Improved Understanding of Naturally Fractured Reservoirs Using Data Assimilation

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Improved Understanding of Naturally Fractured Reservoirs Using Data Assimilation

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Summary

Naturally fractured reservoirs can pose challenges for energy operations such as hydrocarbon production, CO2 storage, and geothermal energy production. Fluid flow in these reservoirs is greatly affected by fracture properties such as orientation and aperture, whose magnitude is mainly influenced by the stresses on the reservoir rocks. Simulating fractures and their behavior tends to be computationally intensive, but recent advances in Discrete Fracture Models (DFM) have successfully overcome computational complexity and allow for the explicit inclusion of discrete fractures in reservoir simulations. However, there are still challenges in dealing with uncertainties, including fracture aperture and the effect of in-situ stresses on the fracture surface and their effect on the fluid behavior. This study explores the use of data-assimilation techniques to help quantify these uncertainties. We combine a recent implementation of DFM on the Delft Advanced Research Terra Simulator (DARTS) with both ensemble and gradientbased data-assimilation methods. Our results show that data assimilation can help to understand the dynamic behavior of fluids in fractured reservoirs. Using this technique, we obtain a more accurate representation of the stresses acting on the reservoir and how they affect the fracture aperture. This information is essential for more efficient reservoir management.

Introduction

Clear understanding of the dynamic behavior of fluids in naturally fractured reservoirs is essential for developing and successfully managing energy related operations such as CO_2 storage, geothermal energy production and hydrocarbon production. Unfortunately, this can be difficult to achieve due to the complexities involved (e.g., due to the effect of in situ stresses on fracture properties such as orientation and aperture). Besides that, modeling the dynamics of such reservoirs is still a challenge. Several techniques have been applied to capture the effect of the fracture stresses, such as Discrete Fracture Models (DFM), where fractures are explicitly represented by individual elements in the reservoir grid (Karimi-Fard et al., 2004) and therefore allow for orientation-dependent fracture apertures (Barton & Bandis 1980).

Recently, Boersma et al. (2021) applied a Discrete Fracture Network to model geothermal production on the multi-physics python/C++ based simulator Delft Advanced Research Terra Simulator (DARTS), where the effective fracture permeability for individual grid cells is calculated based on a mechanical aperture model approach proposed by Barton & Bandis (1980). Besides recent developments in numerical simulation, there are still challenges in understanding the uncertainties that affect the fluid's behavior in fractured reservoirs due to our limited ability to quantify fracture characteristics directly.

Data assimilation can be used to better estimate rock properties, fluid behavior, and the associated uncertainties in fracture networks by integrating the prior knowledge of the reservoir with the assimilation of dynamic observed data, such as wells productions and injections. In this work, we explore the potential use of data assimilation techniques to help understand the effect of in-situ stresses and initial fracture apertures on the fluid flow in a naturally fractured reservoir. We apply ES-MDA (Ensemble Smoother with Multiple Data Assimilation) and Ensemble Randomized Maximum Likelihood (RML), an ensemble- and a gradient-based method, respectively (Evensen et al. 2022). The flexibility of DARTS allows for straightforward coupling of the DFM implementation and fracture properties calculation to such schemes.

The aim of this study is, first, to evaluate the impact of different in-situ stress angles and initial fracture apertures on the two-phase fluid production of a naturally fractured reservoir with a pair of wells. Secondly, the aim is to evaluate the potential of data assimilation combined with DFM in DARTS to quantify uncertainty given observed production data.

