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Enhanced heavy oil recovery for carbonate reservoirs integrating cross-well seismic – A synthetic Wafra case study

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ABSTRACT

Heavy oil recovery has been a major focus in the oil and gas industry to counter the rapid depletion of conventional reservoirs. Various techniques for enhancing the recovery of heavy oil were developed and pilot-tested, with steam drive techniques proven in most circumstances to be successful and economically viable. The Wafra field in Saudi Arabia is at the forefront of utilizing steam recovery for carbonate heavy oil reservoirs in the Middle East. With growing injection volumes, tracking the steam evolution within the reservoir and characterizing the formation, especially in terms of its porosity and permeability heterogeneity, are key objectives for sound economic decisions and enhanced production forecasts. We have developed an integrated reservoir history matching framework using ensemble based techniques incorporating seismic data for enhancing reservoir characterization and improving history matches. Examining the performance on a synthetic field study of the Wafra field, we could demonstrate the improved characterization of the reservoir formation, determining more accurately the position of the steam chambers and obtaining more reliable forecasts of the reservoir's recovery potential. History matching results are fairly robust even for noise levels up to 30%. The results demonstrate the potential of the integration of full-waveform seismic data for steam drive reservoir characterization and increased recovery efficiency.

1. Introduction

Heavy oil reservoirs have in the last decade encountered growing interest in the industry. As with the rapid depletion of the world's largest light oil reservoirs, heavier hydrocarbon components remain in the subsurface, which account for a considerable percentage of the oil in place (Chopra and Lines, 2008). Increasing demand from emerging markets has driven up the price for oil and gas, making heavy oil reservoirs commercially viable. Heavy oil reservoirs are typically found in shallower depths and therefore are easier to access than conventional reservoirs. However, their high viscosity and sulfur content make it more difficult and expensive to extract and process (Dusseault, 2001). The high viscosity of heavy oil makes it rather immobile and challenging to displace via standard water injection. While tar sand recovery in Canada is performed via mining techniques (Dusseault, 2001; Century, 2008), heavy oil reservoirs typically use thermal methods to reduce the viscosity of the oil through heating. Amongst these, steam assisted cyclic gravity drainage and the earlier cyclic steam stimulation technique are the most efficient and frequently employed for recovering heavy oil (Sheng, 2013; Popa et al., 2013; Sorrell et al., 2012; Valera et al., 2013; Alkindi et al., 2013). Steam injection into reservoirs exploits the increase in the temperature of the formation in order to reduce the viscosity of the heavy oil, and via pressure support enhances the oil's mobility. Increasing the oil's mobility leads to higher sweep efficiency and recovery efficiency.

Field studies of heavy oil reservoirs have been plentiful in the Literature. Saskoil and Butler (1990) presented a steam assisted gravity drainage study for a heavy oil reservoir in Canada, showing that oil may be produced economically from the reservoir. To remediate the challenge of steam coning, (Saskoil and Butler, 1990) argued that production wells should operate close to the pressure levels of the supporting aquifer. Tang et al. (2013) presented a steam injection experimental study for extracting heavy oil in carbonate reservoirs, which typically encounter challenges because they are strongly naturally fractured and oil-wet. The authors were able to demonstrate that oil recovery from the carbonate reservoir is primarily dominated by imbibition, viscosity reduction, and in-situ steam generation within the core, where the latter is a promising aspect to increase recovery levels.

With the growing trend towards thermal methods for heavy oil recovery and the increasing availability of reservoir data, history matching of these reservoirs is necessary for determining reservoir

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formation properties and forecast reservoir production. Bao et al. (2013) history matched the SAGD operation of the Liaohe Field in China in order to optimize the thermal injection process as well as the energy intensity of the injected steam. Hiebert et al. (2014) presented a history matching study for determining the size, shape, and growth of the steam chamber in a SAGD project, showing that the incorporation of 4D seismic surveys assists in improving the categorization of the reservoir and the evolution of the steam chamber. The development of 4D seismic has led to increased interest in the integration of geophysical data into history matching and several studies on the integration of 4D time lapse seismic data attributes were conducted (Gosselin and Aanonsen, 2001; Kazemi et al., 2011; Emerick and Reynolds, 2012; Skjervheim et al., 2007). With the growing necessity to obtain a detailed understanding of the interwell regions in reservoirs, cross-well seismic tomography has been considered as a viable technique for overcoming the resolution limits of surface seismic techniques. Zhang et al. (2012) utilized cross-well seismic tomography for monitoring the CO_2 injection process for the Ketzin field in Germany, and showed a clear seismic signal anomaly for the CO_2 injection process. For heavy oil reservoirs, cross-well seismic tomography was used for monitoring the reservoir architecture and steam chamber growth as shown in (Zhang et al., 2007) for the Christina Lake heavy oil reservoir in Canada. The authors indicated that the reservoir heterogeneity may significantly influence the growth process of the steam chamber that was also detected via cross-well seismic data.

