Eindrapportage

January 10, 2022

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Projecttitel	CarbFrac – Fracturing flow and reactive transport in carbonate and chalks hydrocarbon and hydrothermal reservoirs
Penvoerder en medeaanvrager	TU Delft (penvoerder) & TU Eindhoven (medeaanvrager)
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Contents

1 Report

1.1 Summary

Carbonate rocks form major reservoirs and aquifers worldwide and are first order targets for geothermal exploration in the Netherlands and in NW Europe. Characterization and exploitation of these carbonate systems is challenging not only because of the sedimentological complexity, but also because of the interactions between fracturing and dissolution/precipitation patterns.

Within the CarbFrac project, we work on the development of (computer) models that describe the coupled mechanical and fluid flow behavior of geologically complex subsurface carbonate reservoirs. By analysing outcrops and performing numerical experiments, we gain insight into these geological complexities. The flow through these geologically complex reservoirs is analysed (computationally), while taking into account dissolution/precipitation processes that occur in carbonate reservoirs. Computational tools are developed to model the response of reservoirs to hydraulic stimulation and depletion.

1.2 Introduction

To allow for geothermal heat extraction, CO_2 sequestration, or hydrocarbon production to be economically viable, or even possible, the permeability of reservoirs needs to be sufficiently high. Generally, this requires reservoirs to be naturally fractured and/or hydraulically stimulated. Though necessary, the presence of fracture networks in reservoirs complicates the prediction of reservoir mechanic and flow response to stimulation and depletion. Additionally, carbonate rocks typically experience dissolution and precipitation, which may have led to the formation of caves of up to ten meters in diameter, adding to the complexity of response prediction. Predicting reservoir permeability (characterization) and reservoir response to exploitation (pressure changes) is vital to optimize production strategies, open up new exploration strategies and decrease risks during stimulation, production and depletion.

Wintershall and Neptune Energy have major challenging carbonate reservoirs in their portfolio. EBN in addition, is leading the effort of the Ultra Diep Geothermie (UDG) initiative which targets Dinantian carbonates. These carbonates are well known for their sedimentological complexity, but also because they are fractured and host multiscale dissolution features associated with hypothermal activity (e.g., Reijmer at al. 2017).

Prediction strategies traditionally rely heavily on data that can be directly acquired from wells. This local data then needs to be extrapolated to the entire reservoir, resulting in reservoir-scale Discrete Fracture Networks, which are then used for simulations. In the case of carbonate reservoirs, dissolution/precipitation features, typically below seismic scale, need to be included in the model. Performing simulations on these systems is not trivial. The complex geometry, topology and physical characteristics of naturally fractured and artificially stimulated discontinuity networks, however, calls for novel, computational, prediction strategies.

In developing these novel prediction strategies, we identify the following challenges:

- Developing new tools to populate the reservoir model with fracture data.
- Accurate representation of reservoirs with pre-existing (natural) fractures and dissolution features requires the prediction of the topology and reservoir-scale distribution of discontinuity networks (fractures, karstification, and sedimentary bedding), both in the absence and in the presence of fluids.
- Investigate the dynamics of fracture propagation occurring when the reservoir/aquifer is stimulated.
- Balancing reservoir complexity and computational cost in flow simulations.

These challenges are addressed within the CarbFrac project.

1.3 Goal

The overarching goal of the CarbFrac project is to develop models describing the coupled mechanical and fluid flow behavior of carbonate reservoirs. This goal is to be met through three subgoals:

(*i*) To honor the complex geological structure of a carbonate reservoir, the geometry, mechanics and temporal evolution of the reservoir need to be coupled with realistic fracture networks. To enable populating our model volumes with these realistic discontinuity networks, our first subgoal is to derive rules predicting their geometry and physical properties.

(*ii*) Both the complex structural features and the dissolution/precipitation processes occurring in carbonate reservoirs are incorporated in computationally inexpensive modeling tools, allowing the prediction of flow behavior through the discontinuity networks and the surrounding permeable formation.

(*iii*) Developing numerical tools or utilizing tools not previously employed in the context of geomechanics will allow for studying the response of the reservoir-seal system to hydraulic stimulation and reservoir depletion.

1.4 Approach

The CarbFrac project was executed by a consortium of two university partners, Eindhoven University of Technology (prof. dr. ir. D.M.J. Smeulders and dr. ir. J.J.C. Remmers) and Delft University of Technology (prof. dr. G. Bertotti, dr. A. Barnhoorn and dr. D.V. Voskov), and three industrial partners, EBN, Neptune Energy, and Wintershall. The consortium was formed after successful previous collaboration within the 2F2S project (TKIG01025, TKI-T2013-08-UG, TKI-T2014-11-UG, and TKI-T2015-08-UG), which was concluded in 2017. The CarbFrac project was funded by TKI Nieuw Gas and the three industrial partners. Within the project, a PhD candidate was appointed at both of the participating universities. In September 2017, ir. E.A. Bergkamp (Elisa) started at Eindhoven University of Technology. In December 2017, ir. S. de Hoop (Stephan) started at Delft University of Technology.

Consortium partners met around once every year throughout the project, both face-to-face and in online settings (for a total of five sessions). During *knowledge exchange meetings*, the work performed within the project was presented to the industrial partners, leading to fruitful application-oriented discussions. Furthermore, the university partners met regularly at either one of the universities, at conferences, and online.

CarbFrac has become a multiplier for innovative research in the participating Universities and has been fully integrated with other activities occurring in the participating groups. Some of the results of these collaborative efforts are reported on here and are shared as deliverables with the industrial partners.

1.5 Results

The three subgoals of the project are translated into three themes, the results of which are reported here.

1.5.1 Theme 1: Rules for type and spatial organization of discontinuity networks

The formation of fractures and fracture networks are eminently present in the literature, with significant contributions from the TU Delft research group. Modes of investigation can be separated into three kinds: outcrop analysis, numerical models, and laboratory experiments. According to previous research, the main factors contributing to the geometry of the resulting fracture networks are local and regional stresses, lithology, and interfaces between layers of different mechanical properties. Besides the fracture geometry (lengths, spacing, and connectivity), the hydraulic aperture is essential in correctly predicting fluid-flow patterns in fractured reservoirs. In addition to fracture diagenesis, the current in-situ stress conditions in the reservoir largely control the fracture aperture distribution in the fracture network.

Constrains on fracture network geometry and fracture aperture are limited to well logs, borehole images, well tests, and outcrop analogs. However, most fractures are on the sub-seismic scale, while well-related data only provide information on the near well-region. In order to obtain a complete reservoir-scale fracture network, it is necessary to perform interpolation between these scales. The interpolation introduces significant uncertainty in the flow- and mechanic behavior of these reservoirs. Subsequently, this leads to the necessity of many models representing possible states of the subsurface. These models are generated using stochastic (e.g., Multiple-Point Statistics), mechanical (e.g., (Extended) Finite Element Methods), or derived from outcrops. In order to make predictions, these fracture models are meshed and serve as an input to numerical reservoir simulation tools.

