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Modeling formation resistivity changes due to invasion and deformation during initial leak-off test build-up

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ABSTRACT

Leak-off tests (LOTs) are performed to determine the strength of a newly drilled formation below a cased interval and to characterize the upper bound of mud weight that can be safely used while drilling the next section, without risk of formation breakdown and lost circulation. In an LOT, drilling mud is pumped into the wellbore, causing the wellbore pressure to increase and exceed the formation pore pressure. During the initial LOT build up, excess pressure in the wellbore causes the surrounding rock to deform and mud filtrate to invade into the formation via porous flow. In this paper, change in formation resistivity around a wellbore during initial LOT build-up has been investigated. Invasion is modeled assuming two-phase radial Darcy flow and deformation using a 3D finite element model. Invasion may result in an exchange of conductive ions between water-based drilling mud and formation water both by diffusion in the direction favored by the concentration gradient of the ions and by convective transport. This process is incorporated into the model by solving the radial convection-diffusion equation for the aqueous phase using a finite difference method. Archie's law is used to determine the formation resistivity. Findings show that the direct effect of deformation on porosity, therefore on formation resistivity during an LOT, is negligibly small even when the formation rock is highly compressible with compressibility in the order of 10^{-3} psi^{-1}. While salinity solely controls formation resistivity during an LOT conducted in a fully water-saturated interval, water saturation change and salinity change compete to produce a compound effect on formation resistivity of an oil-bearing zone where water saturation varies dynamically due to displacement of formation fluids. Unlike compressibility, the effect of permeability on formation resistivity response is found to be evident and readily observable. While analyzing the formation resistivity responses at various depths of investigation (DOIs), it is found that the effect of DOI on resistivity response can be useful in studying invasion and assessing formation damage during an LOT. In addition to this, through comparing time-lapse resistivity logs at multiple DOIs during an LOT with numerically synthesized resistivity responses, the model promises a novel approach towards determining the permeability of a freshly drilled and unaltered interval.

1. Introduction

During drilling, the drilling mud may move into the rock surrounding the wellbore if the wellbore pressure is higher than the pore pressure in the rock (overbalanced drilling). The replacement of in situ pore fluid with drilling mud is called invasion (Civan, 2007). During the invasion process, solids in the drilling mud are filtered out at the borehole wall since they are typically too large to move into the pore space of the surrounding formation, forming a mud cake that typically has very low permeability (Jaffal et al., 2017). The fluid that does penetrate into the formation is called mud filtrate. The invasion process stops when enough mud cake accumulates to slow the flow of mud filtrate to a rate that is insignificant over the time scale of drilling. This results in a region of finite size surrounding the wellbore in which some of the in-situ fluid has been replaced by mud filtrate.

During a leak-off test (LOT), pumping drilling mud into the wellbore causes the wellbore pressure to increase and exceed the pore pressure, thus allowing mud filtrate to rapidly leak into the formation via invasion (Fig. 1). At the same time, the pressurized wellbore during an LOT may cause the surrounding rock to deform, altering the porosity in the nearby formation. These processes dynamically affect the resistivity of a formation during an LOT, resulting in time-dependent resistivity profiles around the wellbore, since parameters like water saturation, water salinity, and porosity may no longer be constant in space and time in the near-wellbore region.

Time-dependent resistivity profiles have been investigated in the

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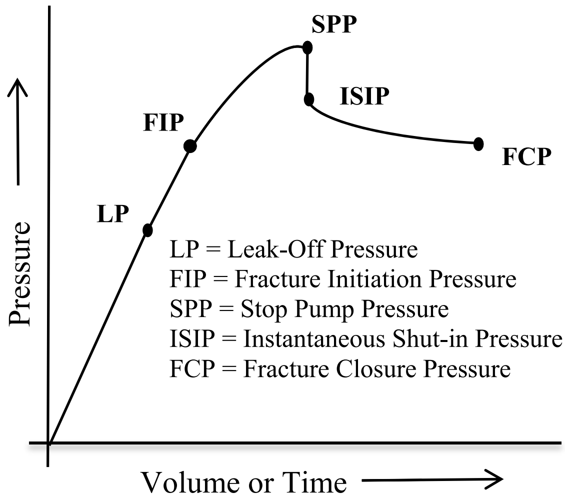

Fig. 1. Schematic of a typical LOT plot (Modified after Postler (1997)).

past using models based on the theory of fluid flow through porous media that take into account mud filtrate invasion with or without consideration of diffusion and fluid mixing (Cozzolino et al., 2000; Tobola and Holditch, 1991; Yao and Holditch, 1996; Zhang et al., 1999). These studies are mostly focused on studying the effects of drilling mud invasion on resistivity logs obtained at various times after drilling. When considerable time has elapsed between drilling and logging, such studies become important to correct resistivity logs that have been affected by invasion. Since the extent of invasion depends heavily on formation permeability, time-lapse resistivity log responses have also been successfully used to estimate reservoir permeability by the method of history matching (Salazar et al., 2005; Tobola and Holditch, 1991; Yao and Holditch, 1996). One major limitation with these methods comes from the fact that mud invasion is a slow and long process that normally takes days, which makes time-lapse logging of resistivity data impractical and economically unfeasible. As a result, these methods usually rely on very few data points in time while doing the history matching. This limitation can be easily overcome by gathering dynamic resistivity data during an LOT, which can be completed within tens of minutes.

