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# REINTERPRETATION OF THE RESULTS OF THE TWO-CYCLE RESERVOIR TEST OF THE MESOZOIC WATER-BEARING DEPOSITS IN THE W-3 WELL IN TERMS OF ASSESSING THE CHANGES IN ROCK PERMEABILITY IN THE ZONES TESTED WITH A DRILL STEM TESTER**

## 1. INTRODUCTION

In oil prospection, as well as in the exploration of thermal water deposits, tests with tubular DST probes (Drill Stem Test) are commonly used. Testing with the help of DST is an important final stage of exploration work, deciding on the further destiny of prospective exploratory levels provided by the borehole and separated by geophysical methods. These tests are currently playing an increasingly important role in the field of assessment of rock permeability changes in the test zone. These changes may be caused by technological factors during the drilling and testing of perspective levels, or it may also be natural variation in radial composite reservoirs [3].

In the case of the two-cycle DST test technology, it is possible to perform a comparative analysis of the data interpretation results obtained in the first and second test cycles. The run times of the first and second test cycles are selected so that the radius of the tested perspective level zone is larger in the second cycle. This allows the assessment of changes in rock permeability in the DST deposit test process in the proximal and distal near-well zones.

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## 2. TECHNICAL AND TECHNOLOGICAL PARAMETERS OF THE TWO-CYCLE TEST No. 56/97 OF THE MESOZOIC STRATA IN THE W-3 WELL PROFILE

The prospective level of the Mesozoic strata in the area of the Carpathian Foredeep was separated in the W-3 exploratory well profile by well-logging [4] and intended for DST. Two-cycled sampling of this level was carried out (Fig. 1) in the non-vented section of the borehole 9 days after drilling. A scavenger with a density of 1200 kg/m$^3$ and a column height of 110 m was used. During the first and second inflow period, a weak outflow of air from the sampling line was observed. After extracting the probe, the reservoir water was found (volume of approximately 6.3 m$^3$), with natural gas symptoms. The salinity of the reservoir water was approximately 91.83 g/dm$^3$ NaCl.

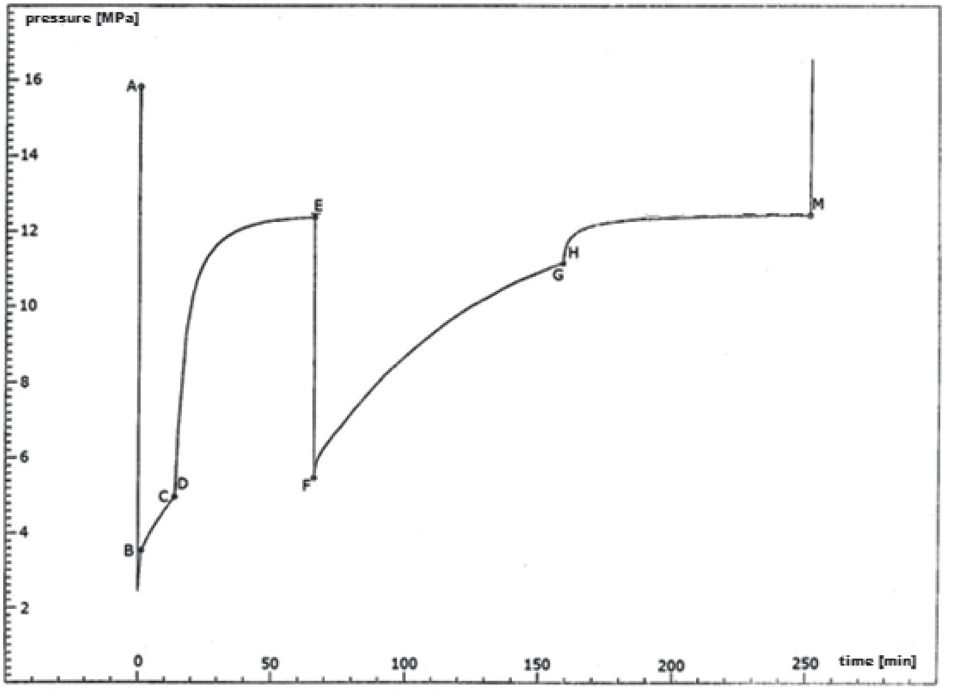


**Fig. 1.** Diagram of changes in bottom pressure recorded during a two-cycle DST test of Mesozoic strata in the W-3 well [4]

