

Original article

# Estimation of Pore Pressure and Minimum Horizontal Stress Using Newton Classical Optimization Procedure based on Well Log Data

Manouchehr Sanei<sup>1\*</sup>, Ahmad Ramezanzadeh<sup>2</sup>, Mina Shafiabadi<sup>3</sup>

1- Postdoctoral Researcher, Shahrood University of Technology, Shahrood, Iran

2- Professor, Shahrood University of Technology, Shahrood, Iran

3- PhD Student, Shahrood University of Technology, Shahrood, Iran

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Eaton Method,  
Blanton Equation,  
Well Log Data

## Abstract

Optimization is one of the branches of applied mathematics that is used in various fields of decision-making such as engineering, mathematics and computer science. The classical method is one of the branches of optimization that can be used to make decisions in various problems. Accurate knowledge of pore pressure and minimum horizontal stress is necessary for the drilling, stability, and completion stages of the wellbore.

Therefore, the purpose of this research is presented in three parts. First, the pore pressure is estimated based on Eaton's relationship. To accurately estimate the pore pressure, the constants of Eaton equation are automatically calibrated and calculated through gradient-based Newton's classical optimization method. Second, the minimum horizontal stress is obtained using the Blanton equation. To estimate properly the minimum horizontal stress, the constant parameter of the Blanton's method is computed via the Newton classical optimization method. Finally, the values of pore pressure and minimum horizontal stress are compared with the measured data to evaluate the accuracy of the results. These results show the ability of the proposed optimization method to accurately determine the pore pressure and the minimum horizontal stress.

## 1. Introduction

Pore pressure is one of the most important parameters for wellbore drilling, wellbore stability, completion, optimization and improvement of reservoir production. For example, wellbore stability problems such as collapse, kicks, and blowouts can be avoided by properly estimating pore pressure (Hu et al. 2013, Duran et al. 2019, Duran et al. 2020, Sanei et al. 2021). In geomechanical studies, minimum horizontal stress is one of the key parameters required for wellbore stability, hydraulic fracturing, wellbore collapse, and sand production (Manshad et al. 2014; Molaghab et al. 2017, Sanei et al. 2017, Sanei et al. 2019, Sanei et al. 2022).

Pore pressure can be measured through various tests, such as modular dynamic tester (MDT),

repeat formation tester (RFT), and drill stem testing (DST). Moreover, the minimum horizontal stress can be measured using different tests, including the leak of the test (LOT), extended leak-off test (XLOT), hydraulic fracturing test (HFT), and formation integrity test (FIT). However, there are many challenges such as time-consuming and high cost in direct measurement. Furthermore, it is not possible to provide a continuous profile of pore pressure and minimum horizontal stress because such tests are typically performed at specific depths and are limited in number (Mousavipour et al. 2020, Ibrahim et al. 2021). Therefore, prediction of pore pressure and minimum horizontal stress with indirect methods is common in the oil and gas industry (Almalike and Alnajm 2019).

Pore pressure prediction in the literature has been

\*Corresponding Author: manouchehr.sanei@gmail.com.

performed using variable data such as logging data, formation characteristics, and drilling parameters. Hottman and Johnson (1965) predicted the pore pressure based on logging data from sonic travel time and resistivity logs. Pennebaker (1968) proposed a method using the sonic travel time ratio instead of the sonic travel time difference as applied by Hottman and Johnson (1965). Eaton (1975) developed an empirical model based on sonic logs to estimate the pore pressure gradient. Gardner et al. (1974) expressed a new model for predicting pore pressure using overburden pressure. Bowers (1995) predicted the pore pressure from sonic log data. Foster and Whalen (1966) used the equivalent depth method to predict pore pressure from electrical logs. Ham (1966) used the equivalent depth method with resistivity, sonic, and density data to estimate pore pressure. Eaton (1972, 1975) proposed empirical models based on the resistivity and conductivity logs to predict formation pressure gradient.

The minimum horizontal stress can be estimated using different methods such as numerical modeling and poroelastic strain model (Zoback et al., 2003; Anderson 1905; Blanton and Olson 1999; Fjar et al. 2008). These models depend on several geomechanical parameters, such as static elastic modulus, static Poisson's ratio, and elastic strains. In addition, such empirical equations including Eaton's method and Blanton's method have been presented by (Eaton 1968; Blanton and Olson 1999) to estimate minimum horizontal stress. Recently, due to the importance of pore pressure and minimum horizontal stress for geomechanical studies, several researches have been conducted on them such as John et al. (2014), Chatterjee and Singha (2018), and Sen and Ganguli (2019), Ibrahim et al. (2021), Gowida et al. (2021), Tanko et al. (2020), and Abdelaal et al. (2022).