Discrete Fracture Model (DFM) is a numerical representation of a fracture model where the fracture geometry is explicitly defined using a conformal unstructured mesh. This results in the most accurate depiction of the fracture network and all the relevant physics. However, the meshing of a realistic naturally fractured reservoir in the DFM framework is often challenging. To solve this computational challenge, TU Delft developed an efficient and robust methodology for handling fracture networks at the reservoir scale. The proposed methodology changes to the topology of the fracture network to reduce the computational complexity while preserving the accuracy of the approximation (see Figure 1). Changes include simplifying the fracture intersections and abutment. The preprocessing framework increases the fracture network's overall connectivity; due to the aperture corrections (similar to effective resistivity in an electrical circuit), the main flow patterns are preserved in the simplified representation. Furthermore, topological fracture analysis on raw fracture data (obtained from outcrops of geostatistical models) can be misleading, due to unrealistic fracture intersection and abutment relations (see Figure 1). The orientation of the fractures in the network also changes due to the preprocessing but is less sensitive than the topology. The presented method opens up avenues for efficient DFM models with similar computational complexity as embedded-DFM (EDFM) and even Dual-Porosity models. However, it still accurately captures the discrete nature of fracture networks for uncertainty quantification and history matching purposes in these complex carbonate reservoirs.

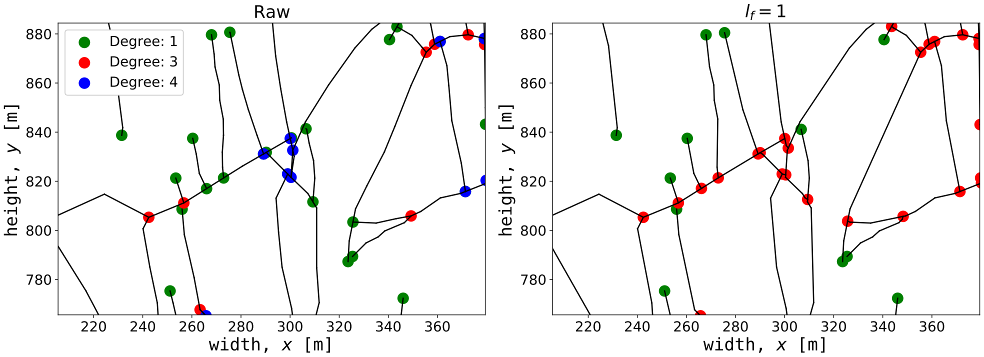

Figure 1: Comparison of fracture network topology of the raw (i.e., unprocessed) input data on the left with the preprocessed topology on the right. I-nodes (degree 1) are end-points of fracture segments, Y-nodes (degree 3) are abutting fractures, and X-nodes (degree ≥4) are intersecting fractures. In this example, due to the manual interpretation, it can be seen that a lot of nodes are characterized as I-nodes or X-nodes, while most seem to be Y-nodes (when considering usual abutment relationships in fracture mechanics and the resolution of the outcrop image). Modified from de Hoop et al. (2021b).

Besides fracture networks as discontinuities, large-scale dissolution (i.e., karst) is essential when accurately predicting carbonate reservoir behavior. The importance of such multi-scale dissolution features is increasingly recognized worldwide. Karsts in subsurface rocks have obviously been known for long time but they were generally interpreted as of meteoric origin, that is, as formed at the surface. In contrast, it is presently well known that many karsts can form at depth as a result of interactions with hot, chemically aggressive fluids rising upward along faults or fracture zones and expanding laterally when upward flow is prevented. Resulting dissolution can form very large cave systems with very different geometries and shapes (Klimchouk, 2009; Palmer, 2011).

During the CarbFrac project, karst development was investigated with two fieldwork expeditions to several caves in Bahia, Brazil. With a team of speleologists and geologists, the cave interior was mapped using a mobile LiDAR device. A worldwide new workflow was developed for this purpose and has allowed us to produce a unique data base of digital cave models; the data base is accessible to partners and forms one of the deliverables of CarbFrac. Furthermore, lithology, mineralization, and internal fractures were analyzed. Besides the two publications that resulted from this endeavor (Bertotti et al., 2020; Pontes et al., 2021), a large data set was generated and is publicly available at de Hoop et al. (2021d; 2021e; 2021f). Accurate prediction of fracture networks can also be valuable in predicting the occurrence of multiscale dissolution features (from increased fracture apertures to actual caves), which are common in carbonate reservoirs. In the CarbFrac project and collaboration with other projects, we have devoted substantial energy to developing knowledge to link fractures to dissolution

The paper Bertotti et al. (2020) focused on one cave in particular (Morro Vermelho Cave). The cave experienced little interaction with meteoric processes and served as an excellent example of a hypogenic cave formed in a strike-slip tectonic regime. During an initial stage, bedding parallel flow led to extensive dolomitization of a 102m thick body of rock experiencing distributed deformation above a deep seated strike slip fault. With progressive displacement, the fault grew upward connecting the two aquifers of the sedimentary succession (quartzarenite and overlying carbonates) allowing for the invasion of SiO2 rich fluids in the carbonates and creating caves with a variety of exotic minerals. Similar minerals are recognized in the Dinantian rocks in Belgium and surrounding areas.

This research indicates that the presence of strike-slip faults in the vicinity of deep-seated carbonate aquifers can lead to extensive mineralization and large-scale dissolution along fractures, severely altering the reservoir properties (e.g., porosity and permeability). The high-resolution LiDAR dataset also allowed for easy detection of small-scale speleogenetic features indicating pathways for rising fluids and other diagnostic features such as “cupolas“, as shown in Figure 2.

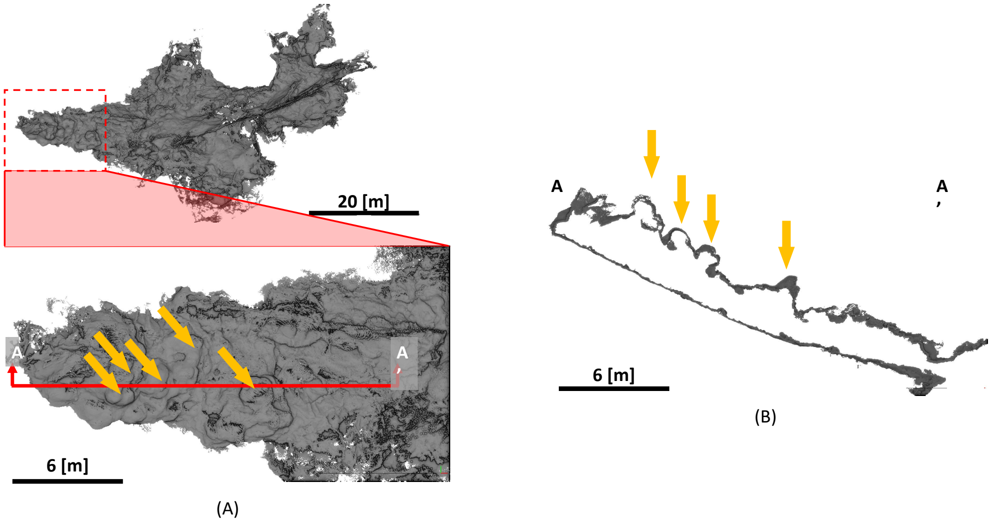

Figure 2: (A) High-resolution LiDAR data from the Morro Vermelho cave in Bahia, Brazil. (B) Visible speleogenetic features (i.e., “cupolas“). Modified from Bertotti et al. (2020).

