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# numeric simulation of field-scale time-dependent Fracture models

Reasoning for PhD proposal.

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## Introduction

### Scope

This document materializes perspectives to foment discussions about research directions and expectations. Technical claims emerged from recent discussions which lack maturity are consolidated as hypotheses to be investigated.

### Objective

We want to build thermo-hydro-mechanical numerical models to investigate the dynamic behavior of faults and fractures and their influence on oil recovery, storage capacity, and safety. This is a phenomenological investigation, such that numerical methods are designed towards the clarification of hypotheses. Computational effectiveness emerges naturally as a requirement to assess complex models but are not a primary goal.

### Motivation

Recent research has been concerned with the numerical modeling of fracture genesis, transmissibility, and interaction with the surrounding matrix. Fracture extension has been thoroughly investigated for hydraulic fracturing in stimulation operations, but still lack a understanding on dynamic faults and fracture behavior after long term drainage.

We refer to fracture dynamics as the phenomena expected during reservoir drainage. For example:

1. Faults and fractures may shear anywhere in the reservoir and its surroundings as the mechanical conditions depart from the initial equilibrium (risk of major oil leaks).
2. Near injecting wells, lower temperature decreases effective stress, and fractures tend to open and propagate (increase of injectivity index).
3. Near injecting wells, fracture-to-matrix fluid leak-off increases effective stress, and fractures tend to close.
4. Near injecting wells, higher pore pressure tends to open and propagate fractures, which may extend towards the caprock and large-scale faults (risk of major oil leaks).
5. Near producing wells, the lower pressure decreases effective stress, and fractures tend to close, reducing the well productivity index and may crush the proppant.
6. Far from wells, conventional reservoir depletion decreases effective stress, and fractures tend to close.

As numerical models focused on these behaviors are typically targeted to well-stimulation designs, they normally consider the reservoir as simplistic continua, and fracture geometry as well-behaved planes. The present project differs from the common ground for the following realizations:

1. Many fractures are present in naturally fractured reservoirs. They interact with each other and with the surroundings, changing the overall fluid transmissibility.
2. Fracture propagation cannot be restricted to planar geometries when temperature is a significant driver (e.g., geothermal systems or long-term fluid injection) or in heterogeneous layered reservoirs. In these cases, fracture branching and swarms must be investigated.
3. Creep and plasticity cannot be neglected in many cases. For example, when salt is the caprock, as in the Brazilian pre-salt reservoirs or in salt caverns for storage.

## Research framework

### Research Questions

**Q1:** What is the relevance of fracture dynamics for reservoir drainage, fluid storage, and operational safety?

**Q2:** To what extent are simple linear models for aperture taking only pressure as a parameter enough to represent the global impact on production and overall design technical and economical appreciation?

### Original Investigation

Research papers and commercial codes on fracturing rarely discuss fracture nucleation after fluid injection in conventional reservoirs. The analysis is conventionally restricted to single fracture models and planar geometries, which are unsuitable for significant temperature gradients, in the presence of complex natural fracture networks and in heterogeneous rocks.

### Vision

This research is a phenomenological study. We want to design methods that help us understand each phenomenon's relevance to the oil recovery and the safety of the operations. We want to design commercially usable technologies that can empower (work together with, rather than replace) existing simulation software and workflows.

### Technical Challenges

#### Nucleation and tracking

Fracture nucleation and tracking are multi-physics phenomena that concur in distinct space-time scales. For example, as temperature and pressure diffusion characteristic time ranges from hours to days, fracture propagation may respond in seconds or faster. The physics involved includes poroelasticity, poroplasticity, pressure diffusion, energy convection and diffusion, salt creep, etc.

#### Fracture interaction in naturally fractured reservoirs

Naturally fractured reservoirs (NFR) contain many fractures and faults, in multiple scales, interacting mechanically and hydraulically with the surroundings. The computational cost of existing technology limits the number of joints that can be modeled together.

#### Fracture multiphase imbibition

We note that many static fracture models are in use, e.g. EDFM, , LGR, etc. EDFM has emerged recently as a method to cope with large number of fractures in infra-mesh resolution. The technology has been extensively validated for single-phase workflow, but there are still open issues in the scope of naturally fractured reservoirs and multiphase flow and capillary continuity.

#### Scalability and computational complexity

Many researchers invested in numerical solution designs for this problem, but papers show avoidance to complex scenarios. It is rare to see the use of 3D models, fracture nucleation and tracking. We conclude that scalability is an issue for most numeric strategies.

We know that meshing is problematic, as mesh refinement explicitly capturing the phenomena leads to prohibitive computational cost, and embedding the phenomena into coarse meshes is unrealistic when fracture interaction comes to play. We believe hybrid adaptive approaches still need to be investigated.

