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Associating Borehole Radar Imaging with Petrophysical Properties for a Mud-Contaminated Reservoir

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Summary

Logging engineers deem mud invasion a harm and attempt to eliminate its impact on logging data. However, from our point of view, the mud-contaminated parts of the formation do also carry some valuable information, notably with regard to the key hydraulic properties. Therefore, if adequately characterized, the invasion effects, in turn, could be utilized for reservoir estimation. Typically, the invasion depth critically depends of the formation porosity and permeability. To achieve this objective, we propose to use borehole radar to determine the mud invasion depth considering a high spatial resolution of ground-penetrating radar (GPR) compared with the conventional logging tools. We implement numerical investigations on the feasibility of this approach. The simulations imply that a time-lapse radar logging is able to extract EM reflection signals from mud invasion front, and the invasion depth and EM velocity can be estimated by the downhole measurement of one source and two receivers. We find that there exists a positive correlation between the estimated invasion depth and permeability curves, and a negative correlation between the estimated velocity and porosity curves. We suggest that borehole radar has potential to estimate permeability and porosity of oil reservoirs, wherein the mud invasion effect is positively utilized.

Associating borehole radar logging data with petrophysical properties in a mud-contaminated reservoir: Can we converse disadvantage to advantage?

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***Abstract*—In the phase of oil drilling, mud filtrate penetrates into porous formations and alters the pore fluid properties. This complicates well logging exploration, and inevitably gives rise to shift in reservoir estimation. Logging engineers deem mud invasion a harm and attempt to eliminate its impact on logging data exploration. However, from our point of view, the mud-contaminated parts of the formation do also carry some valuable information, notably with regard to the key hydraulic properties. Therefore, if adequately characterized, mud invasion effects, in turn, could be utilized for reservoir estimation. Typically, the invasion depth critically depends on the formation porosity and permeability. To achieve this objective, we propose to use borehole radar to determine the mud invasion depth considering a high spatial resolution of ground-penetrating radar (GPR) compared with the conventional logging tools. We implement numerical investigations on the feasibility of this approach by coupling electromagnetic (EM) modelling with fluid flow modelling in an oil-bearing formation disturbed by mud invasion effects. The simulations imply that a time-lapse radar logging is able to extract EM reflection signals from mud invasion front, and the invasion depth and EM velocity can be obtained by a downhole antenna displacement of one source and two receivers. We find that there exists a positive correlation between the estimated invasion depth and permeability curves, and a negative correlation between the estimated velocity and porosity curves. We suggest that borehole radar has potential to estimate permeability and porosity of oil reservoirs, wherein the mud invasion effect is positively utilized. The study demonstrates a potential method of oil reservoir estimation and a novel application of GPR in oil fields.**

***Index Terms*—borehole radar, reservoir estimation, mud invasion**

I. Introduction

Porosity, permeability and water saturation are three essential petrophysical properties for hydrocarbon reservoir estimation. Currently, water saturation and porosity are relatively easily acquired by conventional well logging tools, such as sonic and electrical logging, whereas permeability is still difficult to directly obtained by logging [1]. Initially, reservoir permeability was associated with rock porosity and rock specific surface area, and Kozeny-Carman equation was applied for permeability estimate in tight sandstone gas reservoirs [2]. However, the rock specific surface area is obtained by expensive coring analysis [3]. Empirical formulas are used to evaluate permeability based on logging data, which are only applicable for some special cases [4]. To date, no mathematical model exists to describe the relationship between logging data and reservoir permeability. Compared with the methods that use logging data to evaluate permeability, coring analysis is direct and accurate but costly. A statistics-based porosity-permeability relation is generally used to estimate the magnitude order of permeability. However, permeability is decided not only by pore size but also by pore connectivity, shape and pore throat, which decreases the correlations between porosity and permeability especially in low porosity and permeability reservoirs [5]. To date, it still keeps challenging to estimate the permeabilityespecially in a low-porosity and low-permeability reservoir.