### Technical and reservoir parameters

Stratigraphy: Upper Jurassic – Lower Cretaceous; sampled interval: (1334–1356) m; depth of manometer: 1327 m; well diameter: 216 mm; internal diameter of the test line:

85 mm; thickness of the reservoir level determined by well-logging: 8 m; porosity of the reservoir rock determined by well-logging: 10%.

**Physical parameters of reservoir water**

Water density: $\rho_w$ = 1065 kg/m$^3$; coefficient of dynamic viscosity of water in reservoir conditions: $\mu_w$ = 0.9·10$^{-3}$ Pa·s; coefficient of compressibility of reservoir water: $c_w$ = 5·10$^{-10}$ 1/Pa.

**Technological parameters of the DST test** (Fig. 1)

Hydrostatic pressure of the mud column in the well $P_A$ = 15.81 MPa; pressure at the initial point of the first inflow wave curve $P_B$ = 3.54 MPa; pressure at the end point of the first inflow curve $P_C$ = 4.97 MPa; pressure at the initial point of the second inflow curve $P_F$ = 5.47 MPa; pressure at the end point of the second inflow curve $P_G$ = 11.14 MPa; initial pressure depression during testing: 10,021 MPa; time of the first deposit fluid flow period $t_1$ = 12.5 min; time of the first period of the bottom pressure build-up $\Delta t_1$ = 51.9 min; time of the second period of reservoir fluid flow $t_2$ = 92.7 min; time of the second period of the bottom pressure build-up $\Delta t_2$ = 93.0 min.

## 3. REINTERPRETATION OF THE RESULTS OF THE FIRST CYCLE OF THE DST TEST No. 56/97 OF THE MESOZOIC STRATA IN THE W-3 WELL

The flow rate of the reservoir water inflow to the sampler line, in the first test cycle, is determined from formula (1), based on the increase in bottom pressure during the first inflow period in bottom conditions:

$$Q_{w1} = \frac{\pi \cdot d_w^2 \cdot (P_C - P_B)}{4 \cdot t_1 \cdot \gamma_w} \ [\mathrm{m^3/s}] \tag{1}$$

After substituting numerical values for formula (1), it was obtained: $\boldsymbol{Q_{w1}}$ **= 1.03·10$^{-3}$ m$^3$/s**.

**The value of the reservoir pressure** in the case of two-part dispersion of points as in Figure 2 is determined on the basis of the linear regression equation of the second section: $\boldsymbol{p_{z1}}$ **= 12.722 MPa**.

**Values of directional coefficients** of straight lines (Fig. 2), determined on the basis of linear regression equations are:

– for the perimeter zone $m_1'$ = 7.24 MPa/cycle log (line 1),
– for the zone remote from the wellbore $m_1''$ = 3.75 MPa/cycle log (line 2).

**Table 1**

Coordinates of the points of the first curve of bottom pressure build-up and the corresponding values of the quotient and logarithm of the times quotient

| Size symbol, unit of measurement | The number of the DST test point | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| $P_{di}$ [MPa] | 9.56 | 11.03 | 11.60 | 11.91 | 12.07 | 12.17 | 12.25 | 12.30 | 12.36 | 12.37 |
| $\Delta t_i$ [min] | 5.19 | 10.38 | 15.57 | 20.76 | 25.96 | 31.14 | 36,33 | 41.52 | 46.71 | 51.9 |
| $\frac{t_1 + \Delta t_i}{\Delta t_i}$ | 3.41 | 2.20 | 1.80 | 1.60 | 1.48 | 1.40 | 1.34 | 1.30 | 1.27 | 1.24 |
| $\log\frac{t_1 + \Delta t_i}{\Delta t_i}$ | 0.53 | 0.34 | 0.26 | 0.20 | 0.17 | 0.15 | 0.13 | 0.11 | 0.10 | 0.09 |

