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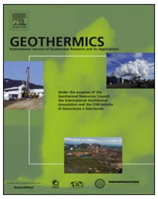

Utilization of the Horner plot for determining the temperature of frozen formations — A novel approach

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ABSTRACT

The most important data on the thermal regime of the Earth's interior come from temperature measurements in deep boreholes. The drilling process greatly alters the temperature field of formations surrounding the wellbore. In permafrost regions, due to thawing of the formation surrounding the wellbore during drilling, representative data can be obtained only by repeated observations over a long period of time (up to 10 years). Usually a number of temperature logs (3–10) are taken after the well's shut-in. Significant expenses are required to monitor the temperature regime of deep wells. In this paper, we introduce a new approach in predicting the undisturbed formations temperatures from shut-in temperature logs in deep wells. The main features of the suggested method are following: the refreezing of the thawed formations (around the wellbore) is completed, the temperature logs are taken after refreezing, the starting point in the well thermal recovery is moved from the end of well completion to the moment of time when the first shut-in temperature log was conducted. It is shown that after refreezing the further cooling of a well can be approximated by a constant (per unit of length) linear heat source. Hence, the Horner equation can be used for predicting the temperature of frozen formations for estimation of the formation temperature. A simple method to process field temperature data is presented. To demonstrate this approach, temperature shut-in time data for four depths from four wells in Alaska were successfully used.

1. Introduction

Temperature logs (we have in mind here a series of punctual temperature measurement along time at a specific depth) are commonly used to determine the permafrost temperature and thickness. Because deep wells in permafrost areas are usually drilled with a warm mud, there is some unknown degree of formation thawing around the well. As a result, the natural temperature field of the formations is disturbed in the vicinity of the borehole and the frozen rocks thaw for some distance from the borehole axis. To determine the static temperature of the formation and permafrost thickness, one must wait for some period after completion of drilling before making geothermal measurements. This is so-called restoration time. The presence of permafrost has a marked effect on the time required for the near-well-bore formations to recover their undisturbed temperatures. The duration of the refreezing of the layer thawed during drilling is very dependent on the natural temperature of formation because the warmest section of the frozen profile will require a longer restoration time; therefore, the rocks at the bottom of the permafrost refreeze very slowly (e.g., Dobinski, 2011). A lengthy restoration period of up to ten years or more is required to determine the temperature and thickness of permafrost with sufficient accuracy (Lachenbruch and Brewer, 1959; Judge, 1973; Melnikov et al., 1973; Judge et al., 1981; Taylor et al., 1982; Clow, 2014). The slow return to thermal equilibrium in the section of the well within permafrost creates serious difficulties in determining the permafrost temperature and thickness. It is clear that in the sections of the borehole below the permafrost, the static (undisturbed) formation temperatures can be predicted from temperature logs taken at relatively short shut-in times. Earlier we proposed "two point method" which permits one to determine the permafrost thickness from short term (in comparison with the time required for temperature restoration) downhole temperature logs (Kutasov, 1999, pp. 125–131).

Only temperature measurements for two depths are needed to determine the geothermal gradient. The position of the permafrost base is predicted by the extrapolation of the static formation temperature − depth curve to 0 °C. The mathematical model of the "two point method" is based on the assumption that in deep wells the effective temperature of drilling mud at a given depth can be considered constant during the drilling process. Precise temperature measurements taken in 15 deep wells located in the Northern Canada (Arctic Islands and Mackenzie

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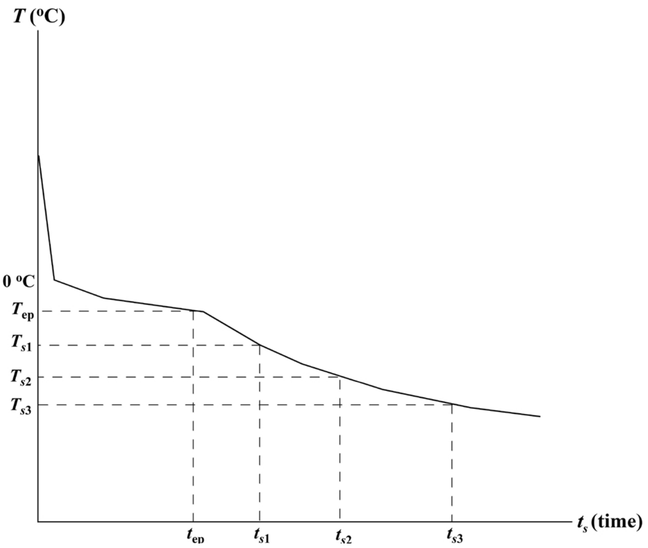

Fig. 1. Shut-in temperatures at a given depth – schematic curve.

Delta) were used to verify the proposed method.

Let us assume that at the moment of time $t = t_{ep}$ the phase transitions (water-ice) in formations at a selected depth are completed, i.e. the thermally disturbed formations (including borehole mud) have frozen. In this case at $t > t_{ep}$ the cooling process is similar to that of temperature recovery in sections of the well below the permafrost base. It is known that only a part of the formation's pore water changes to the ice at 0 °C. With further lowering of the temperature, phase transition of the water continues (Fig. 1), but at steadily decreasing rates. The amount of unfrozen water is practically independent of the total moisture content for a given soil (Tsytovich, 1975). The temperature interval of phase transition depends on mineralogical composition of formations. For example, in some sands the freezing of water is completed at temperature about −2 °C.