In the process of oil drilling, mud filtrate penetrates into the porous formations and alters their pore fluid properties. This brings about logging errors and affects the precision of reservoir estimation. Logging engineers try every way to eliminate the mud invasion effects and correct the shift of the logging data. However, we think the mud-contaminated formation parts also carry some useful information. For instance, the invasion depth is typically decided by the formation permeability and porosity [6]. This evokes our inspiration to open a new path to estimate the percolation-related formation properties. The feasibility relies on two primary considerations: one is that the mud-invasion effects, especially the invasion depth, are able to be adequately characterized by well logging; the other is that a quantitative relationship can be found to link the invasion effects to the formation properties. Conventional logging tools, whether electrical- or acoustic-based methods, have no capability of finely describing the complicated invasion status due to their nature of low frequency. We, therefore, propose to use borehole radar to detect the invasion depth considering the fact that the high-frequency EM is favorable to extract the reflective signals from a discontinuous fluid distribution. Once the invasion depth is decided, we can correlate the invasion depth with the reservoir permeability or porosity for reservoir estimation purpose.

To the best of our knowledge, there is no such a radar logging tool existing for mud invasion detection application. Therefore, we implement an associated numerical modelling to investigate the feasibility by a coupled multiple phase flow and EM scattering modelling. We believe our study can stimulate research to exploit a new application of GPR in oil fields, as well as a novel methodology for reservoir estimation.

II. Numerical modelling

A. Mud invasion modelling

Mud invasion is a complicated flow process, specific to drilling mud types and reservoir categories. Logging engineers generally divide the invaded formation into the flush zone, transition zone and virgin (or undisturbed) zone according to how mud mobile in-situ fluids are displaced by mud filtrate. To create a detectable EM reflection from the invasion front, there are a few crucial factors should be considered: firstly, the flush zone has a relatively low conductivity for low attenuation an low phase distortion of EM wave propagating in the formatior secondly, there is adequate contrast of EM properties a well as relatively sharp transition zone between the flus and virgin zones to arouse noticeable EM reflection events These, consequently, restrict our borehole radar applied to th scenarios that fresh water-base mud invades an oil-bearin layer. For oil-base mud invasion cases, there are long transitio zone, which is primarily caused by the non-wettability an low flow coefficient of oleic phase [7]. Besides, oil-base mu is not as popular as water-base mud in the oil industry a its high costs. Salt water-base mud is excluded from ou applications because it brings about a highly conductive flus zone unfavorable for EM propagation. In addition, a light oi reservoir is more favorable for the EM reflection than a heav oil reservoir because a low viscosity ratio of oil to water form a sharp oil-water transition zone.

We adopt the two-phase (water and oil) isothermal Darc flow equations to describe how the invasion behavior disturb the fluid saturation and pressure distributions over time i the near-well formation [8]. The salinity mixing between th low-salinity mud water and the high-salinity in-situ formation water can be described by the convective-diffusive equation, which is actually a multi-component issue [9]. These equation sets are discretized in a cylindrical coordinate system, and are sequentially solved by the implicit pressure, explicit saturation and implicit salinity solutions [6]. In the previous study, the shape of the invasion front was greatly simplified into a stepped distribution for conventional logging explanations [10]. To simulate more realistic fluid transition profiles, our model include as many factors as possible, such as capillary pressure, gravity, rock and fluid compressibility, and ionic diffusion effect. Besides, a local grid refining scheme is used.

The drilling mud generally contains solid particles to sustain a slightly high downhole pressure with respect to the reservoir. In the process of the inflow of the mud filtrate, the solid components gradually deposit on the well wall and build up a mud cake. The thickness growth of the mud cake and the evolvement of its permeability and porosity over time depend on the pressure drop across the mud cake apart from the textures of the mud itself; in turn, the time-varying mud cake properties influence the inflow rate, inflow volume and invasion depth [7]. To present the interactional process, a set of mud cake growth formulas based on laboratory experiments are coupled with the above flow modelling as formulated by [11].

We developed a Matlab program of multi-phase and multi-component model coupled with the mud cake growth, and it was testified to agree well with the published commercial soft-based results [6]. A mud invasion scenario is simulated with data set synthesized by drilling, fluid and formation properties, as shown by Tab. I. The parameters of porosity, permeability and water saturation are varying with depth and acquired from field coring data as shown in Fig. 1.