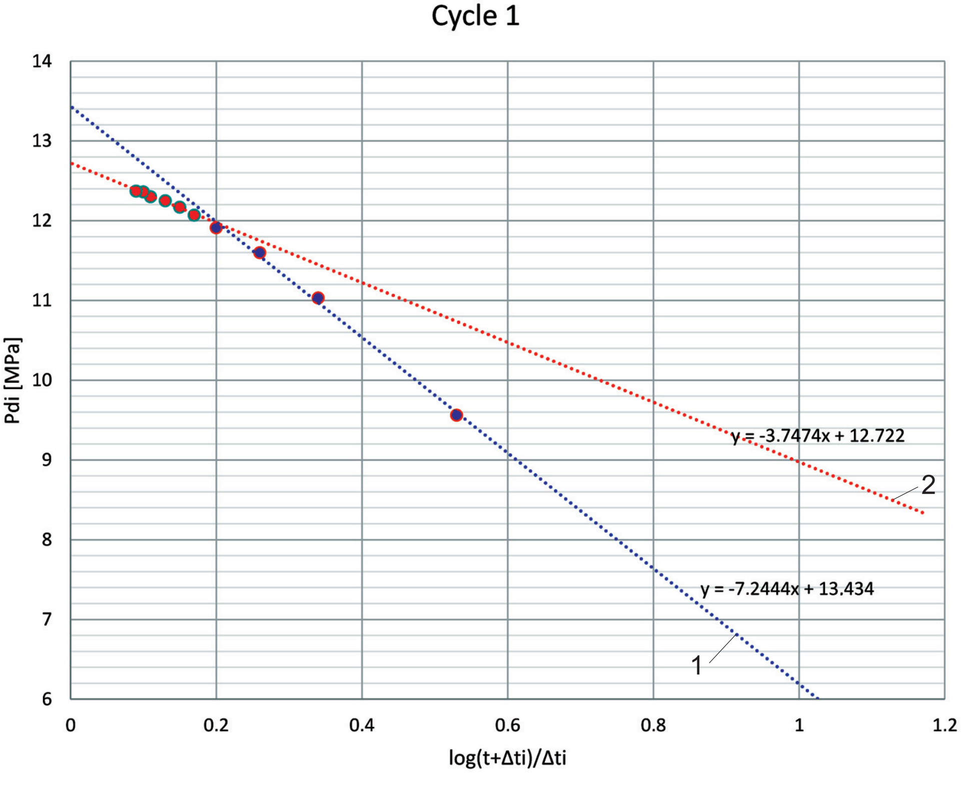


**Fig. 2.** Determination of linear regression equations for two sections of the bottom pressure build-up curve recorded in the first cycle of the DST test in the W-3 well

**The value of the effective permeability coefficient** determined in the reservoir conditions based on the results of the first test cycle, is calculated from formula (2):

$$k_1 = 0.183 \cdot \frac{Q_{w1} \cdot \mu_w}{m_1'' \cdot h} \text{ [m}^2\text{]} \tag{2}$$

The nomenclature is given at the end of the paper.

After substituting the numerical values for formula (2), it was obtained $\boldsymbol{k_1 = 5.65 \cdot 10^{-15}\ \mathrm{m}^2}$.

**The skin-effect value for the reservoir zone** tested in the first cycle was calculated from formula (3):

$$S_1 = 1.151 \cdot \left( \frac{P_{z1} - P_C}{m_1''} - \log \frac{2.25 \cdot k_1 t_1}{f \cdot \mu_w \cdot c_w \cdot r_o^2} \right) \tag{3}$$

After substituting the appropriate numerical values for formula (3), it was obtained $\boldsymbol{S_1 = -2.52}$.

**The radius value of the tested reservoir zone** is calculated from formula (4):

$$R_{b1} = 2 \cdot \sqrt{\frac{k_1 \cdot t_1}{f \cdot \mu_w \cdot c_w}} \text{ [m]} \tag{4}$$

After substituting the appropriate numerical values for formula (4), it was obtained $\boldsymbol{R_{b1} = 19.4\ \mathrm{m}}$.