Methodology

We utilized a similar DFM approach as Wang et al. (2021) by using DARTS to simulate two-phase flow in a 2D reservoir model, injecting a wetting phase in a reservoir primarily saturated with a non-wetting phase. After selecting a fracture network configuration, the apertures are distributed using an empirical relationship of the mechanical closure of initially open fractures due to applied normal stress to each fracture (Barton & Bandis 1980). More details about the stress-to-aperture relationship used in this work can be found in Boersma et al. (2021). To sample the distribution of the maximum in-situ stress angle and initial fracture aperture, an ensemble of 100 initial conditions was created representing a 2D reservoir model with one producer and one injector well with a pre-defined fracture network. To account for uncertainties in the parameters, we considered a normal distribution of the maximum in-situ stress angle varying from 0° to 90° and a Gaussian normal distribution with a mean equal to 0.15 mm and a standard deviation of 0.3 mm for the initial fracture aperture. From the ensemble members, we select three specific scenarios of fracture aperture as a function of stress angles to generate synthetic data for the evaluation of the data assimilation method. Figure 1 illustrates those three scenarios, showing how fracture aperture relates to the in-situ stress direction.

Observed data (well production rates), generated by a synthetic case are assimilated with the framework presented in Figure 2 to evaluate the capability of two data-assimilation methods (ES-MDA and RML) to quantify uncertainties in the unknown parameters.

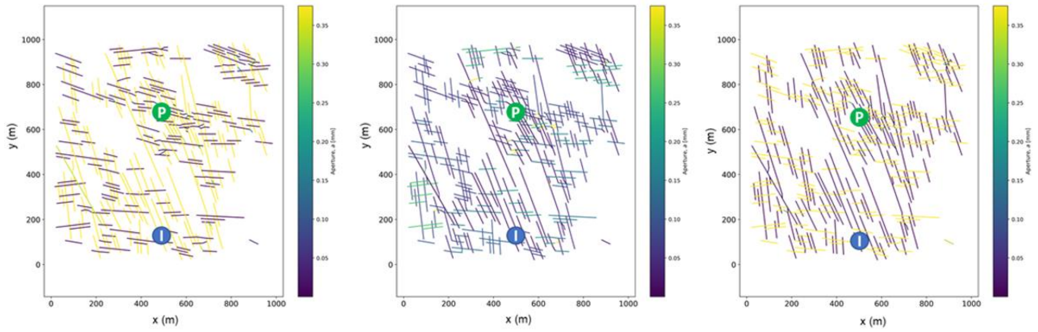

Figure 1 *Fracture networks and wells positions (producer – green and injector – blue) for stress angles, relative to the direction of the y axis, equal to 0⁰ (left); 45⁰ (middle) and 90⁰ (right).*

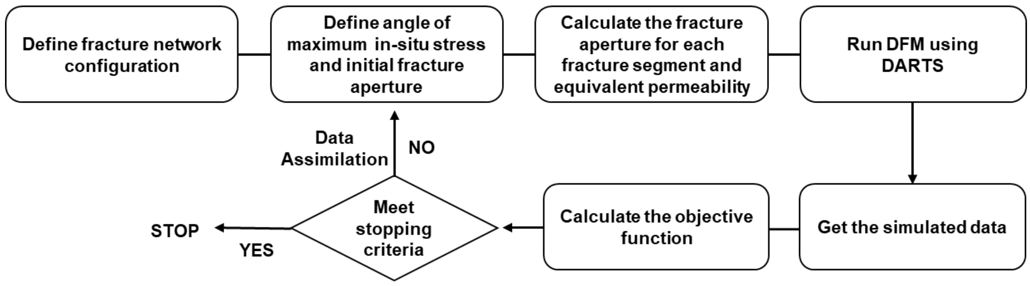

Figure 2 *Data-assimilation framework applied for this study*

Reference Models for the Data-assimilation Workflow

We tested our proposed methodologies on a 2D synthetic case, assimilating synthetic data sampled from the three scenarios of Figure 2. All three reference models have initial fracture aperture of 15 mm and three different in-situ stress angles: 0˚, 45˚ and 90˚, relative to the direction of the y axis (Figure 1). The angle influences the timing of the water breakthrough (Figure 3).