Accurate estimation of pore pressure and minimum horizontal stress using empirical relationships based on well logs information, requires the correct constant parameters of the model. In practice, these parameters are difficult to obtain due to many sources of uncertainty. The evolution of computer provides the opportunity to analyze complex problems using numerical simulations. Despite many advances, there are discrepancies between observed data and numerical modeling predictions (Brand and

Premchitt, 1989).

To overcome the uncertainties related to constant parameters of the model while estimating the parameters, mathematical optimization methods can be used. In general, optimization methods used for geomechanical, geotechnical, and reservoir engineering problems include classical optimization methods, inverse analysis, genetic algorithms and artificial neural networks. One of the types of optimization methods is the classical optimization method, which requires searching for the minimum value of an objective function in the entire domain (Doherty et al. 2012). The classical optimization methods include derivative-free optimization and gradient-based optimization method (Rios and Sahinidis 2012; Chen et al. 2013). One type of gradient-based optimization methods is Newton's method, and previous studies expose its capability to appropriately estimate the model's parameters (Cekerevac et al. 2006, Sanei et al. 2021).

The main purpose of this article is to estimate pore pressure and minimum horizontal stress using empirical relationships and Newton's optimization method. This process is performed using well log data for five wells of the Volve field in the Norwegian North Sea. The empirical relationships are the Eaton and Blanton methods, which are applied to estimate pore pressure and minimum horizontal stress, respectively. The estimated results are compared with the provided Volve information to present the capability of the proposed procedure to correctly determine the parameters.

## 2. Method of Analysis

### 2.1. Optimization Method

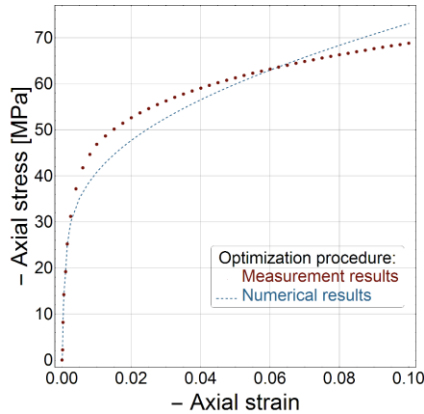
Optimization is a branch of mathematics that can be used for any decision-making problems. In fact, the goal of decision-making is to select the "best" data set among the available options.

### 2.2. Objective Function

The objective function for a certain set of parameters is defined as the difference between the model prediction and the measured data as shown in Fig. 1. The objective function should be positive and constructed based on independent state variables (Cekerevac et al. 2006). It is:

$$F(\mathbf{x}) = \frac{1}{t - t_0} \int \|Y^n - Y^m\| dt \quad (1)$$

where  $(t - t_0)$  is the duration of observation,  $\|Y^n - Y^m\|$  is the norm of the difference between measured data  $Y^m$ , and the numerical approximation  $Y^n$ .



**Fig. 1.** A comparison between numerical approximation and measured data (Sanei et. al 2021)

### 2.3. Newton Method

Newton's method is a root-finding algorithm that uses first and second derivatives and can provide a better approximation if the initial point is close to the target value (Chong and Zak 2001). The Newton method is defined using the gradient  $\nabla F(x)$ , and the inverse of the Hessian matrix,  $H F(x)$ , as:

$$x^{n+1} = x^n - [H F(x^n)]^{-1} \nabla F(x^n), \quad n \geq 0 \quad (2)$$

The objective function  $F(x) = F_X$  is combined of such parameters, e.g.,  $a, b, c$ , and etc. It is defined as  $F_X = F_X(a, b, c)$ :

$$F_X = \sum_{i=1}^{npts} \Delta \cdot \Delta \quad (3)$$

where  $npts$  is the number of measured data. The Hessian matrix and the gradient are:

$$[H F_X] = J (\nabla F_X)^T \quad (4)$$

$$\nabla F_X = \left( \frac{\partial F_X}{\partial a}, \frac{\partial F_X}{\partial b}, \frac{\partial F_X}{\partial c} \right) \quad (5)$$

where  $J$  is the Jacobian matrix.

To provide an accurate estimation using Newton method, a good initial guess  $x^0$  for each parameter is essential.

## 3. Case study: Volve oil field, Norway

### 3.1. Description of the study area

This study is based on data from the Volve oil field, located in the central part of the North Sea, which is shown in Fig. 2. This oil field was discovered in 1993 and its development plan was approved in 2005 (Sen and Ganguli 2019). Field production started in early 2008 and peaked at 56,000 bbl/day. The main drainage strategy was pressure maintenance by water injection, with production wells placed on top of the structure and water injectors on the flanks. The Volve field is formed as a fault block structure with an initial estimate of 173 million barrels of oil in place (Equinor 2021). The reservoir is a small dome-shaped structure formed by the collapse of adjacent salt ridges during the Middle Jurassic age (Equinor 2020; Szydluk et al. 2006). Oil was produced from sandstone in the Hugin formation at an average depth of 2700 to 3100 m true vertical depth (TVD) below sea level. The Volve field had a recovery rate of about 54% and was shut down in 2016 after eight years of field activity.