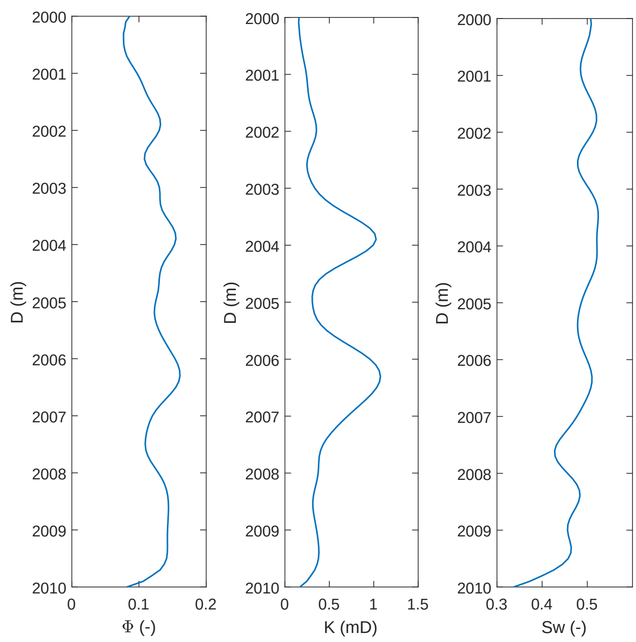

Fig. 1. Porosity, permeability and water saturation curves modified from oil field coring data.

TABLE I
DRILLING, FLUID AND FORMATION PROPERTIES OF THE MUD INVASION SCENARIO [7]

Variables	*Values*	*Units*
Wellbore radius	0.10	m
Mud hydrostatic pressure	27580	kPa
Mud cake maximum thickness	0.005	m
Mud filtrate salinity	0.1E−3	ppm
Mud filtrate	1130	kg/m^3
Mud cake reference permeability	0.05	md
Mud cake reference porosity	0.25	-
Mud solid fraction	0.06	-
Mud cake compressibility exponent	0.4	-
Mud cake exponent multiplier	0.1	-
Formation pressure	25166	kPa
Formation water salinity	160E−3	ppm
Formation temperature	104	°C
Water density	1001	kg/m^3
Oil density	816	kg/m^3
Water viscosity	1.274E−3	Pa·s
Oil viscosity	0.355E−3	Pa·s
Rock compressibility	7.252E−13	1/Pa
Water compressibility	3.698E−10	1/Pa
Oil compressibility	2.762E−9	1/Pa
Connate water saturation	0.15	-
Residual oil saturation	0.10	-
Endpoint relative permeability of water	0.3	-
Endpoint relative permeability of oil	1	-
Empirical exponent for water	2	-
Empirical exponent for oil	2	-
Capillary pressure coefficient	1.87E−2	Pa· m
Empirical exponent for pore-size distribution	20	-
Diffusion coefficient of salt	0.645E−10	m^3/s
Longitudinal dispersion coefficient of salt	0.05	m

B. Borehole radar modeling

Borehole radar logging is a much more complicated environment than the surface GPR measurement, for which more restrictions have to be imposed on the configurations of the radar logging tool. We assume that radar antennas are mounted in the logging string, and a backward caliper arm can push the antennas against the well wall, eliminating EM attenuation and scattering loss caused by the mud filtrate. To decrease the destructive EM interference arising from the metal components of the logging tool, the antennas are deployed in an arc-shaped cavity of the logging string, and are surrounded by special wave absorbing material as suggested by [12]. The downhole transreceiver configurations are designed as one transmitter and two receivers, facilitating a downhole reflection measurement resembling the common depth point measurement on the surface. A ricker current is exerted on the transmitting antenna with the center frequency of 1 GHz for the reason that this working frequency and bandwidth satisfy the penetration depth and spatial resolution requirements in a high-resistivity reservoir, as analyzed by [13].

We use gprMax, a general purpose finite-difference time-domain (FDTD) GPR simulator [14], to build up a borehole radar model in the mud-filled downhole environment. The antennas are simplified as a point source of hertz dipole, the grid sizes are 2 mm, and perfectly matched layer is imposed on the outer boundaries of the simulation domain. We pick up the electrical component parallel with the well as useful signals because the borehole antennas are generally designed with wire dipole along the well axis as described by [15].

To couple the flow model to the EM model, the water saturation, water salinity and porosity, simulated by the mud invasion simulations, are conversed into permittivity and conductivity as the propagation media of the EM model. The permittivity is conversed through the complex refractive index model (CRIM), a widely used dielectric mixed formula in the geological materials [16]. In a deep reservoir, high temperature and high salinity have significant impacts on water permittivity, while pressure effects can be neglected [17]. We included the salinity and temperature effects in our CRIM model by polynomially fitting the laboratory data presented by [17]. For this consideration, an obvious change is that water permittivity drops into approximately 58 at the temperature of 100 °C or so, while it is normally deemed 88 in the surface GPR measurement. The other change is that water permittivity becomes frequency independent in our applied radar frequency range when the reservoir temperature is above °C 100 [17]. The effective electrical conductivity is calculated by Archie's law under the assumption of a sandstone-type reservoir [18].