The paper Pontes et al. (2021) focused on linking the role of fractures in fold hinges to the development of karst conduits. Petrographic and structural analyses were performed alongside the collection of high-resolution LiDAR data. The results of this paper indicate that the development of the observed karst system is potentially related to the presence of fracture corridors formed alongside sets of fold hinges. This karstification, in turn, provides large continuous high permeable zones which serve as preferential fluid pathways during reservoir production. Results are among the deliverables.

Caves can have a wide range of shapes and dimensions. Maps have been made by speoleologists for long time, but 3D models have only been possible with the development of portable LiDAR technology the use of which in caves we have pioneered. Furthermore, a comprehensive shape analysis was done on the acquired LiDAR surveys. A skeleton was extracted from the LiDAR survey. Along each edge (i.e., limb of the skeleton), a cross-section through the LiDAR survey was made. All the points in the neighborhood were projected onto this cross-section. Fitting a curve through the projected points resulted in a parametrization of the 3D structure of the cave. This allowed an analysis of width and height changes along the skeleton's edges (i.e., cave tunnels). Enlargement of the width of the cave tunnels indicates possible intersecting fractures and therefore converging fluid flow through the fracture network locally, enhancing the dissolution. Link to relevant MSc. thesis can be found here.

Another exciting result from the TU Delft research group links the presence of natural fractures in a pavement outcrop to a nearby cave network (Boarsma et al., 2019). The result shows a similar orientation of fractures and cave conduits. Stress-based aperture fluid-flow simulation indicate that the main flow conduits align with the cave orientation, further linking the fractures to the cave development.

Furthermore, recent work on automatic fracture detection and graph theory applied to fracture networks at the TU Delft research group enhanced our understanding of fracture networks. The automatic fracture detection algorithm allows us to easily and quickly convert large-scale outcrop images to a usable fracture network for modeling purposes (Prabhakaran et al., 2019). Treating fractures as a spatial graph (i.e., every fracture segment is an edge and the end-points of the segments are vertices) allows for an in-depth analysis of the characteristics of the fracture network. A graph distance-based analysis and hierarchical clustering provide a quantitative method for characterizing the intra-network spatial variation (Prabhakaran et al., 2021).

Finally, advanced fracture modelling and interpolation workflows were developed within the TU Delft research group. A geologically realistic statistical method was developed using Multiple-Point Statistics (MPS). This method relies on a set of small synthetic training images which represent the geological variability of fracture parameters observed locally in the field. The training images contain all the statistical characteristics of the fracture network and therefore allow for the representation of a complex arrangement of fracture networks (Bruna et al., 2019). Another statistical method for creating geologically constrained Discrete Fracture Networks was developed in Boersma (2020).

At TU/e, propagation of a hydraulic fracture in a reservoir with discrete and layered heterogeneity is studied. Predicting the type of fractures formed and their height has been impossible until now as no theory is available. At TU Delft, we have approached this in a series of rock mechanic experiments, conducted partly in collaboration with other projects. Fractures are observed to cross, kink, deflect or get arrested in a reservoir with strong layer interfaces. The Young's modulus contrast between the layers is the most important parameter in a layered reservoir with higher contrast causing the fracture to deviate from its initial path. This phenomenon is observed in an enhanced manner in deeper reservoirs with less stress anisotropy. Thin layers of stiff rock were observed to act as barriers for fracture propagation across layers (see Figure 3). These barriers tend to become stronger with an increase in the bedding plane orientation. The inclusions which are stronger than the surrounding host rock tend to attract the fractures towards them whereas the softer inclusions were found to deflect the fractures away from them. Also, a multi-stage hydraulic fracture network problem is investigated in an isotropic, anisotropic and heterogeneous layered reservoir.

1.5.2 Theme 2: Production from carbonate NFR fields

We have seen that caves can have a high degree of regularity (in directions but also in tunnel size) and that they seem to be partly conditioned by fracture networks. To investigate the relations we have performed innovative modelling studies. The numerical reservoir simulations studying dissolution patterns and the production from carbonate reservoirs were carried out in the newly developed platform Delft Advanced Research Terra Simulator (DARTS). This platform is based on the newly proposed Operator-Based Linearization (OBL) procedure. In this method, an additional form of discretization, besides the usual spatial and temporal, is used, particularly a physics discretization. The conservation equations are grouped in state and space-dependent terms, such that knowing the state or spatial location will result in being able to compute the grouped term (from now on referred to as operator). The operator form of the equation is then approximated via multi-linear approximation of the operators. The exact value of the operator is calculated

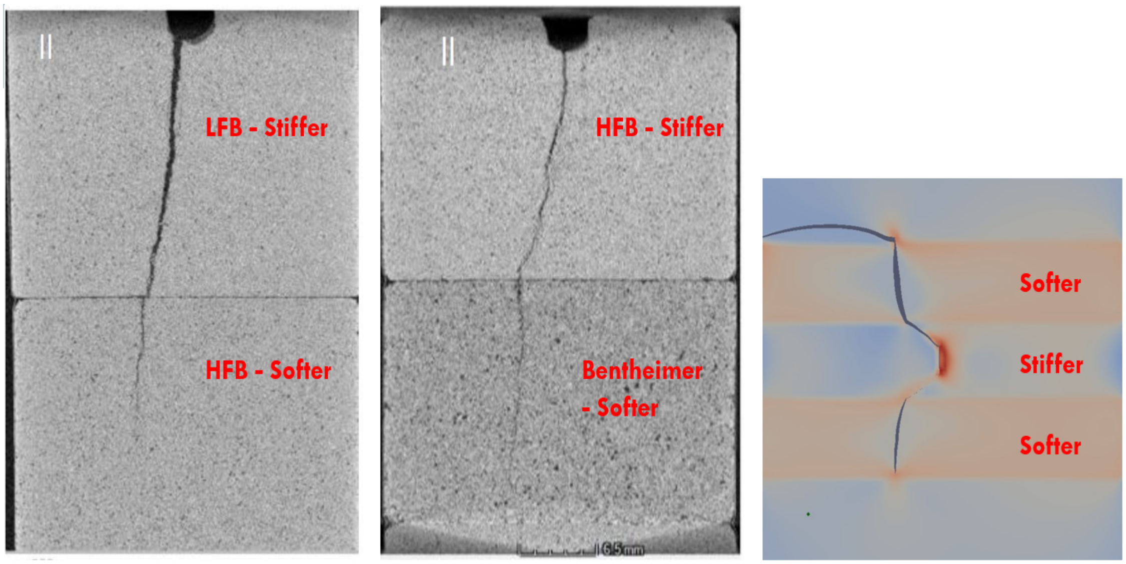

Figure 3: Propagation of a hydraulic fracture from brittle into softer rocks. The direction of propagation changes over the rock interface, as is also predicted by the numerical model.