**Fig. 2.** Geolocation of Volve field (Wang et al. 2021)

Equinor and other oil and gas companies worked in Volve field have released all information freely to the public. Published information includes subsurface geology, geophysics, borehole logs, and various drilling and production reports from the reservoir (Equinor 2021). For this study, five wells have been selected from Volve field, namely F-1A, F-1B, F-4, F-5, and F-11T2.

### 3.2. Geological setting

As stated, the petrophysical and geomechanical data selected in this study are related to five wells in the Volve oil field. The reservoir part of this

field is related to the Hugin and Heather formations and the caprock of this field is related to the Draupne formation. As seen in Figure 3 and Figure 4, this field consists of formations (zones) such as Hordaland, Grid, Balder, Sele, Lista, Ty, Ekofisk, Tor, Hod, Blodoks, Hidra, Rodby, Asgard, Draupne, Heather, Hugin, Sleipner, Mime, Skade, Skagerrak, Utsira, Smith Bank, Tryggvason, and Heimdal. Geological and petrophysical studies state that the rocks of the field are mainly sandstone, limestone, siltstone, claystone, calcite, marl, tuff, and coal as the lithology of each formation is illustrated in Fig. 3 and Fig. 4. The Volve oil field is geologically complex and requires detailed knowledge of geology, tectonic structures, geophysical-seismic, and petrophysical for better understanding. One of these complications is the number of faults in the field, i.e., 54 faults (3D geostatistical model of the reservoir is indicated in Fig. 5). Therefore, accurate estimation of petrophysical and geomechanical parameters with this range of anisotropy is a very complex and difficult task and requires sufficient experimental knowledge in the field of geology, petrophysics, and geomechanics.

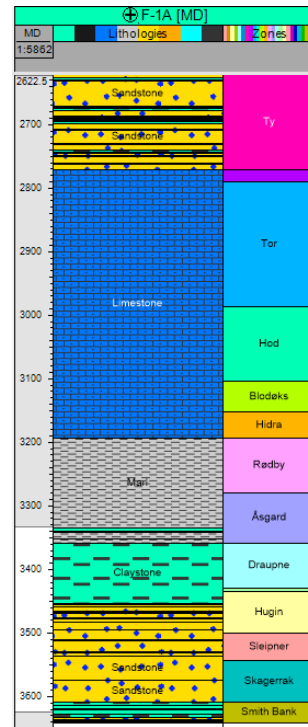


Fig. 3. Stratigraphic column of studied zones and formations for well F-1A in Volve oil field, Norway

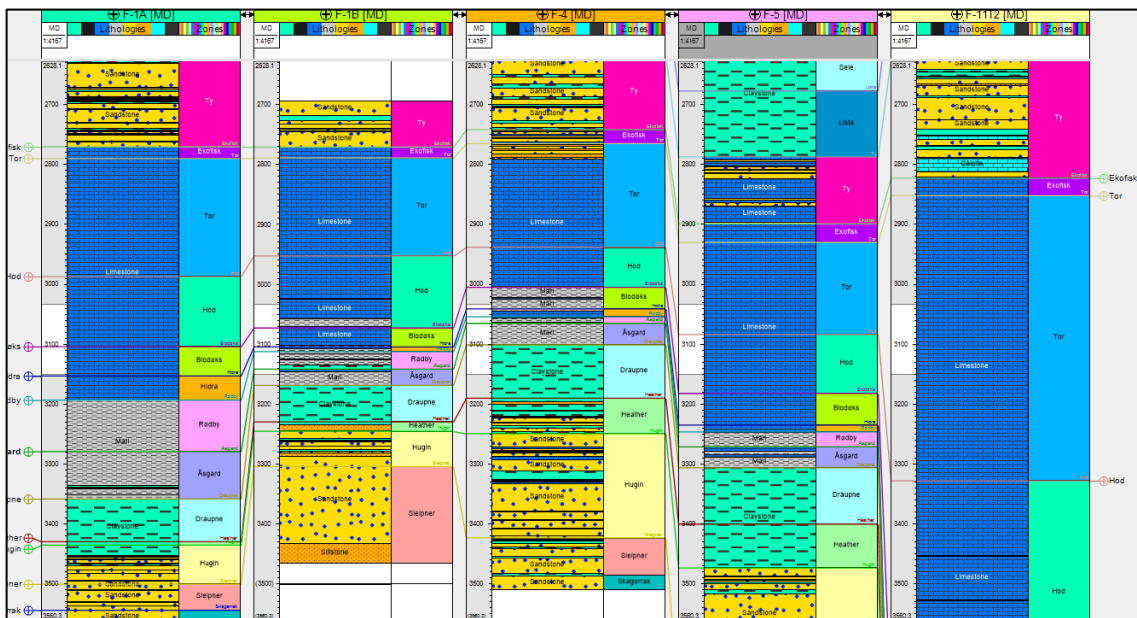


Fig. 4. Stratigraphic column of studied zones and formations in the Volve oil field, Norway

