{-6} s

predictive methods and verification methods. At the initial well planning, formation fracture gradient is calculated following the predictive methods. Afterwards, during drilling operation, fracture pressure is verified by pressure test after casing is cemented. The verified result is useful for well planning in the next drilling operation.

1.2.1.1. Hubbert–Willis. Hubbert and Willis (1957) introduced fundamental principle of fracture gradient. In their statement, fracture gradient appears as the pressure needed to overcome the minimum principle stress given by (Bourgoyne, 1991):

$$p_{ff}/D = \sigma_{min}/D + p_f/D \quad (1)$$

where: p_{ff} is fracture pressure (psi); D is depth (ft); σ_{min} is effective minimum stress (psi); and p_f is formation pressure (psi).

Hubbert and Willis (1957) concluded that the minimum stress of normal faulting regions, such as the U.S. Gulf Coast area, is equal to horizontal matrix stress. Another assumption in this calculation is the value of overburden stress gradient which equal to 1 psi/ft. Therefore, the fracture pressure is approximately (Bourgoyne, 1991):

$$p_{ff}/D = \left(1 + 2p_f/3D\right) \quad (2)$$

where: D is depth (ft); p_{ff} is fracture pressure (psi); p_f is formation pressure (psi).

1.2.1.2. Matthew–Kelly. Matthews and Kelly (1967) published another calculation of fracture pressure gradient. They stated that an observed fracture pressure is exerted due to the force necessary to overcome the “matrix load”. As the result, Matthew and Kelly introduced a new variable, “matrix stress coefficient”, which was determined empirically from field data taken in normally pressured formations, such as Gulf Coast sand reservoirs, as a function of depth (Baker Huges INTEQ, 1996).

$$p_{ff}/D = \left(K_i.\ \sigma_z\right)/D + p_f/D \quad (3)$$

where: K_i is Matthew–Kelly stress ratio; σ_z is effective vertical stress (psi); D is depth (ft); p_{ff} is fracture pressure (psi); p_f is formation pressure (psi).

However, this method contains several weaknesses which may result in improper fracture gradient estimation. One of the weaknesses is that this method assume that the overburden stress is equal to 1.0 psi/ft. Moreover, the matrix stress coefficient used in their study is only limited in Gulf Coast area. Therefore, this method can be only used within a single field due to the variation of matrix coefficient (Baker Huges INTEQ, 1996).

1.2.1.3. Eaton. Eaton (1969) proposed a calculation for fracture gradient by using another independent variable, Poisson's ratio that shows a relationship between horizontal and vertical matrix stress (Baker Huges INTEQ, 1996).

$$\nu = -\varepsilon_2/\varepsilon_1 \quad (4)$$

$$p_{ff}/D = (\nu/(1-\nu)).\left(\sigma_{min}/D\right) + p_f/D \quad (5)$$

where: ν is Poisson's ratio; D is depth (ft); ε_1 is longitudinal contraction (ft); ε_2 is lateral expansion (ft); σ_{min} is effective minimum stress (psi); p_{ff} is fracture pressure (psi); p_f is formation pressure (psi).

For any area outside Gulf Coast, Eaton's method can be applied if the Poisson's ratio is available (Baker Huges INTEQ, 1996). The Poisson's ratio can be obtain from overburden gradient data, actual fracture pressure for several depth, and formation pressure data (Eaton, 1969).

1.2.2. Fracture gradient verification

A pressure test called leak-off test is conducted by closing the well at the surface and pumping drilling fluid into the closed well at a constant rate until the pressure show a departure from the increasing pressure trend. Leak-off pressure (LOP) is shown by the first point where the slope starts to decrease on the leak-off test curve (Bourgoyne, 1991).

Leak-off test (LOT) data is used as data verification for planning future field drilling and production operations because it measures the minimum horizontal stress (S_h). Sometimes the test is stopped until reach leak-off and the formation is only pressured up until a certain value. This test is called formation integrity test (Prassl, 1990).

2. Methods

This study proposes a new methodology to predict fracture gradient by modifying the constant value in Eaton and Matthew–Kelly equation with limited experimental data in field. The new method to determine fracture gradient is shown in Fig. 1.

2.1. Data collecting

The data was collected from mud logging and wireline logging, including Gamma ray, Density, Porosity, Resistivity, and Sonic Logging, and also LOT and FIT as fracture pressure verification.