precisely in the supporting points. The actual value of the operator corresponding to the current state is then computed via interpolation. One of the main benefits is the simple Jacobian matrix assembly since the partial derivatives of the operators w.r.t. the state is simply the gradient of the multi-linear interpolant. For more details regarding DARTS and OBL, please see our webpage.

The first main addition to the existing DARTS framework during the CarbFrac project consisted of implementing kinetic and equilibrium chemistry. The equilibrium chemistry was implemented using the element balance formulation. This formulation reduces the number of global equations by the number of local chemical equilibrium equations. This allows the simulation of a large set of components with relatively few global equations, thereby significantly reducing the computational complexity. Several tests were performed to compare the equilibrium and kinetic framework. Reasonable agreement was found in the limit of infinitely fast kinetic rate (see Figure 4). More results related to the element reduction framework can be found in the MSc. thesis and paper.

Due to the simple partial derivatives of the conservation equations with respect to the primary unknowns and the flexible Jacobian matrix assembly inherited from the OBL method, the extension of operator computation through the use of a third-party tool was easily achieved, further extending the DARTS framework. The geochemical tool PhreeqC was used to calculate accurate chemical properties and reaction rates and was coupled with the DARTS simulation framework. Results from the simulation were compared with experiments found in the literature (injection of carbonated water causing wormholing phenomena). All the results related to the PhreeqC extension can be found in the MSc. thesis.

In order to further validate the numerical framework, a benchmark project was proposed together with the Centre Inria de Paris and the University of Pau. We tried to validate state-of-the-art numerical codes on the complicated coupled multi-phase reactive transport problems in the benchmark. Test cases consist of 1D and 2D geometries with heterogeneity and different fluid chemistry. Preliminary results can be found on this website. Currently, over six other universities worldwide want to contribute to the benchmark. Results for publication are expected in 2022.

Besides chemistry-related additions to DARTS, the unstructured meshing capabilities were developed during the CarbFrac project. This includes fully unstructured mesh based on several meshing formats with and without the presence of discrete fractures. Fractures are treated using the typical DFM approach (i.e., fractures are a lower-dimensional feature in the meshing domain; however, they are assigned a volume in the computational domain based on the aperture

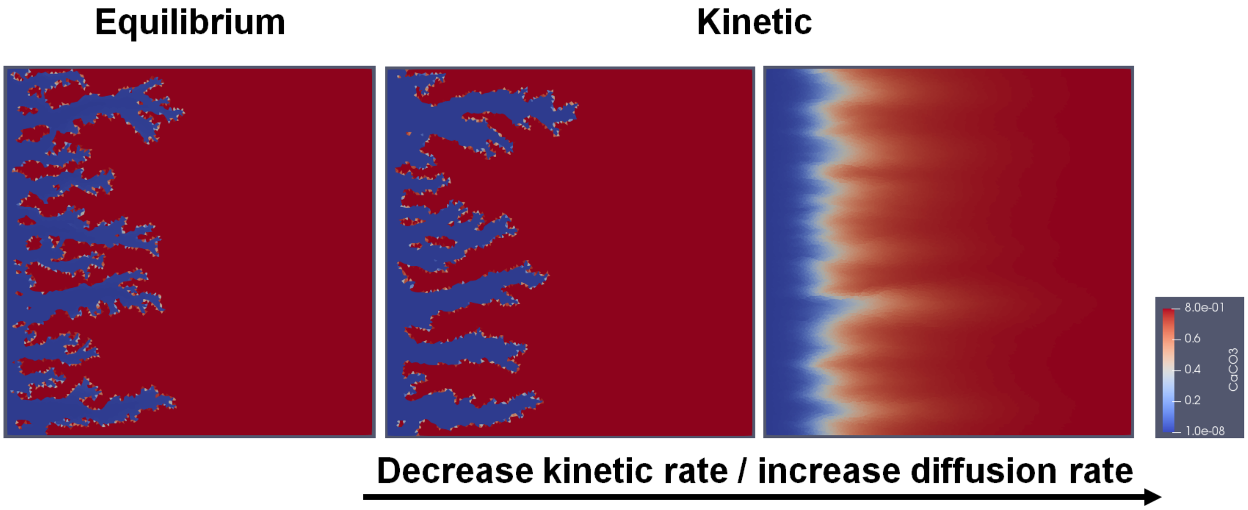

Figure 4: Numerical simulation results from the reactive transport framework developed in the Delft Advanced Research Terra Simulator (DARTS). Comparison between chemical equilibrium and kinetic reactions (of varying kinetic rates). The blue color indicates a large portion of the porous is media, while red indicates no dissolution has occurred. Reasonable agreement was found in the limit of infinitely fast kinetic rate (small changes can be attributed to the unstable nature of the equations in combination with numerical perturbations). Modified from de Hoop et al. (2020a).

of the fracture). Besides fully unstructured mesh, Adaptive Mesh Refinement (AMR) was also implemented during the CarbFrac project. The AMR uses a multi-level connection list, and adaptivity arises from the hierarchy in the connection list. A flow-based upscaling method (global upscaling) is applied to obtain the coarser level transmissibilities. Simulation is started on the coarsest level (except for the grid surrounding well locations). A refinement criterion is checked at each step, and wherever necessary, the mesh is refined to more accurately capture the dynamic solution. Figure 5 displays an example of the AMR approach to geothermal simulation. The AMR solution is in close agreement with the reference solution while using substantially less degrees of freedom (20% at the start and around 60% at the end of the simulation). Implementation of the AMR method and additional results can be found in de Hoop et al., (2021a).

As previously mentioned, the fracture preprocessing strategy allows for large-scale uncertainty quantification of complex physical processes. The preprocessing framework results in a fully conformal, uniformly distributed grid for realistic fracture networks at a required level of precision. The main characteristics of the fracture network are preserved in coarser representation, meaning that these results could be utilized for a reduced uncertainty quantification workflow. The proposed workflow is similar to earlier work by Scheidt and Caers and the work developed in the conference paper for fluvial reservoirs (de Hoop et al., 2018). However, here we utilize coarse-scale models, obtained via our efficient and robust preprocessing procedure, to rank and partition the high-fidelity parameter space. Subsequently, a small subset of high-fidelity models is chosen to represent the complete ensemble statistics. As a result, the computational time of the uncertainty quantification is reduced by several orders of magnitude, while the reduced approach converges to similar statistics as the entire high-fidelity ensemble of models. This is summarized in Figure 6.