**The radius of the perimeter zone with changed permeability of reservoir rocks $\boldsymbol{R_{z1}}$** was determined on the basis of the approximation of the exponential value of the integral function with the value of the logarithmic function at the breakpoint of the straight line (the curve of bottom pressure build-up in the semi-logarithmic coordinate system). The so-called "logarithmic approximation" known in hydrogeology are used [2]:

$$-Ei(-x) \approx \ln \frac{t + \Delta t_z}{\Delta t_z} \approx 2.3 \log \frac{t + \Delta t_z}{\Delta t_z} \tag{5}$$

where $\Delta t_z$ is the time corresponding to the breakpoint of the straight line in the semi-logarithmic coordinate system (Fig. 2), whereas $x$ is calculated from the dependence:

$$x = \frac{R_z^2 \cdot f_w \cdot \mu_w \cdot c_w}{k \cdot \Delta t_z} \tag{6}$$

After transformation of the dependence (6), the relationship is obtained to determine the value of the radius of the rock zone with changed permeability, which for the first cycle of the DST test takes the form (7):

$$R_{z1} = \sqrt{\frac{x \cdot k_1 \cdot \Delta t_{z1}}{f_w \cdot \mu_w \cdot c_w}} \text{ [m]} \tag{7}$$

The collapse of the bottom pressure build-up curve in the first cycle of the DST test (Fig. 2) occurs after the time $\Delta_{tz1}$ since the periodic valve closing, for which the value of the decimal logar is:

$$\log \frac{t_1 + \Delta t_{z1}}{\Delta t_{z1}} = 0.2 \quad \text{(Tab. 1, Fig. 2).}$$

Thus, the function value calculated from formula (5) is:

$$-Ei(-x) \approx 2.3 \log \frac{t + \Delta t_{z1}}{\Delta t_{z1}} = 2.3 \cdot 0.2 = 0.46.$$

However, the value $x_1 \approx 0.6$ [1] and is read from the tables for this function value.

Thus, calculated from formula (7) the value of the radius of the zone of reservoir rocks with changed permeability, $\boldsymbol{Rz_1 = 9.69}$ **m**.

## 4. REINTERPRETATION OF THE RESULTS OF THE SECOND CYCLE OF THE DST TEST No. 56/97 OF THE MESOZOIC STRATA IN THE W-3 WELL

**The flow rate of the reservoir fluid flow** to the sampler line in the second test cycle was calculated from formula (8), based on the increase in bottom pressure during the second inflow period (Fig. 1):

$$Q_{w2} = \frac{\pi \cdot d_w^2 \cdot (P_G - P_F)}{4 \cdot t_2 \cdot \gamma_w} \text{ [m}^3\text{/s]} \tag{8}$$

After substituting the appropriate numerical values for formula (8), it was obtained $\boldsymbol{Q_{w2} = 0.554 \cdot 10^{-3}}$ $\boldsymbol{m^3/s}$.

**The reservoir pressure** determined on the basis of the extrapolation of the bottom pressure build-up curve recorded in the second cycle of the DST test (Fig. 3, line 2) is: $\boldsymbol{P_{z2} \approx 12.51}$ **MPa**.

**Table 2**

Coordinates of the points of the second curve of bottom pressure build-up and the corresponding values of the quotient and logarithm of the times quotient

| Size symbol, unit of measurement | The number of the DST test point | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| $P_{di}$ [MPa] | 12.09 | 12.22 | 12.30 | 12.34 | 12.35 | 12.36 | 12.38 | 12.39 | 12.40 | 12.41 |
| $\Delta t_i$ [min] | 9.3 | 18.6 | 27.9 | 37.2 | 46.5 | 55.8 | 65.1 | 74.4 | 83.7 | 93.0 |
| $\frac{t_1+\Delta t_i}{\Delta t_i}$ | 10.97 | 5.98 | 4.32 | 3.49 | 2.99 | 2.66 | 2.42 | 2.25 | 2.11 | 2.00 |
| $\log\frac{t_1+\Delta t_i}{\Delta t_i}$ | 1.04 | 0.78 | 0.64 | 0.54 | 0.48 | 0.43 | 0.38 | 0,35 | 0.32 | 0.30 |