In practice, however, the moment of time $t = t_{\rm ep}$ cannot be determined. This can be done only by conducting long-term repetitive temperature observations in deep wells.

Earlier we assumed (Kutasov and Eppelbaum, 2003, 2015) that three shut-in temperatures $T_{\rm s1}$, $T_{\rm s2}$, and $T_{\rm s3}$ are measured at a given depth (Fig. 1). For this case we proposed "Three Point Method" of predicting the formation temperatures (Kutasov and Eppelbaum, 2003, 2015). Because the starting point of thermal recovery is moved to $t = t_{s1}$ (Fig. 1) the application of the "Three Point Method" of predicting the undisturbed formation temperature does not depend: (a) on the well drilling history (vertical depth versus time, stops in mud circulation), drilling technology used (properties of drilling fluids, penetration rate, bit size, casings, cementing techniques). To process field data by the "Three Point Method" a computer program (Kutasov, 1999, pp. 318–320) was prepared. This program allows to determine the formation temperature, the dimensionless radius of thermal influence (R_x) and parameter A.

$$R_x = \frac{r_{ix}}{r_{wx}}, \qquad A = \frac{\gamma}{r_{wx}^2}, \tag{1}$$

where r_{wx} is the radius of a cylindrical source (radius of a borehole) with a constant wall temperature (T_{s1}), r_{ix} is the radius of thermal influence and γ is the thermal diffusivity of frozen formations.

2. Horner equation

The Horner method is widely applied in hydrocarbon engineering (e.g., Kutasov and Eppelbaum, 2005; Goutorbe et al., 2007; Bassam et al., 2010; Espinoza-Ojeda et al., 2011) and for studying hydrogeological characteristics (Beardsmore and Cull, 2001; Morin et al., 2010; Eppelbaum et al., 2014) to process the pressure-build-up test data for wells produced at a constant flow rate. From a simple semilog linear plot, the initial reservoir pressure and formation permeability can be estimated. Using the similarity between the transient response of pressure and temperature build-up, it was suggested to use the Horner method for prediction of formation temperature (in non-permafrost regions) from bottom-hole temperature surveys (Timko and Fertl, 1972; Dowdle and Cobb, 1975; Fertl and Wichmann, 1977; Jorden and Campbell, 1984). It is assumed that the wellbore can be considered as a linear source of heat.

In the Horner method, the thermal effect of drilling is approximated by a constant linear heat source. This energy source is in operation for some time t_c and represents the time elapsed since the drill bit first reached the given depth. For a continuous drilling period, the value of t_c is identical with the duration of mud circulation at a given depth. The well-known solution for the infinitely long linear source with a constant heat flux rate in an infinite-acting medium is (Carslaw and Jaeger, 1959)

$$T_r(r, t) = T_f - B\, Ei\left(-\frac{r^2}{4\gamma t}\right), \qquad B = \frac{q}{4\pi\lambda}, \tag{2}$$

where T_i is the formation temperature, r is the radial distance, q is the heat flow rate per unit length, t is the time, γ is the thermal diffusivity of formation, λ is the thermal conductivity of formations, and Ei is the exponential integral. Some values of thermal properties of formations are presented in the literature (Kappelmeyer and Hänel, 1974; Somerton, 1992; Kutasov, 1999; Eppelbaum et al., 2014).

The expression for the borehole temperature is (Eq. (2) at $r = r_w$) is

$$T_w(r_w, t_c) - T_i = B\, Ei\left(-\frac{1}{4t_{cD}}\right), \qquad t_{cD} = \frac{\gamma\, t_c}{r_w^2}, \tag{3}$$

where t_{cD} is the dimensionless drilling mud circulation time at a given depth, and r_w is the well radius.

Using the principle of superposition, the following equation for shut-in temperature T_s can be obtained:

$$T_s(r_w, t_s) - T_i = \frac{q}{4\pi\lambda}\left[-Ei\left(-\frac{1}{4(t_{cD} + t_{sD})}\right) + Ei\left(-\frac{1}{4t_{sD}}\right)\right], \qquad t_{sD} = \frac{\gamma\, t_s}{r_w^2}, \tag{4}$$

where t_s is the shut-in time and t_{sD} is dimensionless shut-in time. The logarithmic approximation of the exponential integral function (with a good accuracy) is valid for small arguments

$$Ei(-x) = \ln x + 0.57722, \qquad x < 0.01. \tag{5}$$

From Eqs. (4) and (5) we obtain the Horner equation

$$T_s(r_w, t_s) = T_i + B\, \ln\left(1 + \frac{t_c}{\Delta t}\right). \tag{6}$$

In many cases, the dimensionless parameters t_{cD} and t_{sD} are small ones and Eq. (5) cannot be applied.

3. Novel approach

As we mentioned earlier that at $t > t_{ep}$ (Fig. 1) the cooling process is similar to that of temperature recovery in sections of the well below the permafrost base (unfrozen formations). Let us assume the starting point of thermal recovery is at $t = t_0 = t_{s1}$ (Fig. 1). It can happen that to the starting point t_0 (t_{s1}) is less than $t_{\rm ep}$. In this case the starting can be moved to $t_0 = t_{s2}$.

We did not have an access to the drilling histories (reports) of selected boreholes to estimate the time of thermal disturbance, t_c, (at a given depth) caused mainly by circulation of the drilling mud. For this reason, we consider a beginning of thermal disturbance the moment of time when bit reached the given depth and end of thermal disturbance