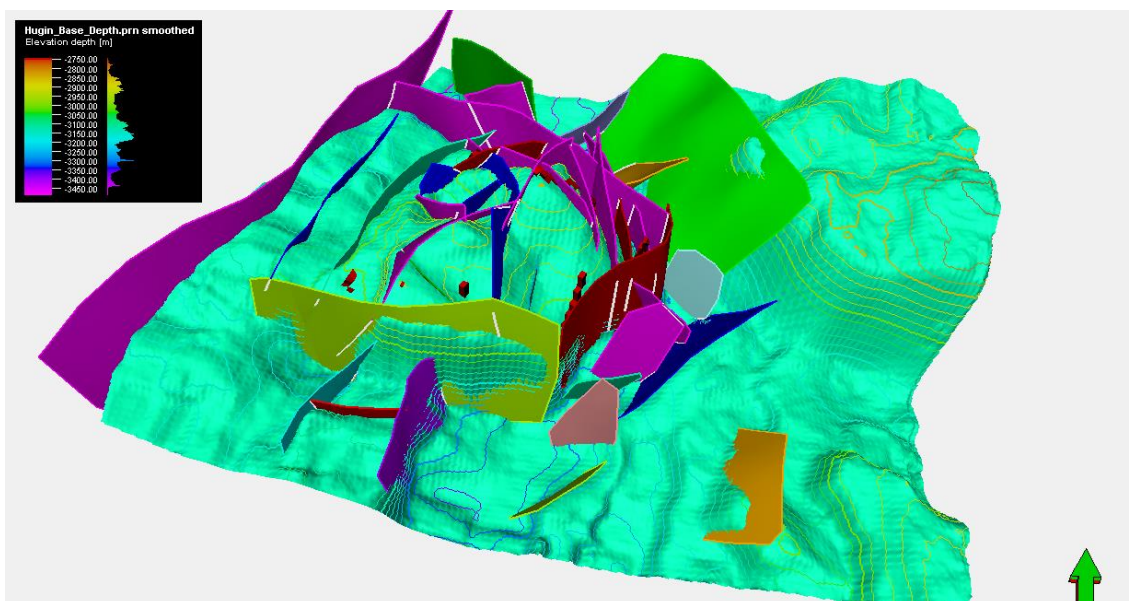


Fig. 5. Three-dimensional view of Volve oil field, Norway

#### 4. Estimation of pore pressure and minimum horizontal stress

So far, several methods have been presented to measure or estimate pore pressure and minimum horizontal stress in the oil and gas industry. The methods of measuring pore pressure and minimum horizontal stress are generally expensive and very limited. The presented methods for estimating pore pressure and minimum horizontal stress based on well logs can provide correct values when the parameters of the models are selected and calculated appropriately.

As stated above, the purpose of this study is to emphasize the ability of classical Newton method to accurately calculate the parameters of any structural model that can be presented based on measured data. Therefore, in this research, two empirical models are chosen to estimate pore pressure and minimum horizontal stress so that these parameters can be accurately and automatically estimated using the ability of Newton's classical optimization method. It means this scheme can be applied to any models and their appropriate parameters can be proposed automatically.

##### 4.1. Estimation of pore pressure

Pore pressure is one of the most significant parameters for geomechanical and geological analyses which usually ranges from hydrostatic pressure to overpressure. Pore pressure can be

calculated from well log data using various empirical equations such as Eaton (1975), Gardner et al. (1974), Bowers (1995), etc. In this section as expressed above, the Eaton model is chosen to demonstrate the ability of Newton's classical optimization method to automatically estimate pore pressure. Pore pressure can be estimated from resistivity and sonic logs using the well-known Eaton equation (Eaton 1975). Eaton's method is one of the conventional methods of pore pressure prediction, which considers compaction disequilibrium as the main mechanism of overpressure generation. Eaton's equation is:

$$p_p = S_v - (S_v - p_{hyd}) \times \left( \frac{DT_n}{DT} \right)^a \quad (6)$$

where  $S_v$  is the overburden stress and  $DT$  is the measured sonic transit time available from compressional sonic well logs. The  $DT_n$  is the sonic transit time on the normal line which can be estimated using the Zhang's equation (Zhang 2011), as follows:

$$DT_n = DT_{sh} + (DT_{ml} - DT_{sh})e^{-cz} \quad (7)$$

where  $DT_{sh}$  is the compressional transit time in the shale matrix,  $DT_{ml}$  is the mudline transit time,  $c$  is the constant, and  $z$  is the depth. The hydrostatic pressure  $p_{hyd}$  is:

$$p_{hyd} = \int_0^z \rho_w(z) g dz \quad (8)$$

where  $\rho_w$  is the density of water. In this study, the average gradient of hydrostatic pressure is