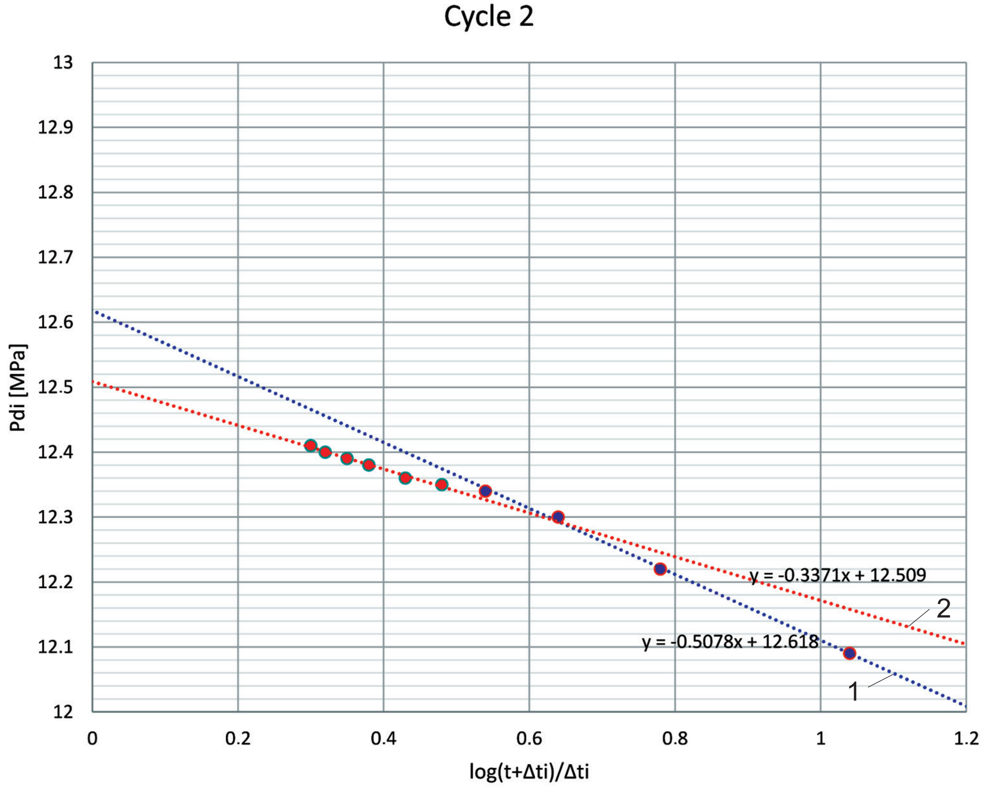


**Fig. 3.** Determination of linear regression equations for two sections of the bottom pressure build-up curve recorded in the second cycle of the DST test in the W-3 well

**The value of the reservoir pressure** in the case of two-part dispersion of points as in Figure 3 is determined on the basis of the linear regression equation of the second section: $\boldsymbol{p_{z1}}$ **= 12.509 MPa.**

**Values of directional coefficients** of straight lines (Fig. 3), determined on the basis of linear regression equations are:

- for the perimeter zone $m_2' = 0.51$ MPa/cycle log (line 1),
- for the zone remote from the wellbore $m_2'' = 0.34$ MPa/cycle log (line 2).

**The value of the effective permeability coefficient** determined in the reservoir conditions based on the results of the second test cycle, is calculated from formula (9):

$$k_2 = 0.183 \cdot \frac{Q_{w2} \cdot \mu_w}{m_2'' \cdot h} \ [\mathrm{m}^2] \tag{9}$$

After substituting the numerical values for formula (9), it was obtained $\boldsymbol{k_2 = 33.55 \cdot 10^{-15}\ m^2}$.

**The skin-effect value for the reservoir zone** tested in the second cycle was calculated from formula (10):

$$S_1 = 1.151 \cdot \left( \frac{P_{z2} - P_C}{m_2''} - \log \frac{2.25 \cdot k_2 t_2}{f \cdot \mu_w \cdot c_w \cdot r_o^2} \right) \tag{10}$$

After substituting the appropriate numerical values for formula (10), it was obtained $\boldsymbol{S_2 = -1.50}$.