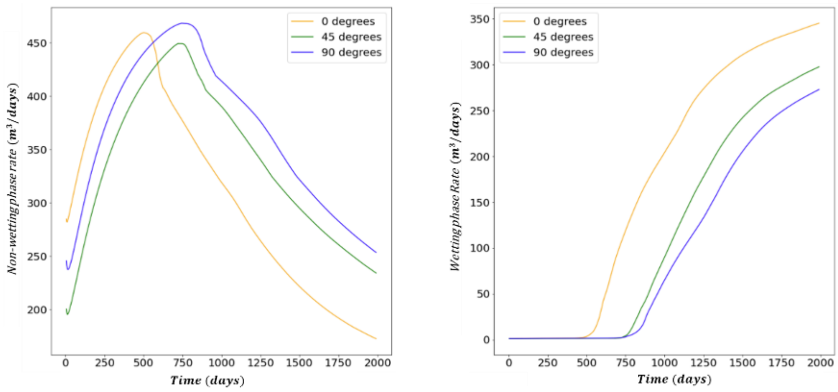

Figure 3 *Non-wetting phase (left) and wetting phase (right) productions for the three reference cases, varying the angle of in-situ stresses.*

When the stress angle is aligned to the wells (stress angle equals 0˚), there is a clear preferred path for the injected fluid from the injector to the producer. When the angle is equal to 45˚ and perpendicular to most fractures, their aperture is low and the flow in the reservoir is dominated by the matrix flow. An angle equal to 90⁰ creates divergence of the flow, as the open fractures are perpendicular to the wells which causes a slower breakthrough. The production data sampled from the three reference models are used as synthetic measurements in experiments to evaluate the performance of the data-assimilation methods.

Evaluation of the Performance of the Data Assimilation

The posterior distribution of rates, using the proposed ES-MDA framework, is closer to the observed data than the prior distribution of rates for all three different scenarios of this study (Figure 4). In all three scenarios, the data-assimilation framework successfully creates a posterior with narrower uncertainty than the prior while closely fitting the production data. The posterior distribution of the maximum in-situ stress angle and initial fracture aperture is significantly narrower than its prior distirbution after assimilating the well production rates (Figure 5).

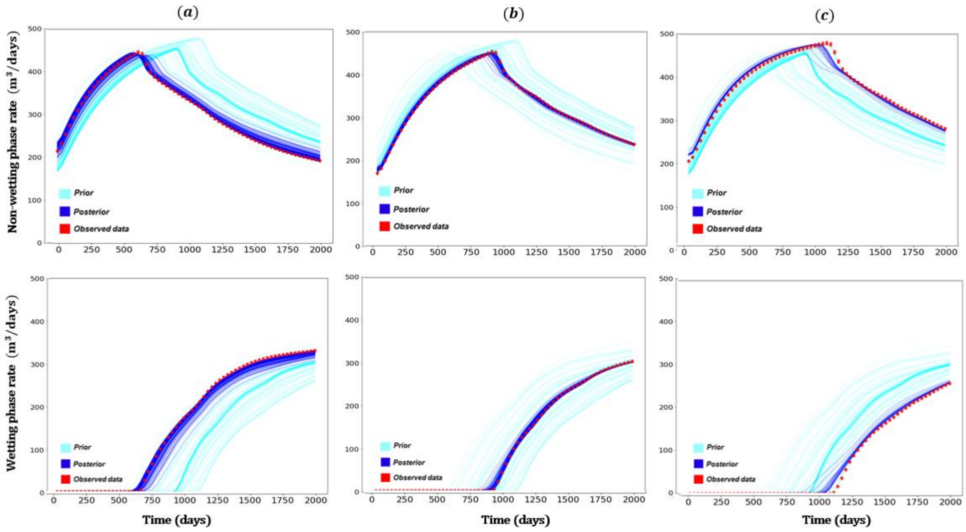

Figure 4 *Non-wetting phase and wetting phase production of the three reference cases 0^0 (a); 45^0 (b) and 90^0 (c) for the ES-MDA data-assimilation scheme. Posterior estimates of the rates are indicated in dark blue, observations in red and prior realizations in light blue.*