1.03 g/cm<sup>3</sup>.

#### 4.1. Estimation of minimum horizontal stress

Minimum horizontal stress is one of the most important parameters for geomechanical analyses. The minimum horizontal stress can be estimated from well log data using various empirical equations such as Eaton (1968), Blanton and Olson (1999), poroelastic equations (Fjar et al. 2008), etc. In this section, as stated above, the Blanton model is selected to provide the capability of Newton's classical optimization method to automatically estimate the minimum horizontal stress.

The minimum horizontal stress  $S_h$  can be calculated using the Blanton's relationship (Blanton and Olson 1999), as follows:

$$S_h = k * (S_v - p_p) + p_p + S_{tec} \quad (9)$$

where  $S_v$  is the vertical stress,  $p_p$  is the pore pressure, and  $k$  is the coefficient of earth stress. The tectonic stress  $S_{tec}$  is represented as (Daines 1982):

$$S_{tec} = F - [(S_v - p_p) * (\frac{\nu}{1-\nu}) + p_p] \quad (10)$$

where  $F$  is the fracture reopening and  $\nu$  is the Poisson's ratio.

### 5. Applied Newton method for parameters estimation

In this section, the parameters of the Eaton and Blanton model are computed using the classical Newton method in order to estimate pore pressure and minimum horizontal stress, respectively.

#### 5.1. Estimation of pore pressure using Newton method

To determine the pore pressure at the desired depth, firstly, the quantity of vertical stress  $S_v$  and hydrostatic pressure  $p_{hyd}$  are calculated. Then, the quantity of  $DT_n$  is estimated using Zhang's equation which has an unknown parameter, namely  $c$ . The objective function in Eq. (7) to adjust the parameter of the Zhang method from well-logging data is expressed as follows:

$$f_{zhang} = \sum_{i=1}^{npts} \Delta \cdot \Delta \quad (11)$$

where

$$\Delta = DT_n - DT_{sh} - (DT_{ml} - DT_{sh})e^{-cz} \quad (12)$$

where  $npts$  is the number of data. The parameter  $c$  is computed using Newton method in Eq. 2.

The Hessian matrix  $[\mathbf{Hf}_{zhang}]^{-1}$  and the gradient of objective function  $\nabla f_{zhang}$  are defined as follows:

$$[\mathbf{Hf}_{zhang}] = J(\nabla f_{zhang})^T \quad (13)$$

$$\nabla f_{zhang} = \left( \frac{\partial f_{zhang}}{\partial c} \right) \quad (14)$$

After estimating the constant  $c$ , the quantity of  $DT_n$  is obtained. The parameter  $a$  in the Eaton's equation can be defined as an unknown or  $a = 3$ . If the parameter  $a$  is unknown, the objective function in Eq. (6) to adjust the parameter of the Eaton method from measured data is expressed as follows:

$$f_{eaton} = \sum_{i=1}^{npts} \Delta \cdot \Delta \quad (15)$$

where

$$\Delta = p_p - S_v + (S_v - p_{hyd}) \times \left( \frac{DT_n}{DT} \right)^a \quad (16)$$

The parameter  $a$  is computed using Newton method in Eq. 2. The Hessian matrix  $[\mathbf{Hf}_{eaton}]^{-1}$  and the gradient of objective function  $\nabla f_{eaton}$  are defined as follows:

$$[\mathbf{Hf}_{eaton}] = J(\nabla f_{eaton})^T \quad (17)$$

$$\nabla f_{eaton} = \left( \frac{\partial f_{eaton}}{\partial a} \right) \quad (18)$$