1.5.3 Theme 3: Response of a naturally fractured reservoir to pressure changes and stimulations

Understanding fracture propagation under high fluid pressures is of key importance to predict the response of the aquifer/reservoir to simulation. Within the TKI co-sponsored 2F2S project, TU/e researchers developed an X-FEM based framework capable of modeling propagating hydraulic fractures. In the development of this framework, focus laid on properly describing the mechanics of the porous formation and on deriving and implementing the rules describing propagation of fractures. However, the description of the fluid flow in the fracture and the coupling between the fracture flow and the pore fluid in the encompassing permeable formation were not studied in detail. While adequate within the context of the 2F2S project, the description of the fluid dynamics within the system needed further attention

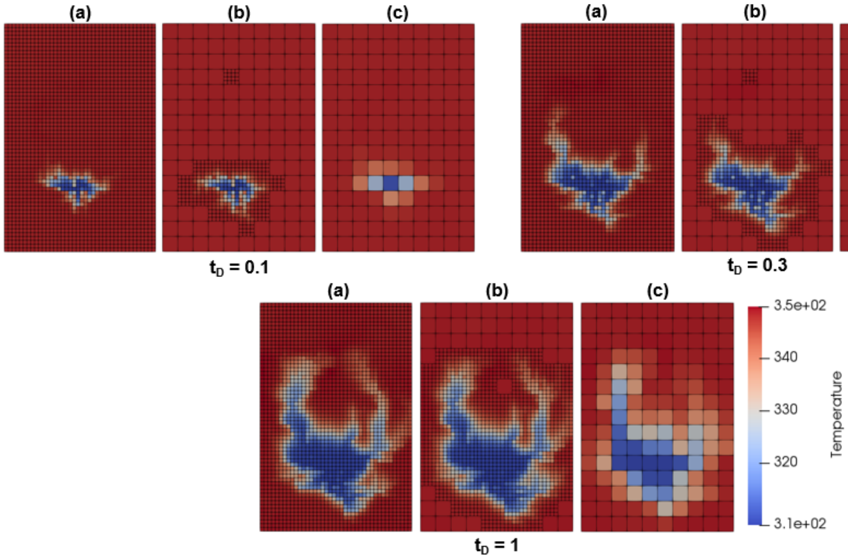

Figure 5: Temperature distribution of a heterogeneous fluvial model with low net-to-gross ratio at three different times: at t_D = 0.1, 0.3 and 1 (t_D refers to a dimensionless time, where 1 is equal to thermal breakthrough at the producer in the high-fidelity model). (a) is the fine-scale solution (level 0); (b) is the Adaptive Mesh-Refinement (AMR) solution; (c) is the coarse-scale solution (level 1). The AMR solution has a similar accuracy in terms of temperature distribution and cold water breakthrough as the fine-scale model, while using less degrees of freedom (around 20% at the start of the simulation to around 60% at the end) hence a significant reduction in computational time is achieved. Modified from de Hoop et al. (2021a).

to allow for the modeling of more realistic fluid-flow behavior, and consequently, more realistic fracture-reservoir interaction and fracture propagation behavior.

In the initial stages of the CarbFrac project, discussions were held with the industrial partners and a literature study was conducted to identify the relevant aspects of the fluid-flow behavior at the fracture scale. In this study, we focused specifically on the interplay between the flow in fractures, faults and inclusions, and the surrounding porous formation. We identified two relevant phenomena that where not captured by the existing model. Firstly, in the process of hydraulic stimulation, the high pressure at which fluids are pumped into a well should lead to the propagation and nucleation of fractures in the formation. At this stage, a reduction of pressure due to leakage of fluid through the porous fracture walls should be avoided. By adding additives to fracture fluids and as a result of formation damage in the fracturing process, the walls of fractures clog up, leading to a thin layer of reduced permeability. This phenomenon, called the skin effect, is essential to our field of application, and had therefore be captured by our model. Secondly, it was found that when fluid flows along a porous medium, for example in the case of a fracture fluid flowing along the walls of the fracture, it will slip due to the presence of the fluid filled pores. We also wanted to include this phenomena in the model.

Based on our literature study, we formulated the interface conditions that should hold at the interface between a fracture, or, in general, a fluid-filled inclusion, and a porous medium. In these interface conditions, the skin layer was included through a fluid entry resistance parameter. To avoid having to resolve a thin skin layer in a numerical model (requiring a very small, and therefore computationally-expensive, mesh), the fluid entry resistance parameter is instead employed to be able to model the steep pressure gradient over the skin layer as a jump in fluid pressure between the fracture and the formation. Furthermore, a slip parameter was included to control the slip at the fracture walls.

The set of interface conditions was implemented in a numerical model in which a porous medium described by Biot's equations (with Darcy flow) is coupled to a fracture flow described by Stokes' equations. At this point, the porous medium and the fracture have the same dimensionality, i.e., a 2D fracture is embedded in a 2D formation, or a 3D fracture is embedded in a 3D formation. Propagation is not yet included in the coupled model.

The developed (coupled) numerical model was employed to simulate both fluid injection and fluid extraction in 2D and 3D fractures, in both homogeneous and heterogeneous porous formations. Figure 7 shows selected results of a test case where fluid is injected into a fracture embedded in a porous formation. The results show the influence of

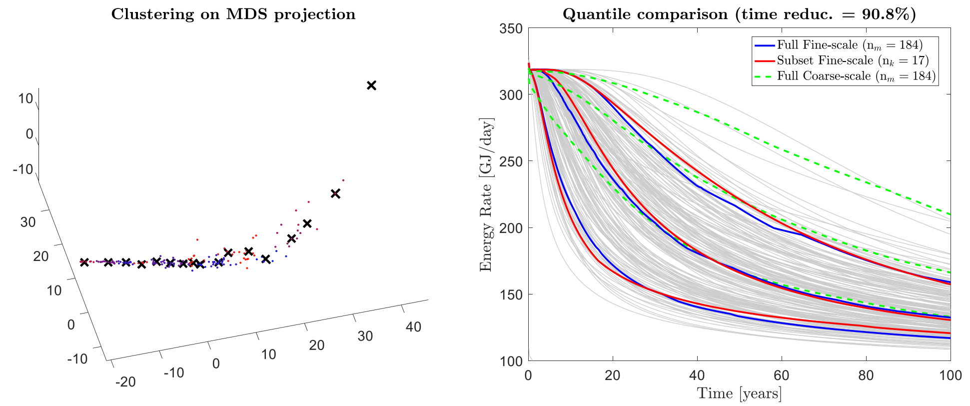

Figure 6: The general uncertainty quantification workflow of reconstructing the stochastic ensemble response. First, use coarse scale information to construct distances between ensemble members (obtained with the advanced fracture processing algorithm). Project the differences between each response in a lower dimensional space using MDS. Finally, perform clustering on the lower dimensional representation, where each cluster represents similar responses. Reconstruct the quantiles based on subset of responses (the medoid of each cluster) and compare with full ensemble statistics. Modified from de Hoop et al. (2021c).

the skin effect on the pressure in the formation can be substantial. The coupled model and all test cases have been reported extensively in the journal publication Bergkamp et al. (2020).

