Introduction

Naturally fractured reservoirs (NFRs) are in the centre of attention due to their large reserves of geo-energy (e.g. hydrocarbon) worldwide (Berkowitz (2002); Geiger-Boschung et al. (2009); Dietrich et al. (2005)). However, when compared to conventional reservoirs, fractured reservoirs tend to show a more complex and heterogeneous character. The distribution and characteristics of fractures cannot be adequately sampled along a 1-D borehole and are mainly invisible on seismic images (Bruna et al. (2019)). With these challenges in mind, NFRs are made up of two mediums, rock matrix and fractures. In general, hydrocarbons tend to be primarily stored in the rock matrix but the fractures play a substantial role in the flow and transport field. Understanding how these flow paths behave can enhance hydrocarbon recovery and play an important role when enhanced recovery methods are considered to further develop a naturally fractured reservoir.

Fractured reservoirs are not only of interest for the development of hydrocarbon reservoirs, or extraction of other geo-energy resources. They are also relevant for safe cyclic storage of green gas and permanent storage of greenhouse gases (e.g. carbon dioxide). Once these fractured reservoirs are depleted, they can be filled with e.g. CO$_2$ to be stored safely underground. To be sure no gasses leak to the surface, the characteristics of fractures must be examined in detail, as the fractures may be a cause of flow and thus leakage.

The fractures are in both cases the cause for enhanced flow in the reservoir. In the first case this enhanced flow is desired whereas the flow in the second case is definitely not. Knowing how the fractures effect the flow is a crucial step towards a more reliable energy production and an environmentally friendly subsurface engineering.

This research suggests using pEDFM, described by Tene et al. (2017), to consistently model fractures with a wide range of conductivity contrasts towards the matrix. However, a modeling approach relies on input parameters including fracture properties. A meaningful simulation can only be performed once the characteristics of the fractured media are also meaningfully defined. In this work, we define the fracture network properties based on the principle stress, $\sigma_1$, minor principle stress, $\sigma_3$, and the orientation of $\sigma_1$. As such, our simulator populates the discrete fracture properties based on the geological information.

After the fracture characterisation step, multiphase flow simulations are performed. However, taking all existing fractures explicitly in the computational framework makes the simulations too expensive to run. Still it remains a challenge as to which fractures to be modeled explicitly and which fractures can be used to alter the matrix effective properties (i.e. homogenised). This research proposes an adaptive strategy in which fractures are dynamically present or homogenised during the time-dependent multiphase simulations.

Method

As mentioned before, it is very difficult to locate individual fractures in the subsurface and this is why outcrop studies on fracture pavements are being performed as they can be considered as an analogy to subsurface fracture sets (Bruna et al. (2019)). Studies based on outcrop data result in 2D fracture networks that can predict fracture sets with fractures ranging from millimeters to tens of meters long with all possible orientations. The outcome of this analogue to subsurface fracture sets can be used to evaluate flow through fractures in pressure and saturation simulations.

The reservoir rock can consist of different sets that have consequently been formed in different settings. To be able to classify these fractures, a model is built based on the Mohr-Coulomb failure theory and will be referred to as the critically-stressed-fracture theory (Zoback (2010)). The theory describes a fracture being hydraulically active, thus flow enhancing, or a fracture being hydraulically inactive. Inactive fractures do not play major roles in the flow path, unless they are impermeable, i.e., barriers.

To classify the fractures, three assumptions are made. The current major principle stress, $\sigma_1$, minor
principle stress, $\sigma_3$, and the orientation of $\sigma_1$ are considered. The current major principle stress and minor principle stress are used to plot the Mohr-Coulomb circle. A friction coefficient (here 0.6 following (Rogers (2003))) is then used to determine the failure envelope. Whenever the Mohr-Coulomb circle intersects this friction coefficient, a range consisting of $\theta_1$ and $\theta_2$ is determined. Once a pole of a fracture falls in this range, the fracture is considered to be hydraulically active as it falls in the Mohr-Coulomb failure envelope and is critically stressed (Allmendinger (2015)). Automating this process enables the user of this classification system to characterize entire fracture sets rapidly. The pEDFM simulator is as such extended to receive all fractures and their corresponding properties.

Fracture properties are according to the critically-stressed-fracture theory static properties. This means that before a simulation of, e.g., reservoir depletion the properties of the fractures can be determined and remain the same throughout the entire field life of the reservoir (assuming stress conditions in the reservoir are constant). However, the fracture characteristics also depend on effective stress Bandis et al. (1983). This effective stress changes as a result of production and therefor a characterization based on effective stress would be needed to determine fracture properties in a semi-static manner. Semi-static is used as pore pressure is a dynamically changing property as time passes, but stress conditions of $\sigma_1$ and $\sigma_3$ in the reservoir remain constant.

Problematic for a pEDFM simulator will be the count of fractures if a real fracture set is being implemented. This is due to the large amount of fractures being present in a real life data set. With a fracture classification scheme as described above, we address the critical question if all of these fractures are important to be taken into account. Built on the state-of-the-art dynamic multilevel method HosseiniMehr et al. (2018), we develop a dynamic coarsening strategy based on the local conductivity contrast between matrix and fractures. In this multiscale framework, fractures are automatically detected to be either explicitly represented or alter their embedding matrix properties. We illustrate the significant speed-up gained by this automatic strategy through several test cases.

**Test cases and results**

We set $\sigma_1 = 38$ MPa, $\sigma_3 = 8$ MPa and the direction of $\sigma_1$ to 0° azimuth (i.e., North-South). A test case is run based on an outcrop data. The fracture characterization was performed based on the static data of $\sigma_1$ and $\sigma_3$. This means no pore pressure data was taken into account in the characterization of this data. The fracture data used to simulate the flow and transport is based on the Brazil I outcrop from Bertotti’s group at TU Delft (Bisdom et al. (2016)). This pavement is analysed and a fracture set is interpreted manually, which can be used as analogue for our pEDFM simulator. Out of the total of 446 fractures 73% (327) is categorized as hydraulically inactive, receiving a permeability of $10^{-22}$ m$^2$. The remaining 27% (119) is considered to be hydraulically active and are therefore considered to have the permeability of $10^{-6}$ m$^2$. Figure 1 show how saturation and pressure are distributed in a reservoir. In this test case, the matrix is homogeneous. 2 injector wells and 2 producers are added in the left and right (top and bottom), respectively.

![Figure 1](image_url)  
*Figure 1* Interpreted fracture set from outcrop data of (Bisdom et al. (2016)) (left) along with the saturation (center) and pressure (right) fields.
From figure 1 it is clear that fractures have differences when compared to the ability to allow for fluid flow. This can be seen from the irregular pattern that can be seen close to the fractures. Note that not all fractures are explicitly playing major role in the flow and transport. Fractures that are categorized as hydraulically inactive still have to be classified whether they are flow barriers or not.

Conclusions

We developed a geologically relevant framework for the pEDFM fracture modeling approach. It was based on the acting stress field in the domain. In addition, an adaptive strategy is implemented to explicitly represent the important fractures. All other fractures will be homogenised with the embedding matrix. Further tests and analyses will be carried out in order to fully develop the loop between geological and geophysical data interpretations and dynamic multiphase simulation.

References