#### 5.2. Estimation of minimum horizontal stress using Newton method

To estimate minimum horizontal stress at the desired depth, firstly, the quantities of vertical stress  $S_v$ , pore pressure  $p_p$ , and tectonic stress  $S_{tec}$  are computed. The objective function in the Eq. (9) to adjust the parameter of Blanton method from measured data is expressed as follows:

$$f_{blanton} = \sum_{i=1}^{npts} \Delta \cdot \Delta \quad (19)$$

where

$$\Delta = S_h - k * (S_v - p_p) - p_p - S_{tec} \quad (20)$$

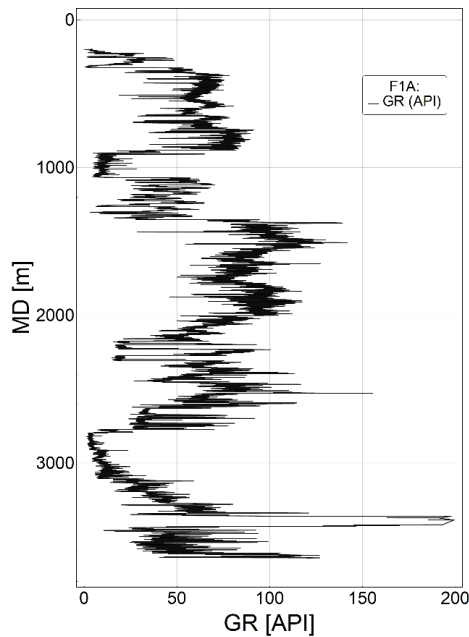
The parameter  $k$  is computed using Newton method in Eq. 2. The Hessian matrix  $[\mathbf{H}f_{\text{blanton}}]^{-1}$  and the gradient of objective function  $\nabla f_{\text{blanton}}$  are defined as follows:

$$[\mathbf{H}f_{\text{blanton}}] = J(\nabla f_{\text{blanton}})^T \quad (21)$$

$$\nabla f_{\text{blanton}} = \left( \frac{\partial f_{\text{blanton}}}{\partial k} \right) \quad (22)$$

## 5. Result and discussions

The purpose of this study is to emphasize the ability of the classical Newton method to compute the appropriate parameters of any model that can calculate the desired values appropriately with the measured data. Therefore, empirical models for estimating pore pressure and minimum horizontal stress including Eaton and Blanton methods are



only selected to demonstrate the capability of the Newton optimization methods to automatically estimate their parameters. In this study, well logs from five wells of the Volve field are used to estimate the pore pressure and minimum horizontal stress.

### 6.1. Determination of pore pressure using well logs

To estimate the pore pressure, sonic logs are used. The normal compaction trend (NCT) of the transit time as proposed in subsection 5.1 is obtained for well F-1A using Newton's method. The result is expressed by Eq. (23), as follows:

$$DT_n = 62 + (183 - 62) \times e^{-0.0012 z} \quad (23)$$

Moreover, the result expressed in Eq. 23, is shown in Fig. 6.

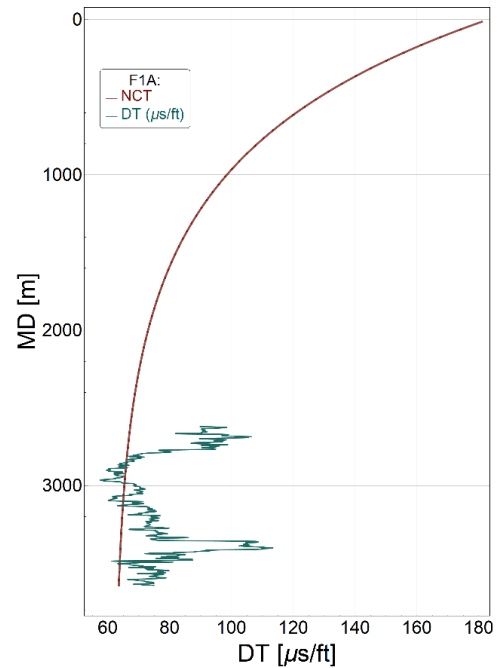


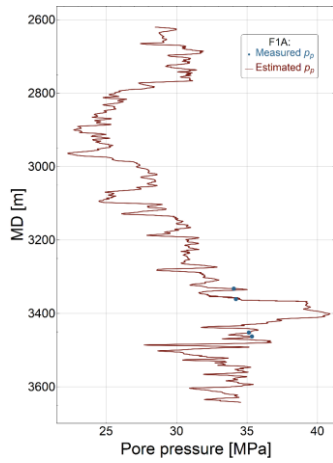
Fig. 6. The graphs of (left) gamma-ray log, and (right) normal compaction trend (NCT) for well F-1A

By replacing Eq. (23) into Eq. (16), Eaton's equation can be presented as:

$$p_p = S_v - (S_v - p_{hyd}) \times \left( \frac{62 + (183 - 62) \times e^{-0.0012 z}}{DT} \right)^a \quad (24)$$