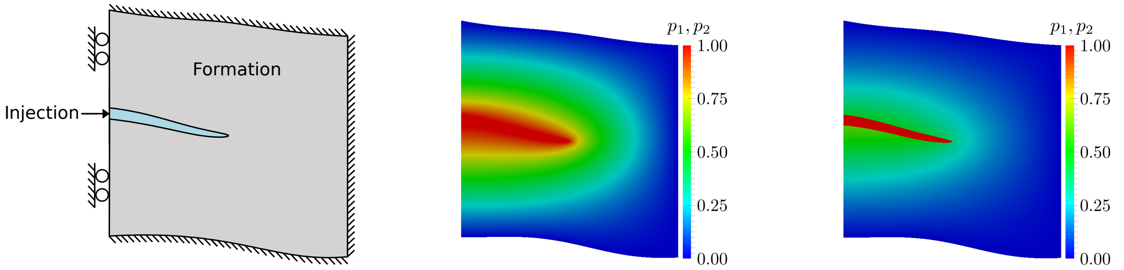

Figure 7: Fluid is injected into an existing fracture embedded in a porous formation. Fluid can freely leak from the outer boundaries of the simulated formation. In the middle figure, the pressure at steady state in the case of no skin is shown. On the right, the pressure at steady state in the case of skin is shown. As can be seen, the skin at the fracture walls prohibits fluid from leaking into the reservoir, resulting in a pressure jump from the fracture to the formation. The formation is heterogeneous. In both cases, the permeability is four times higher in the horizontal direction than in the vertical direction. More results are presented in Bergkamp et al. (2020).

The developed coupled model demonstrates the behavior of our enhanced interface conditions at the scale of a single, relatively short, fracture. When modeling larger fractures, the need to resolve the fluid flow within the fracture led to an undesirable increase in mesh elements, and therefore in computational cost. To upscale our computer simulations to larger fractures and fracture fields, we reduced the dimensionality of fractures, to reduce computational cost. In reality, fractures are typically much longer than their aperture. Consequently, we can model longer fractures as lines (in 2D). When performing simulations, the reduction in dimensionality of fractures means we avoid the need for a computationally expensive mesh over the thickness of fractures.

In our line fracture model, the fracture flow model was based on a thin-film approximation of the compressible Navier-Stokes equations, while the formation was again described by Biot's equations coupled with Darcy flow. At the interface between the fracture and the formation (the fracture walls), our previously derived set of interface equations still held, meaning that we could model both the skin effect and the (partial) slip of the fracture fluid flow over the fracture walls. Figure 8 shows selected results of a test case where fluid is injected into a fracture embedded in a porous formation.

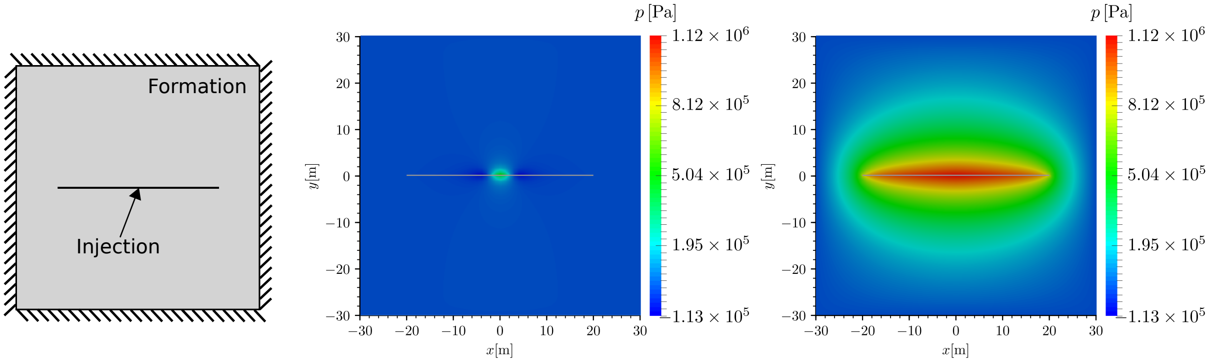

Figure 8: Fluid is injected into the center of an existing (initially closed) line fracture embedded in a porous medium. Fluid can freely leak from the outer boundaries of the simulated formation. In the middle figure, the formation pressure at the initial stages of the simulation is shown. On the right, the formation pressure at steady state is shown. In this simulation, no skin is present at the walls of the fracture. More results are presented in Bergkamp et al. (2021).

The line fracture numerical model was based on a thermodynamic framework in which all energy storage and dissipative mechanisms in the system were identified, including the mechanisms related to the interface effects. This framework allows us to visualize the power balance within the system while fluid is being pumped into or extracted from a fractured formation. Furthermore, the fracture volume rate balance was analyzed. The ability to easily derive the power balance and the fracture volume rate balance provides us with direct quantifiable feedback. For example, the fracture volume rate balance was shown to be especially sensitive to the skin effect, where significant clogging of the fracture walls resulted in severely limited leak-off from the fracture into the reservoir, as can be seen in Figure 9. Looking at the power balance, this reduction in leak-off was shown to result in more elastic energy being stored in the poroelastic structure. The dimensional-reduction of the model including the thermodynamic framework en numerical model test cases can be found in Bergkamp et al. (2021).

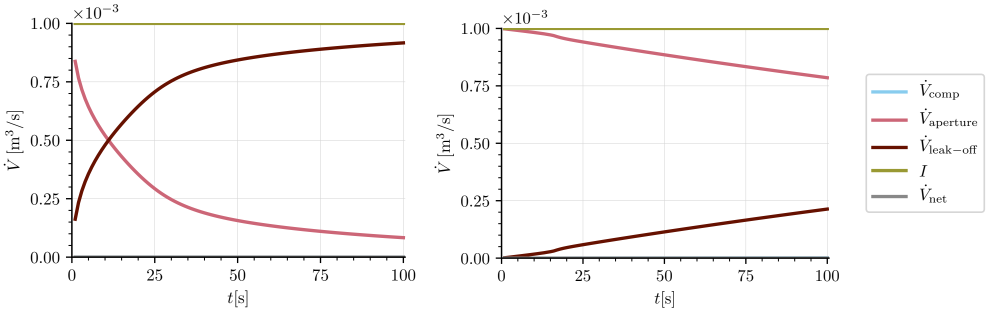

Figure 9: Fracture volume rate balance for the case of no skin (left) and skin (right). As can be seen, the skin effect leads to an increase in aperture of the fracture, versus leak-off into the reservoir. More results are presented in Bergkamp et al. (2021).