The built-up model of the borehole radar is illustrated by Fig. 2, and the geometric and EM parameters are prescribed by Tab. II. Through the conversion from fluid properties to EM properties, a real-time EM response on fluid flowing is observed.

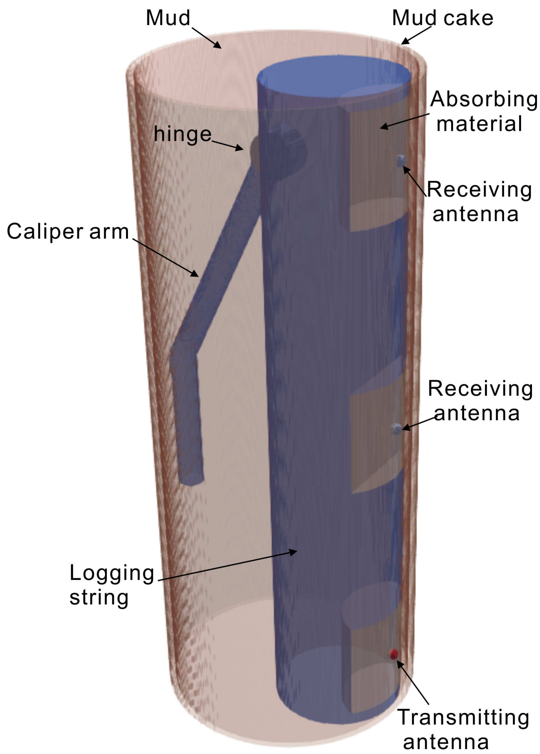

Fig. 2. Schematic of borehole radar model.

TABLE II
GEOMETRIC AND EM PROPERTIES FOR BOREHOLE RADAR MODEL

Variables	*Values*	*Units*
Logging string radius	0.05	m
Antenna offset	0.20	m
Cavity radius	0.04	m
Cavity length	0.08	m
Cementation factor	1	-
Cementation exponent	2	-
Saturation exponent	2	-
Relative permittivity of oil	2	-
Relative permittivity of sandstone	4.65	-
Relative permittivity of water in 100 °C	57.930	-

III. RESULTS AND DISCUSS

We run the mud invasion simulations, and extract the flui distribution and EM property curves at different times, a shown in Fig. 3. The comparative analysis indicates that (1 With the prescribed fluid properties, we simulate a shar invasion front, presenting a favorable geometric profile fo EM reflection event (Fig. 3(a)). (2) There is a hysteresi effect for the water salinity advancement relative with the water saturation (Fig. 3(b)). It is caused by the mixing and dispersion of the different salinity between the in-situ formation water and the mud water. The hysteresis is thought as the preliminary reason for the so-called low-resistivity annulus, which commonly occurs in a fresh water-base mu invasion case (Fig. 3(c)). (4) The conductivity presents a obviously high contrast in the order of magnitude relative t the permittivity contrast (Figs. 3(c) and (d)). We, therefore can infer that the conductivity dominates the EM reflectio events. (5) The effective permittivity presents a gradual declin with the decrease of water saturation (Figs. 3(d). An abnorma drop can be observed in the transition zone portion cause by the influence of the salinity on water permittivity. Th permittivity is not expected to make significant impact on th EM reflections because the magnitude drop advances ahead o the conductivity interface.

By comparing the invasion status at the two invasion times we also find out that there are adequate differences of EM properties in invasion front whereas little in the flush zone. W thus can propose to utilize a time-lapse logging matter to extract the reflection signals from the invasion front. Time-lapse logging has proved to be effective for extract the information of the changed portions of the background, especially applied to fluid flow monitoring [19]. We implement time-lapse radar logging operations in the invasion of 24 and 26 hours, and obtain the time-lapse radar profiles. Fig. 4 shows the radar profile in the first receiver. Note that a too long time interval for time-lapse logging is possible to arouse undesired EM reflection in the early-period radar signals due to the growing fluid saturation difference in the flush zone, while a too short time interval can not extract observable time-lapse signal from the invasion front due to insufficient invasion advancement.