Heavy oil extraction has become of considerable interest in Saudi Arabia in the last decades, particularly for the Wafra oil field, which has drawn considerable investment for recovering heavy hydrocarbon components using steam drive (Al-Gamdi et al., 2013). Growing investment, enhanced formation understanding and tracking the evolution of the steam chamber are key components to optimize field production strategies and reservoir recovery.

In this work, we present a cross-well seismic assisted reservoir history matching study of a steam drive heavy oil reservoir using an ensemble based history matching technique. The studied reservoir approximates a subpart of the Wafra oil field and the field development setup was organized to match the real field operations as close as possible. Utilizing cross-well seismic data, obtained from a full-waveform solver, that exhibit a strong signal contrast caused by the steam injection leads to a considerable enhancement in the matching of the observed well data and forecasting the well deliverability. The study outlines the feasibility and benefits of the integration of cross-well seismic data for reservoir history matching purposes and the applicability for developing optimized production strategies for enhancing reservoir characterization of the Wafra oil field.

2. Methodology

In this section, the thermal history matching framework integrating cross-well full-waveform seismic data is presented. We first briefly outline the reservoir simulator, then introduce the full-wave acoustic waveform solver followed by the history matching technique. A flowchart representation of the history matching setup is shown in Fig. 1.

2.1. Reservoir simulator

For the reservoir model we used the thermal reservoir simulator E300 in Eclipse (GeoQuest, 2014). Thermal reservoir simulation assumes that the mass of each component, as well as the energy and the volume is preserved, leading to the following system of equations,

$$-\frac{\mathrm{d}}{\mathrm{d}t}\left(V_p m_{fl}\right) = F_{fl} + Q_{fl} \quad (1)$$

$$-\frac{\mathrm{d}}{\mathrm{d}t}\left(V_b e\right) = F_e + C_e + Q_{HL} + Q_e \quad (2)$$

$$V_p = V_f \quad (3)$$

where V_p is the pore volume, V_b the bulk volume, m_{fl} the molar densities for either the hydrocarbon or water component, F_{fl} the net flow rate into neighboring grid blocks, Q_{fl} the net flow rate into the wells during the time step, e the bulk internal energy density, F_e the convective enthalpy flow rate into neighboring grid blocks, C_e the conductive energy flow rate into neighboring grid blocks, Q_{HL} the conductive energy flow rate to the surrounding rocks (heat loss), Q_e the net enthalpy flow rate into the wells during the time step, and V_f the fluid volume. The subscript fl denotes either the N hydrocarbon components or water.

These equations are complemented by thermodynamic equilibrium conditions, flash equations for the change between the different components and heat conduction equations for relating

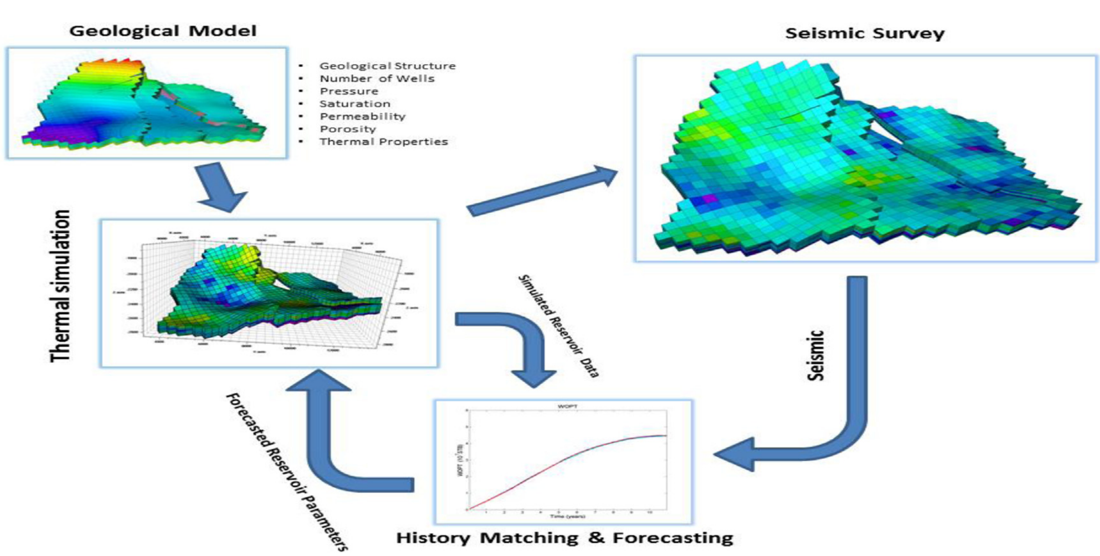

Fig. 1. Flowchart representation of the seismic assisted History Matching framework.