**The radius value of the tested reservoir zone** is calculated from formula (11):

$$R_{b2} = 2 \cdot \sqrt{\frac{k_2 \cdot t_2}{f \cdot \mu_w \cdot c_w}} \ [\mathrm{m}] \tag{11}$$

After substituting the appropriate numerical values for formula (11), it was obtained $\boldsymbol{R_{b2} = 128.8\ m}$.

The collapse of the bottom pressure build-up curve in the first cycle of the DST test (Fig. 2) occurs after the time $\Delta t_{z1}$ since the periodic valve closing, for which the value of the decimal logar is:

$$\log \frac{t_1 + \Delta t_{z1}}{\Delta t_{z1}} = 0.2 \quad \text{(Tab. 1, Fig. 2).}$$

Thus, the function value calculated from formula (5) is:

$$-Ei(-x) \approx 2.3 \log \frac{t + \Delta t_{z1}}{\Delta t_{z1}} = 2.3 \cdot 0.2 = 0.46.$$

However, the value $x_1 \approx 0.6$ [1] and is read from the tables for this function value.

Thus, calculated from formula (7) the value of the radius of the zone of reservoir rocks with changed permeability, $\boldsymbol{Rz_1 = 9.69}$ **m**.

**The radius of the zone of reservoir rocks with changed permeability for the second cycle** $\boldsymbol{R_{z2}}$ is calculated from equation (12):

$$R_{z2} = \sqrt{\frac{x \cdot k_2 \cdot \Delta t_{z2}}{f \cdot \mu_w \cdot c_w}} \tag{12}$$

where $\Delta_{tz2}$ corresponds to the breakpoint of this bottom pressure build-up line in the semi-logarithmic coordinate system (Fig. 3).

The collapse of the bottom pressure build-up curve in the second cycle of the DST test (Fig. 3) occurs after the time $\Delta_{tz2}$ since the periodic valve closing, for which the value of the decimal logar is:

$$\log \frac{t_1 + \Delta t_{z1}}{\Delta t_{z1}} = 0.64 \quad \text{(Tab. 2, Fig. 3).}$$

Thus, the function value calculated from formula (5) is

$$-Ei(-x) \approx 2.3 \log \frac{t + \Delta t_{z1}}{\Delta t_{z1}} = 2.3 \cdot 0.64 = 1.47.$$

However, the value $x_2 \approx 0.15$ [1] and is read from the tables for this function value.

Thus, calculated from formula (12) the value of the radius of the zone of reservoir rocks with changed permeability, $\boldsymbol{Rz_2 \approx 13.7}$ **m**.

## 5. CONCLUSIONS

1. Based on the reinterpretation of the results of the DST deposit test No. 56/97 in the W-3 well, it was found that the tested water-bearing Mesozoic strata are characterized by good permeability of reservoir rocks in the tested zone of the reservoir, but this permeability is much lower in the near-wellbore zone than in a zone distant from the well.
2. Determination of linear regression equations for individual sections of the first and second pressure build-up curve in the semi-logarithmic system enabled accurate determination of the reservoir pressure value and directional coefficients of the analyzed straight lines.

3. The application of the logarithmic approximation method to determine the radius of the near-wellbore zone with changed permeability of aquifers allowed for the final evaluation of these changes in the zones tested with the sampler.
4. The graph of the pressure build-up curve in the semi-logarithmic system is a line consisting of two sections with differing slopes ($m_2 < m_1$), which proves the beneficial process of self-cleaning rocks from the creeper. This is also indicated by the negative skin-effect value calculated on the basis of the first and second DST test cycles.
5. Comparing the values of calculation results for selected reservoir parameters and indicators for the first and the second cycles, it is stated that during the DST test, as a result of pressure during the depression test, self-cleaning of rocks in the near-well zone from the scraping substance may have occurred. The phenomenon was more intense in the first cycle than in the second one, because the flow rate of the reservoir water flow was higher in the first cycle than in the second one. The good reservoir properties of the studied water-bearing pore-fractured Mesozoic strata were conducive to this phenomenon.