The downhole antenna configurations of one source and two receivers allow to simultaneously solve the reflection depth

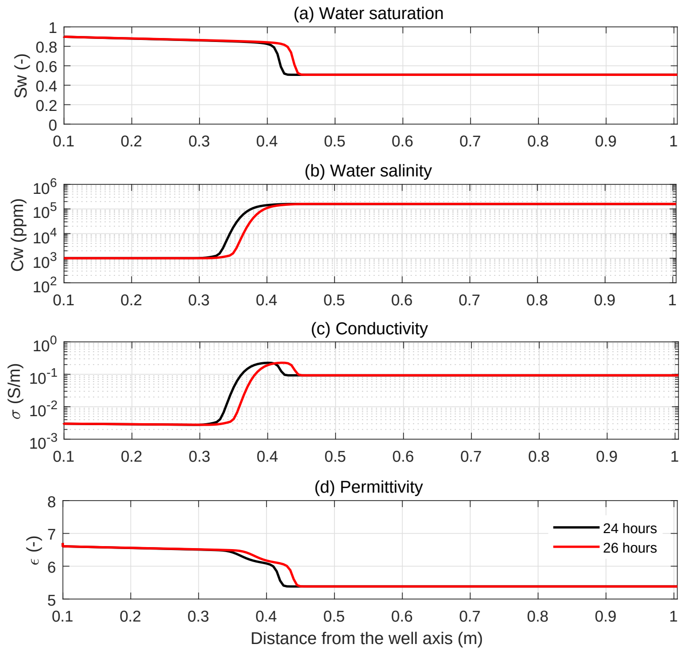

Fig. 3. Radial distributions of (a) water saturation, (b) water salinity, (c) effective conductivity and (d) effective permittivity in the invasion of 24 (black curve) and 26 (red curve) hours, respectively.

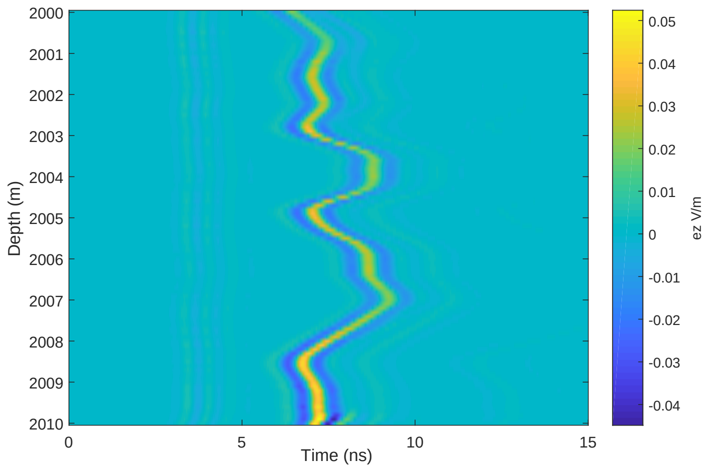

Fig. 4. Time-lapse radar profile in the first receiving antenna in the invasion of 24 and 26 hours.

and wave velocity, by which means we can converse the travel time of the reflection signals into invasion depth. The curve of the calculated invasion depth is presented in the conductivity distribution image for comparison purpose (Fig. 5). The good agreement proves that the reflective signals extracted from the time-lapse borehole radar logging can effectively estimate the mud invasion depth. We compare the estimated invasion depth and velocity curves with the prescribed porosity, permeability and water saturation curves, and find out that there are remarkable negative correlations between the wave velocity and porosity while positive correlations between estimate invasion depth and permeability, as shown in Fig. 6 and Fig. 7 These implications indicates potential possibility to explai or inverse the porosity and permeability with mud invasio effects.