## Target Applications

#### Offshore carbonate reservoir

Consider an ultra-deepwater, salt as caprock, conventional heterogeneous naturally fractured carbonates, with porosity ranging from 10 to 25%, average layer permeability of to , and high stiffness (bulk modulus ). After natural depletion, the reservoir undergoes secondary enhanced oil recovery (cold water and gas flooding), with a high-temperature gradient around the injecting wells. The caprock consists of thick salt layers, mainly composed of Halite.

#### Offshore sandstone reservoir

Consider an ultra-deepwater, conventional heterogeneous layered sandstone with porosity ranging from to and average layer permeability of to . After natural depletion, the reservoir undergoes secondary enhanced oil recovery (cold water and gas flooding) above the fracturing limits. The caprock consists of overlaying heterogeneous shale layers.

#### Storage in salt caverns

Consider a salt cavern built inside a Halite dome. During normal operation (years), the salt cavern is subject to cyclic pressure and temperature variations due to seasonal injection and production of the stored fluids. After abandonment, the cavern is subject to long-lasting creep (centuries), impacting the thermodynamic evolution towards equilibrium. Long-term fluid leaks through the salt due to nano-permeability and micro-fracturing of the cavern are expected.

## Expected Research Outcomes

### Modeling Outcomes

#### Validate EDFM methodology in multiphase flow

The literature review conducted recently identified a potential limitation of EDFM when modeling multiphase flows. The problem is at the fracture and matrix cells interface, where the numerical upwind may not properly honor the physics.

#### Identify primary parameters related to fracture dynamics

Investigate and rank the most important aspects of fracture dynamics that impact oil recovery rates or safety. Propose proxy models for the applications studied, which can be included in commercial simulators and industry models.

#### Add fracture dynamics capabilities to active workflows

Although identifying primary parameters related to fracture dynamics is a product of its own (previous item), we find it important to use these findings to integrate the most important parameters into an active numerical simulation workflow.

### Operational Outcomes

#### Increased injection rates

With proper estimations of fracture dynamics, operators can safely increase injection rates, limiting the fracture propagation to a small radius around the injecting well. Alternatively, the operator may feel confident operating long-term fluid injection above the fracturing pressure. That would be the case of produced water injection, for example, which may reduce the permeability of the rock around the well.

#### Maximize salt cavern storage capacity

Enhance current simplistic design workflows of salt caverns with geomechanical considerations, especially considering long-term creep and fracture propagation constraints.

#### Optimize salt cavern abandonment

After abandonment, the salt cavern is expected to be maintenanceless and leakage-free for centuries to millenniums. Hence, proper geomechanical modeling of the cavern can support and optimize the operations, with special attention to fracture nucleation and propagation on the fracture wall.

## Closure

Fracture propagation is highly nonlinear, multiphysical, and multiscale (see Fig. 1). It is impractical from a computational cost model propagation in field scale, which can show many fractures.

We propose working in a hybrid environment where the pressure, temperature, and saturation fields can be seen as boundary constraints for smaller-scale fracture propagation models. A set of parameters must be chosen to embed small-scale findings into field-scale models as an approximation.

Proper modeling of the fracture nucleation can lead to a natural way of handling complex fracture geometries and branching. This is especially true in non-isothermal environments, subject to small stress contrast, where secondary and tertiary fractures are expected.

The maturity of the research draft described so far in this document is limited by uncertainties naturally present in early work. It seems productive to break down the problem into smaller pieces and limit the scope of individual discussion. For that, Tab. 1 lists relevant hypotheses with tentative maturity classifications. The idea hereafter is to work on each hypothesis and increase maturity and support decision-making gradually.

Figure 1 – Technologies to be investigated during the research

A diagram of a science experiment

Description automatically generated with medium confidence

Table 1 – Maturity assessment of important hypotesis, to become assumptions and hypotheses for this research.