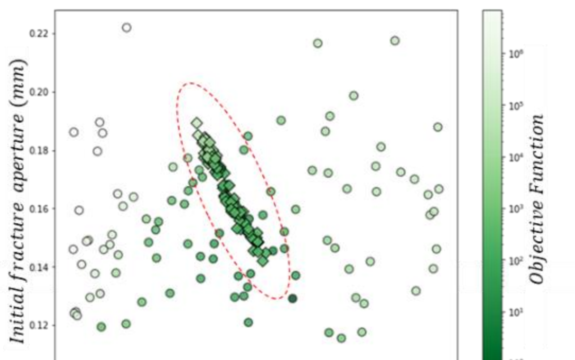

Figure 5 *Initial fracture aperture and maximum in-situ stress angle of one reference scenario (45^0) for the ES-MDA data-assimilation scheme. The coloring of the symbols represents the value of the cost function. Posterior distributions are highlighted by the red dashed ellipses.*

We evaluate the the gradient-based data-assimilation method (RML) with synthetic data for which the initial guess stress of the angle is 90° and the initial fracture aperture is 0.10 mm assimilated in a reference model with an angle of 45^0 and an initial fracture aperture of 0.15 mm. Figure 6a shows the close fit of the history matching estimate to the observations, where the posterior angle and initial aperture suggested by the framework is 42^0 and 0.14 mm, respectively, after 30 iterations of minimization of the objective function. So, this method also presents a posterior that is narrower than the prior, while closely fitting the production data.

Figure 6b illustrates an overview of the objective function of this problem, where the single global minimum suggests that gradient-based methods will be effective. This is confirmed by the results in Figure 6a. The objective functions for both methods (ES-MDA and RML) are detailed in Evensen et al. 2022.

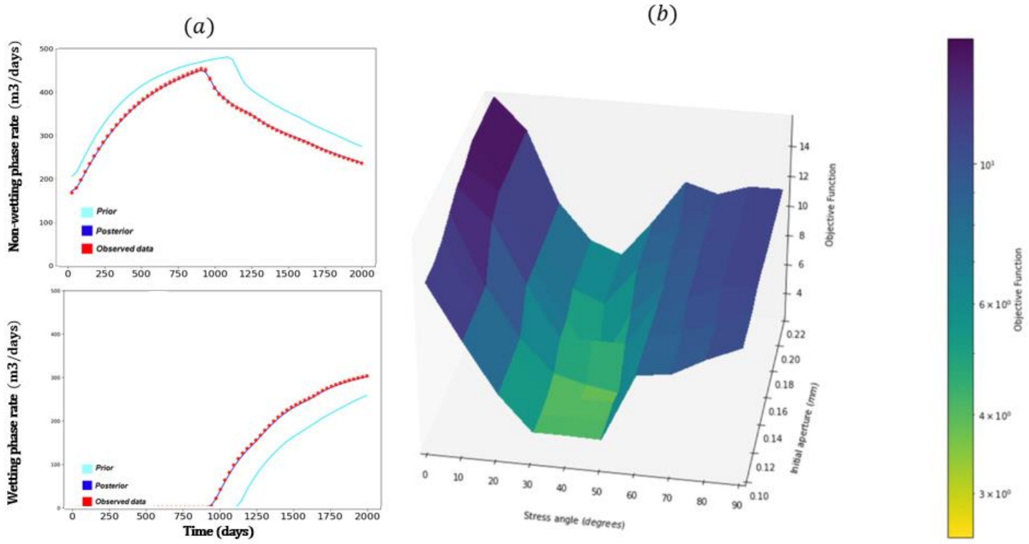

***Figure 6** (a) Results for the history matching using RML. (b) Objective function of this problem as a function of stress angle and initial fracture aperture.*

Conclusions

The results of our data-assimilation experiments show that the proposed data-assimilation framework can be used to quantify uncertainty when in-situ maximum stress angle and initial fracture aperture are considered as unknowns. The DFM method implemented in DARTS provides an easy, fast and flexible way to compute dynamic behavior of naturally fractured reservoirs which allows a straightforward implementation of a data-assimilation framework. Both ensemble and gradient-based data-assimilation techniques are effective for this synthetic problem. It is important to highlight that similar frameworks can be applied for different operations with naturally fractured reservoirs (e.g., geothermal and CO2 storage).

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