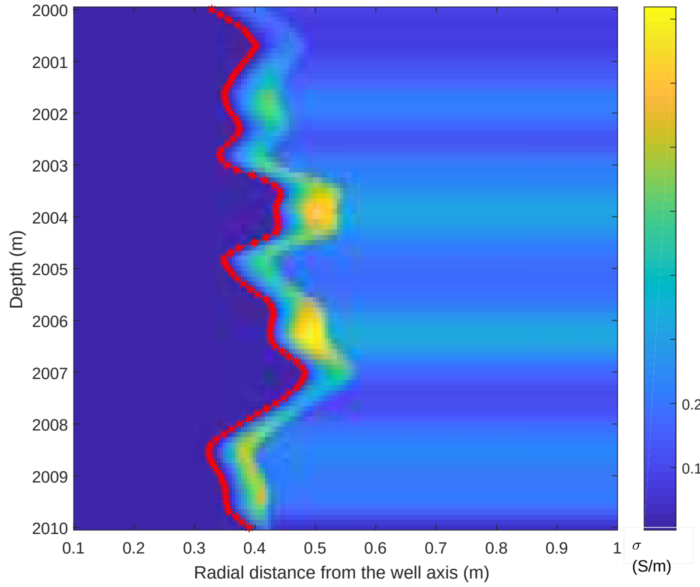

Fig. 5. Estimated invasion depth (red start curve) and the conductivity distribution image at 24 hours.

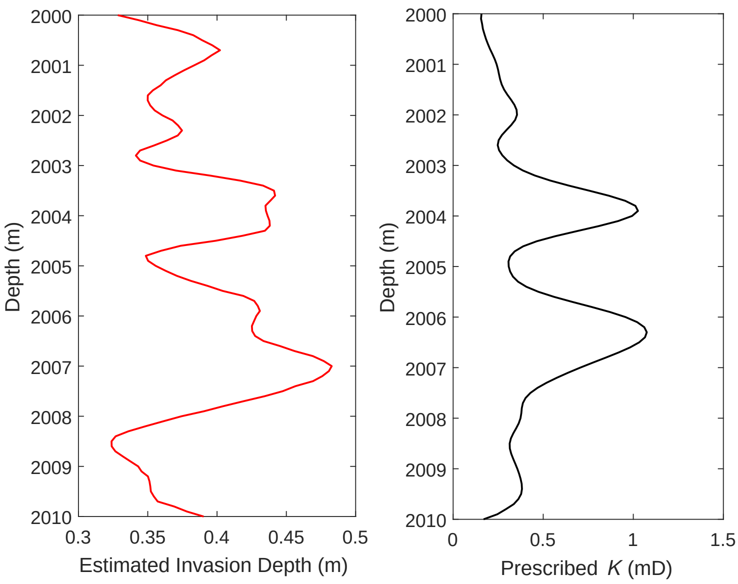

Fig. 6. Estimated invasion depth curve (left) versus prescribed permeability curve (right).

IV. Conclusions

We establish a numerical model coupling flow and EM models to investigate the potential of the borehole radar on hydrocarbon reservoir estimation. The simulation results show

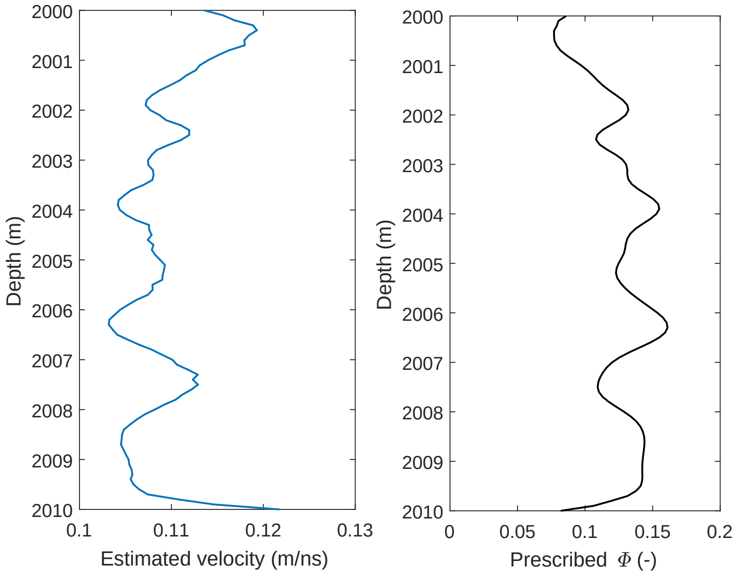

Fig. 7. Estimated invasion depth curve (left) versus prescribed permeability curve (right).

that (1) time-lapse borehole radar logging has capability of precisely estimating the invasion depth; (2) the estimated invasion depth curve has good correspondence with the permeability curve; (3) the estimated velocity curve negatively correlates with the porosity curve. These findings suggest that borehole radar has great potential for reservoir estimation application.

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