The dimensional reduction of our fracture flow model and fracture geometry prepared our model for an extension to propagating fractures. To extend our model, we employed the theory of Linear Elastic Fracture Mechanics (LEFM). LEFM has been implemented in our computer model and preliminary test cases show promising results. The linear nature of LEFM combined with the thermodynamic framework introduced in Bergkamp et al. (2021) allows for a rigorous analysis of the trade-off between fracture propagation and leak-off of fracking fluid into the reservoir. The propagating fracture model and accompanying analysis of the power and fracture volume rate balances for propagating fractures (combined with skin and slip effects) is expected to lead to the submission of a journal publication by the team of researchers at TU/e in 2022.

1.6 Follow-up

The activities performed during 2F2S first and CarbFrac now, are at the core of the research lines in the two academic institutions. As such, there is a substantial amount of ongoing work which will be finalized in the future.

Work at TUDelft will continue on analyses of fracture and caves systems in carbonate rocks of interest to geothermal exploitation such as the Malm of the Alpine foredeep basin and on the Dinantian rocks in NW Europe. COVID permitting, we will start again with work on (hypogenic) caves in Brazil. Further development of DARTS and the chemical and thermodynamic framework will be carried out by several MSc. students and Ph.D. candidates. This work includes adjoint gradient optimization and history matching, hydrate formation, carbon sequestration, and coupling flow with geomechanics.

At TU/e, new academic staff is appointed within the NWO DeepNL program. She will focus on subsurface activities such as hydrogen and CO_2 storage.

Wintershall and Neptune Energy have major challenging carbonate reservoirs in their portfolio. EBN in addition, is leading the effort of the Ultra Diep Geothermie (UDG) initiative which targets Dinantian carbonates. These carbonates are well known for they sedimentological complexity but also because they are fractured and host multi-scale dissolution features associated with hypothermal activity. The results of this research have improved carbonate reservoir management and targeting strategies. These insights are vital for future operations in more traditional but also new energy subsurface activities such as geothermal and gas storage initiatives.

1.7 Conclusions and recommendations

Within the CarbFrac project, we aimed to develop models describing the coupled mechanical and fluid flow behavior of carbonate reservoirs, taking into account their complex geological structure. To that end, we defined three subgoals at the start of the project.

As shown in de Hoop et al. (2021b) (under review), it is essential to consider the scale at which the fracture data is collected. Finding the right balance between accurately capturing the fracture characteristics and efficient computation is vital for predicting the behavior of the complex carbonate reservoirs. Newly developed geologically accurate interpolation techniques, such as Bruna et al. (2019), are excellent at bridging the sub-seismic scale between the near-well region and the seismic scale. Other methods, such as seismic attribute analysis (MSc. thesis), might provide additional information on the geometry of the discontinuity networks in carbonate reservoirs. An extensive set of caves were investigated and linked to both strike-slip faulting regime and fracture corridors in fold hinges, further enhancing our understanding of such chemically altered carbonate reservoirs, fulfilling the first goal set out in this project.

Additions were made during this project to the state-of-the-art reservoir simulation framework DARTS. The extras include but are not limited to a fully unstructured discretization framework, kinetic and equilibrium chemistry, adaptive mesh refinement for the general fully unstructured grid, and efficient and robust fracture modeling. Several of these elements result in an efficient uncertainty quantification procedure applied to geothermal energy and hydrocarbon production in the complex carbonate reservoirs fulfilling yet another goal in this project.

Regarding the third subgoal of the CarbFrac project, researchers at TU/e worked on the coupling between the flow in propagating fractures and surrounding porous media. In the coupling between the fracture and the surrounding formation, we focused on incorporating fluid dynamics relevant to the application field of interest, as discussed with our industrial partners. The resulting computer model can handle propagation of large-scale fractures in both homogeneous and heterogeneous porous media, including the modeling of the influence of a skin layer and fluid slip at the walls of the fracture, with limited computational costs.

Research on carbonate reservoirs/aquifers will be of great importance in the future. Building on the successful integration of outcropping and experimental (numerical and analog) studies we recommend to strengthen the following indications:

- Attention should be dedicated to the prediction of the geometric and physical properties of faults which have not been addressed by this study and, for that matter, by other studies worldwide. Fault properties such as permeability are of key importance not only for reservoir studies but also for seal integrity (also for CO2 storage);

- The link between fluid flow and cave geometry is still at its infancy and a substantial amount of work needs to be done. Building on the work performed in CarbFrac we aim at using dimensionless parameters found to be of relevance in small scale studies to hydrogeological characteristics of basin scale systems;
- More work is needed on caves in order to enlarge the data base of digital cave models. At TUDelft we have recently acquired a portable LiDAR and we are, therefore, in an excellent position to lead these efforts.

1.8 Contribution to TKI program aims

This study has led to innovation and strengthening of the NL knowledge position. CarbFrac was fully aligned with the overall goals of the Upstream Gas program, namely the development and implementation of innovative exploration and production ideas and techniques which contribute to optimal gas production from the Netherlands' subsurface. In particular, CarbFrac focuses on complex carbonate plays. Producing plays are known in the various carbonate formations in the onshore and offshore of the Netherlands and, more specifically, chalk reservoirs from giant fields in the North Sea. In addition, carbonate rocks are also considered for geothermal exploration as deep as well as ultradeep wells. Exploration, well-drilling and plant construction make up a large share of the overall costs of any drilling project but geothermal energy in particular. Drilling costs can account for as much as one third to one half of the total cost of a geothermal project. Capital costs are closely related to the characteristics of the local resource system and reservoir. Generation costs depend on a number of factors, but particularly on the temperature of the geothermal fluid. Geothermal energy carries a relatively high commercial risk because of the uncertainties involved in identifying and developing reservoirs that can sustain long term fluid and heat flow. This study has contributed to optimizing the output of subsurface reservoirs and to dissemination of the results.

2 Project execution

2.1 Problems and challenges during project

Until the beginning of 2020, the project did not encounter many problems and challenges that needed resolution to guarantee further proper execution of the research. However, like for many of us the COVID-19 pandemic did introduce from March 2020 a new way of working (more from home, less exchange face-to-face, laboratory work that could not take place for a while) together with some logistic challenges for this project. However, the team involved has been able to adapt and prevent much delay in the project's progress. In a general sense the multidisciplinary nature of the project's activities, consisting of a combination of fieldwork, numerical simulation and laboratory experiments, posed an overall exciting challenge, but which has given nice results as combining several different data sources (point cloud, field measurements and numerical simulation results) gave exciting insights for the research groups and the industrial partners of the project.