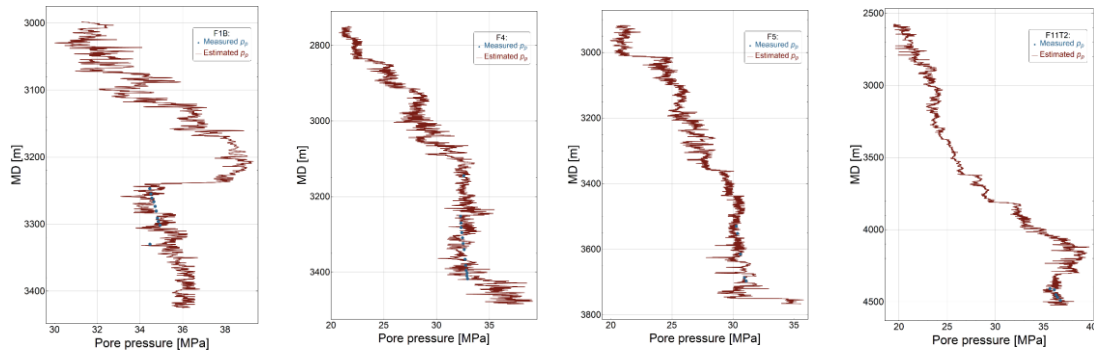
To accurately estimate pore pressure, the Eaton's exponent, which is normally 3, sometimes is

required to be modified. If the parameter  $a$  is unknown, the pore pressure given in subsection 5.1 for well F-1A is calculated using Newton's method. The exponent  $a$  is obtained using the Newton optimization method, which is  $a = 0.96$ . Finally, by replacing all the parameters in Eq. (24), the pore pressure can be obtained. The pore pressure is obtained for well F-1A and illustrated in Fig. 7.



**Fig. 7.** Pore pressure for well F-1A of Volve oil field

The mentioned procedure for well F-1A is repeated for the other four wells in the Volve oil field, and the pore pressure estimation results of the other four wells are presented in Fig. 8. Fig. 8 displays that the predicted pore pressure values are in good agreement with the measured data. The results clearly show the ability of Newton's optimization method to estimate pore



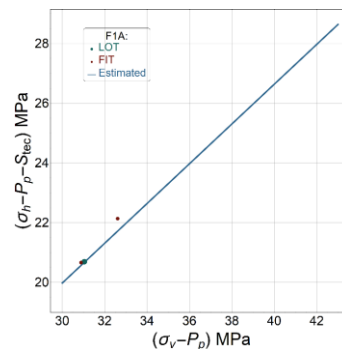
**Fig. 8.** Pore pressure for four wells, namely F1B, F4, F5, and F11T2 of Volve field

The minimum horizontal stress as expressed in subsection 5.2 is obtained for well F-1A using the Newton's method. The coefficient of earth's stress  $k$  by using the Newton optimization is obtained. The procedure to calculate the constant  $k$  is indicated in Fig. 9. The coefficient of earth's stress  $k$  is obtained using the Newton optimization, which is  $k = 0.666$ . Then, by replacing the parameter  $k$  in Eq. (9), the minimum horizontal stress can be estimated. The minimum horizontal stress is obtained for well F-1A and illustrated in Fig. 10.

pressure.

**6.2. Determination of minimum horizontal stress using well logs**

To estimate the minimum horizontal stress, sonic logs are used. It is essential to mention that the number of Leakoff tests (LOT) and minifrac tests in the Volve oil field is limited. However, the number of Formation integrity tests (FIT) is remarkable. Therefore, in this study where the LOT test did not exist, we tried to increase the LOT test information by developing a relationship between the LOT test and the FIT test in order to increase the accuracy of horizontal stress estimation. It should be noted that the study of Volve oil field data showed that the amount of stress presented by the FIT test is approximately 95% of the LOT test. Therefore, after estimating the minimum horizontal stress, the values of the LOT test are approximately 5% less than the estimated minimum horizontal stress. This process was performed for five wells in the Volve oil field.



**Fig. 9.** The procedure to calculate the constant  $k$  using the Newton optimization method

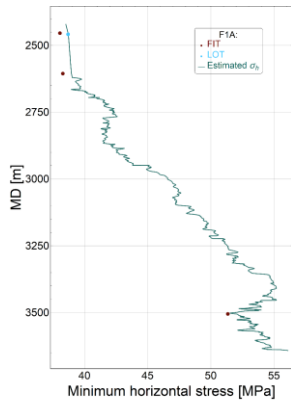


Fig. 10. Pore pressure for well F-1A of Volve oil field

The mentioned procedure for well F-1A is repeated for the other four wells in the Volve oil field, and the minimum horizontal stress estimation results of the other four wells are presented in Fig. 11.

Fig. 11 shows that the predicted minimum horizontal stress values are in good agreement with the measured data. The results clearly illustrate the capability of the Newton's optimization procedure to estimate the minimum horizontal stress.