## NOMENCLATURE

$c_w$ – coefficient of compressibility of the reservoir fluid [1/Pa],
DST – Drill Stem Test,
$D_o$ – diameter of the borehole [m],
$d_w$ – internal diameter of mud tubes [m],
$f$ – porosity of reservoir rocks (decimal fraction)
$h$ – the thickness of the reservoir rock layer [m],
$H_m$ – the depth of the manometer [m],
$h_p$ – height of the mud column (stemming) [m],
$k_1$ – effective permeability of rocks determined on the basis of the results of the first cycle of the DTS test [m$^2$],
$k_2$ – effective permeability of rocks determined on the basis of the results of the second cycle of the DST test [m$^2$],
$m'_1$ – directional coefficient of dependence $P_{di} = f((t+\Delta t_i)/\ \Delta t_i)$, in the near-well zone, determined on the basis of the results of the first cycle of the DST test (Fig. 2, line 1) [MPa/cycle log],
$m''_1$ – directional coefficient of dependence $P_{di} = f((t+\Delta t_i)/\ \Delta t_i)$, in the zone away from the borehole wall, determined on the basis of the first test cycle DST (Fig. 2, line 2) [MPa/cycle log],

$m'_2$ – directional coefficient of dependence $P_{di} = f((t+\Delta t_i)/\ \Delta t_i)$, in the near-well zone, determined on the basis of the results of the first cycle of the DST test (Fig. 3, line 1) [MPa/cycle log],

$m''_2$ – directional coefficient of dependence $P_{di} = f((t+\Delta t_i)/\ \Delta t_i)$, in the zone away from the borehole wall, determined on the basis of the first test cycle DST (Fig. 3, line 2) [MPa/cycle log],

$P_A$ – hydrostatic mud pressure [MPa],

$P_B$ – pressure at the initial point of the first inflow curve [MPa],

$P_C$ – pressure at the end point of the first inflow curve [MPa],

$P_F$ – pressure at the initial point of the second inflow curve [MPa],

$P_G$ – pressure at the end point of the second inflow curve [MPa],

$P_{di}$ – bottom pressure at the *i*-th point of the DST test [MPa],

$P_{z1}$ – reservoir pressure determined on the basis of the results of the first DST cycle [MPa],

$P_{z2}$ – reservoir pressure determined on the basis of the results of the second DST cycle [MPa],

$Q_{w1}$ – flow rate of the reservoir fluid flow in the first DST cycle [$m^3/s$],

$Q_{w2}$ – flow rate of the reservoir fluid flow in the second DST cycle [$m^3/s$],

$R_{b1}$ – the radius of the tested zone determined on the basis of the results of the first DST cycle [m],

$R_{b2}$ – the radius of the tested zone determined on the basis of the results of the second DST cycle [m],

$R_{z1}$ – radius of the near–wellbore zone, with changed permeability, determined on the basis of the results of the first DST cycle [m],

$R_{z2}$ – radius of the near–wellbore zone, with changed permeability, determined on the basis of the results of the second DST cycle [m],

$S_1$ – skin–effect, determined based on the results of the first DST cycle,

$S_2$ – skin–effect, determined based on the results of the second DST cycle,

$t_1$ – duration of the first period of the reservoir fluid inflow [min],

$t_2$ – duration of the second period of the reservoir fluid inflow [min],

$\Delta t_1$ – duration of the first period of bottom pressure build-up [min],

$\Delta t_2$ – duration of the second period of bottom pressure build-up [min],

$\Delta t_i$ – time of the *i*-th point of registration of the bottom pressure build-up curve [min],

$\Delta t_{z1}$ – duration of the first cycle of bottom pressure build-up, to the point of refraction of the straight line (Fig. 2) [s],

$\Delta t_{z2}$ – duration of the second cycle of bottom pressure build-up, to the point of refraction of the straight line (Fig. 3) [s],

$\beta_w$ – coefficient of change of reservoir fluid volume [$m^3/m^3$],
$\gamma_w$ – specific gravity of reservoir fluid [$N/m^3$],
$\mu_w$ – reservoir water viscosity [Pa·s],
$\rho_w$ – reservoir water density [$kg/m^3$].

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