The idea of time-lapse resistivity logging during an LOT is however new to the drilling industry. Traditionally, formation strength tests like LOTs and formation integrity tests (FITs) are carried out to gather pressure versus time data to confirm the strength of the cement bond above the casing shoe, investigate the capability of the wellbore to withstand additional pressure, and collect data on formation strength and in-situ stresses (van Oort and Vargo, 2008). There are excellent guidelines available in the literature to successfully perform and interpret LOTs for such purposes (Postler, 1997; van Oort and Vargo, 2008). LOTs, by their nature, damage the formation to an extent causing some loss of tensile rock strength and breakdown of the near-wellbore hoop stress; however, the damage typically does not extend far enough from the wellbore to affect the region controlled by far-field stresses (van Oort and Vargo, 2008; Wang et al., 2011).

LOTs affect properties in the near-wellbore region that have an influence on electrical resistivity. These properties include porosity, water saturation, and water conductivity. Since the resistivity of a formation is a function of the volumes and electrical properties of conductive fluids present in the formation, rock deformation and mud filtrate invasion during an LOT will result in changes in resistivity of the formation around the wellbore. The evolution of the resistivity around the wellbore can thus be used to study how drilling fluid is invading the formation and how the formation rock is deforming due to the applied pressure gradient.

Due to more rapid invasion and the relatively short duration of LOTs, dynamic resistivity data can be gathered continuously and conveniently in a matter of minutes with a single run of a logging-while-drilling (LWD) resistivity tool. Such time-dependent resistivity data can, for instance, prove useful in estimating the permeability of a freshly drilled interval. LWD resistivity-at-the-bit (RAB) tools are designed to operate under high pressure and can be used for time-lapse logging before, during, and after an LOT to investigate changes in the formation (e.g., Tobola and Holditch, 1991).

This paper investigates resistivity changes around the wellbore due to invasion and deformation that occur during the initial phase of an LOT. The effect of deformation is investigated using a finite element model in Abaqus, and the effect of mud filtrate invasion is incorporated using radial Darcy flow in the vicinity of the wellbore. The two effects are combined in order to investigate resistivity at any point radially outward in the formation during an LOT. Using Archie's law, the true formation resistivity value is determined at each point in the formation. Resistivity profiles so obtained are useful in modeling the expected RAB tool response of a laterolog resistivity measurement of the formation by solving response functions for a particular setting of electrodes in the tool (e.g., Cozzolino and da Conceicao da Silva, 2007; Nam et al., 2008; Pardo et al., 2008). Comparing predicted response with measured field data could help determine important formation properties through an inversion or history matching method.

2. Methodology

The effect of invasion on resistivity has been investigated in the past by invoking Archie's law at every location in the formation (Archie, 1942; Cozzolino et al., 2000; Liu et al., 1999; Tobola and Holditch, 1991; Yao and Holditch, 1996). The same technique has been extended to further include the effect of deformation in order to investigate the combined effects of invasion and deformation. In addition, any transport of conductive ions that occurs during invasion due to diffusion and fluid mixing is included. Resistivity at any radial position in the formation at any time during an LOT is a function of porosity, water saturation, and formation water resistivity as well as textural properties of the rock. Assuming azimuthal symmetry around wellbore, the resistivity R of the formation at any distance r away from the wellbore at any time t during an LOT can be given by Archie's law (Archie, 1942):

$$R(r,\, t) = \frac{aR_{eq}(r,\, t)}{\varphi(r,\, t)^m S(r,\, t)^n}\,, \tag{1}$$

where R_{eq} = equivalent formation water resistivity, φ = porosity, S = water saturation, a = tortuosity factor, n = saturation exponent, and m = cementation exponent. Porosity in Archie's equation incorporates the effect of deformation, whereas water resistivity and water saturation are altered due to invasion during an LOT. Note that the formation water resistivity term commonly seen in Archie's equation as R_w has been replaced by equivalent resistivity R_{eq}. The reason behind this is that resistivity of the water in the formation is not necessarily constant during LOT. Due to invasion during an LOT, the invaded zone may contain a mixture of mud filtrate and formation water.

In case of oil-based mud, since the mud filtrate is non-conductive, R_{eq} is simply replaced by the formation water resistivity R_w, and water saturation may change due to invasion. In case of water-based mud, which has been chosen for this particular study in order to demonstrate the full applicability of the method, if the formation is oil-bearing, water saturation may, once again, change due to invasion. Also, in such a scenario, since mud filtrate leaking into the formation behaves as a conductive fluid, the resistivity of the mixture of mud filtrate and formation water denoted by R_{eq} is the volumetrically weighted harmonic average of the resistivity of mud filtrate and that of the resident formation water at any location in the formation (Cozzolino et al., 2000). Furthermore, for conductive water-based mud, formation water resistivity may change due to convective-diffusive transport of conductive