|  |  |
| --- | --- |
| HYPOTESIS | MATURITY |
| PHYSICS |  |
| Multiphase flow does not impact fracture propagation as long as we estimate the global temperature and pressure fields well. | Believe |
| Multiphase flow has limitations when using EDFM in NFR due to the upwind numerical strategies of the commercial simulators. | Believe. Need to investigate. |
| Temperature-driven fracture dynamics in heterogeneous reservoirs are not planar. Branching and fracture swarms cannot be neglected. | Evidence |
| Linear Poroelastic Fracture Mechanics is insufficient for fracture propagation. Plasticity and creep are relevant in many cases. | Don't know. Need to investigate |
| Creep is important to model fracture propagation in a salt layer, as it acts within minutes-to-hours. | Believe |
| Reactive transport is secondary in propagation but may fill the fracture and reduce permeability. | Believe |
| Pressure and temperature evolution *cannot* make a fracture to become a blocking path. The model may focus only in conductive fractures. | Believe |
| Fracture propagation characteristic time concur with pressure diffusion only in early times or with high-efficiency fluids, in which case fully coupling applies. Higher times are expected otherwise (weak coupling is enough) | Believe |
|  |  |
| HYPOTESIS | MATURITY |
| NUMERICS |  |
| Only small-scale meshes can deal with the complex physics of fracture propagation. | Believe |
| EDFM works in coarse meshes and has no resolution to model physics behind fracture propagation driven by low-efficiency fluids. In fine meshes, we know better technology. | Believe. What do we learn from Lily's work? |
| Phase field models are expensive for 3D models because they require high resolution to map a 2D mesh in volumetric elements. We do not know any technology to overcome that. | Believe |
| FEM provides more mathematical flexibility than FVM and FDM to work with fracture mechanics. | Believe |
| We can numerically estimate the velocity vector at the tip of an existing fracture, which can be mapped to a point (2D domain) or a line (3D domain). | Don't know. Need to investigate. |
| We can numerically estimate a nucleation vector in any point P of the continua. | Don't know. Need to investigate. |
| Conforming meshes require remeshing but are still less expensive because they explicitly represent the fracture domain and fracture interaction is a natural outcome. | Believe |
| Non-conforming meshes cannot model fracture interaction effectively. It is unrealistic to embed mechanical interactions of complex geometry. Some technologies are ILSA, XFEM, Phase-field, SBFEM. | Believe |
|  |  |
| HYPOTESIS | MATURITY |
| APPLICATIONS |  |
| The relaxation (opening) of natural fractures prevent fracture extension because they are strain release mechanisms. This is the case in low-temperature fluid injection, but might not happen in scenarios of stress contrasts. | Believe |
| Natural fractures closure to reservoir depletion can be handled effectively with simple tables (, e.g., CROCKTAB) in flow simulators. | Believe |
| Cold drilling fluids are enough to fracture the rock even in original pressure. This process has no time dependency and occur in stiff rocks under thermal stresses. | Believe |
| Salt cavern fracture analysis for safety needs hundreds to thousands of years. | Evidence. |
| Increase in HF effective stress due to depletion causes proppant crushing. Existing simulators tables can handle that effectively (e.g., CROCKTAB). | Believe |

## Worksplit

This section proposes a tentative worksplit to refine and prioritize, and a tentative timeline (Tab. 2).

#### EDFM Review *(ongoing)*

Investigate and write a paper on the state-of-the-art of fracture modeling and latest contributions in EDFM techniques.

#### Homogenization of mechanical parameters in fractured poroelastic media *(ongoing)*

Validate simulator and discuss issues regarding the macroscale mechanical behavior of a NFR, with varied fractured densities. Compare with existing methodologies. Use this effort to test and improve the simulator.

#### Multiphase flow in EDFM

Investigate potential issues on EDFM when using multiphase flow. Use a reference refined 2D model in a zero-pressure-gradient zone, initialized with water in the fractures and oil in the matrix to see if the mass exchange is consistent under different capillary pressure and relative permeability scenarios.

#### Add temperature and heat exchange

Repeat the same effort adding temperature evolution. Verify to what extent existing fractures can relax strain energy and prevent fracture propagation. Provide stress analysis on the tip of the fractures and verify whether they are stable and in which conditions they would propagate.

#### Propagate planar fractures in a NFR, rethink the simulation strategy

Add propagation capabilities to the model, considering that the fracture path is known a priori. Use cohesive elements for that. Integrate the results to EDFM workflow and do flow simulations.

#### Implement a 2D algorithm for fracture branching, considering remeshing

Progress from the last item towards remeshing, that is, tracking the fracture paths as an adaptive mechanism to control the remeshing. Engines are likely needed: 1) discover the potential fracture paths; 2) do the remeshing; 3) DG in time to the marching algorithm.

#### Plasticity and creep

Plasticity and creep pose significant nonlinearity to the models. This may cost significant implementation effort.

#### Implement a 3D algorithm.

The same, but in 3D.

Table 2 – Tentative timeline *(draft)*

|  |  |
| --- | --- |
| Year/sem |  |
| 2024/1 | EDFM Review  Define research scope.  Homogenization of Biot parameters |
| 2024/2 | Multiphase flow in EDFM (try Yifei’s code)  Literature review on physics, and asymptotic formulations.  Write and defend the proposal.  Implement and validate simple fracture dynamics in an elastic environment (THM). |
| 2025/1 | Back-integrate with EDFM.  Basic fracture branching. |
| 2025/2 | Application: fracture branching in heterogeneous media  Consider plastic and creep environments. |
| 2026/1 | Application: fracture propagation in salt rock (caprock and caverns)  3D implementation, and improvements. |
| 2026/2 | Wrap up results. |
| 2027/1 | Refine results.  Write dissertation. |