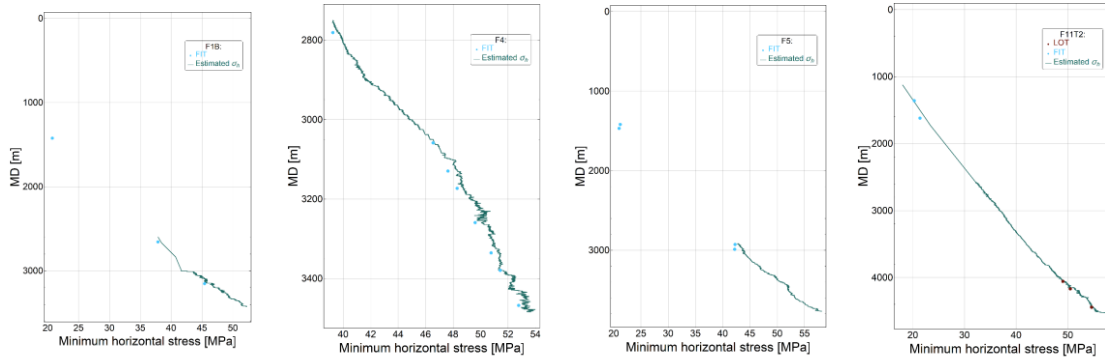


Fig. 11. Minimum horizontal stress for four wells, namely F1B, F4, F5, and F11T2 of Volve field

To emphasize the ability of the classical Newton method to estimate pore pressure and minimum horizontal stress using the well log data, the results of pore pressure, hydrostatic pressure, minimum horizontal stress, and vertical stress for well F-1A are presented in Fig. 12.

Finally, the results of pore pressure and minimum horizontal stress for the other four wells are illustrated in Fig. 13. The results of Fig. 13 clearly emphasize the capability of the proposed procedure to estimate the pore pressure and minimum horizontal stress.

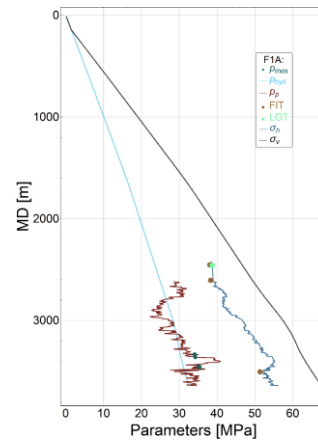
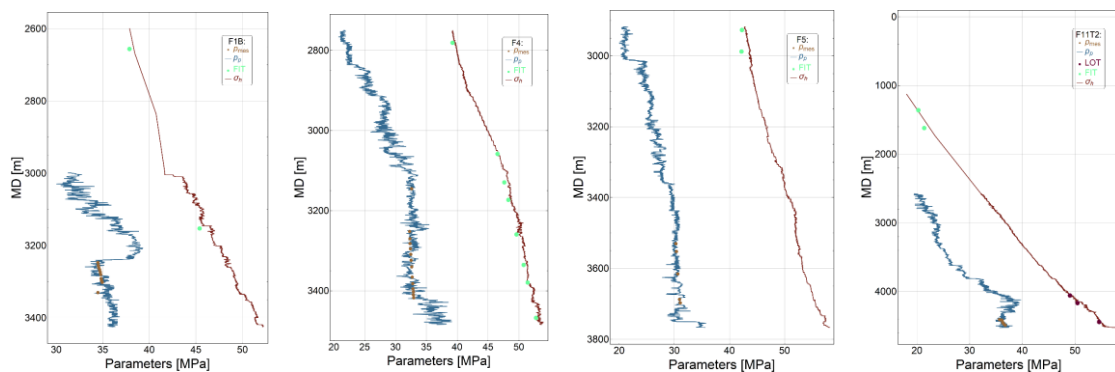


Fig. 12. All parameters were measured and estimated for well F-1A of the Volve oil field



**Fig. 13.** Pore pressure and minimum horizontal stress for four wells, namely F1B, F4, F5, and F11T2 of Volve Field

## 7. Conclusions

In this study, the ability of the classical Newton method to estimate reservoir pore pressure and minimum horizontal stress using log data belonging to five wells of the Volve field, Norway was demonstrated. Pore pressure was estimated using the combination of Eaton's method and Newton's optimization method based on the data of the sonic well logs. The results indicated that the pore pressure was estimated with good precision for all five wells. The minimum horizontal stress was estimated by applying the combination of Blanton's method and Newton's optimization method based on well log data. The results showed that the minimum horizontal stress was correctly estimated.

## Acknowledgments

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## Data Available Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

## Conflict of Interest

The authors declared that they have no conflicts of interest in this work.

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