2.2 Changes to project plan/budget

The project has been executed according to the plan to a large extent. Some minor change concerned that some rock data could not be measured in the laboratory due to the COVID-19 pandemic and which was replaced by values from literature (as to serve in a subsequent step as input for the numerical modeling work of the project). Similar to the project plan, the realized project costs do not deviate much from what was originally budgeted and approved by TKI Nieuw Gas.

2.3 Dissemination and publicity

Knowledge has been disseminated through the project website, www.2f2s.org. Furthermore, a list of published and presented works is provided below.

Deliverables

- Database of digital cave models
- Code for modelling of fractures using Multiple-Point Statistics
- Cave shape analysis code
- Code for automatic fracture detection
- Code for advanced fracture preprocessing
- Code for uncertainty quantification workflow
- Access to the DARTS simulation platform

Journal publications

1. Bergkamp, E.A., Verhoosel, C.V., Remmers, J.J.C. & Smeulders, D.M.J.: A staggered finite element procedure for the coupled Stokes-Biot system with fluid entry resistance. Computational Geosciences 24(4), 1497–1522 (2020)
2. Bergkamp, E.A., Verhoosel, C.V., Remmers, J.J.C. & Smeulders, D.M.J.: A dimensionally-reduced fracture flow model for poroelastic media with fluid entry resistance and fluid slip. Under review (2021)
3. Bertotti, G., Audra, P., Auler, A., Bezerra, F.H., De Hoop, S., Cayo, P., Prabhakaran, R., & Lima, R.: The Morro Vermelho hypogenic karst system (Brazil): Stratigraphy, fractures, and flow in a carbonate strike-slip fault zone with implications for carbonate reservoirs. AAPG Bulletin 104.10: 2029-2050 (2020)
4. Boersma, Q. D., Bruna, P. O., De Hoop, S., Vinci, F., Tehrani, A. M., & Bertotti, G. The impact of natural fractures on heat extraction from tight Triassic sandstones in the West Netherlands Basin: a case study combining well, seismic and numerical data. Netherlands Journal of Geosciences, 100 (2021)
5. de Hoop, S., Jones, E., & Voskov, D.: Accurate geothermal and chemical dissolution simulation using adaptive mesh refinement on generic unstructured grids. Advances in Water Resources, 103977 (2021a)
6. de Hoop, S., Voskov, D., Bertotti, G., & Barnhoorn, A.: Advanced Fracture Preprocessing Algorithm for High-Enthalpy Geothermal Flow in Complex Natural Fractured Reservoirs. Under review (2021b)
7. Pontes, C., Bezerra, F.H., Bertotti, G., La Bruna, V., Audra, P., De Waele, J., Auler, A., Balsamo, F., De Hoop, S., & Pisani, L.: Flow pathways in multiple-direction fold hinges: Implications for fractured and karstified carbonate reservoirs. Journal of Structural Geology, 146, 104324 (2021)
8. Wang, Y., de Hoop, S., Voskov, D., Bruhn, D., & Bertotti, G.: Modeling of multiphase mass and heat transfer in fractured high-enthalpy geothermal systems with advanced discrete fracture methodology. Advances in Water Resources, 154, 103985 (2021)

Conference presentations with proceedings

9. de Hoop, S., Voskov, V., Vossepoel, F., & Jung, A.: Quantification Of Coarsening Effect On Response Uncertainty In Reservoir Simulation. Conference paper. ECMOR XVI - 16th European Conference on the Mathematics of Oil Recovery (2018)
10. de Hoop, S., Voskov, D.V., & Bertotti, G.: Studying the Effects of Heterogeneity on Dissolution Processes Using Operator Based Linearization and High-Resolution LiDAR Data. Conference paper. ECMOR XVII (2020a)
11. de Hoop, S., & Voskov, D.: Fast And Robust Scheme For Uncertainty Quantification In Naturally Fractured Reservoirs. Conference paper – SPE Reservoir Simulation Conference, Galveston, TX, USA, 4-6 October (2021c)

Conference presentations

12. Bergkamp, E.A., Verhoosel, C.V., Remmers, J.J.C. & Smeulders, D.M.J.: Generalized fluid-flow modeling in the Enhanced Local Pressure model for hydraulic stimulation. Presentation – ECCM-ECFD 2018, Glasgow, United Kingdom, 11-15 June 2018
13. Bergkamp, E.A., Verhoosel, C.V., Remmers, J.J.C. & Smeulders, D.M.J.: Finite Element Analysis of a coupled Stokes-Biot system. Presentation - SIAM Conference on Mathematical and Computational Issues in the Geosciences, Houston, TX, USA, 11-14 March 2019
14. Bergkamp, E.A., Verhoosel, C.V., Remmers, J.J.C. & Smeulders, D.M.J.: Finite Element Analysis of a coupled Stokes-Biot system. Presentation - VIII International Conference on Coupled Problems in Science and Engineering, Sitges (Barcelona), Spain, 3-5 June 2019
15. Bergkamp, E.A., Verhoosel, C.V., Remmers, J.J.C. & Smeulders, D.M.J.: Finite Element Analysis of a coupled Stokes-Biot system. Presentation - European Numerical Mathematics and Advanced Applications Conference, Egmond aan Zee, The Netherlands, 30 September-4 October 2019
16. Bergkamp, E.A., Verhoosel, C.V., Remmers, J.J.C. & Smeulders, D.M.J.: Extended finite element analysis of a coupled fracture-reservoir model. Presentation – InterPore2020, online due to COVID-19, 31 August-4 September 2020
17. Bertotti G., Bezerra, F.H., de Hoop, S., & Voskov, D.: The Geology of flow through carbonate rocks: from fracture networks to (hypogenic) karsts. Geoscience & GeoEnergy Webinars, 3 December 2020. Video of talk.
18. de Hoop S. & Voskov D.: Parametrization Technique for Reactive Multiphase Flow and Transport. Presentation – SIAM Conference on Mathematical and Computational Issues in the Geosciences, Houston, TX, USA, 11-14 March (2019a)
19. de Hoop, S. & Voskov, D.: Comparison between equilibrium and kinetic reactions in the parameterization framework. Abstract – European Numerical Mathematics and Advanced Applications Conference, Egmond aan Zee, The Netherlands, 30 September-4 October (2019b)
20. de Hoop, S., Voskov, V., & Bertotti, G.: Studying the Effects of Heterogeneity on Karstification and Wormholing Phenomena Using Operator Based Linearization and High-Resolution LiDAR Data. InterPore2020, online due to COVID-19, 31 August - 4 September (2020b)
21. Wang, Y., de Hoop, S., Voskov, D., Bruhn, D., & Bertotti, G.: Modeling of High-Enthalpy Geothermal Projects in Fractured Reservoirs. Abstract – World Geothermal Congress 2020, Reykjavik, Iceland, April 26 – May 2, (2020)

Posters

22. Bergkamp, E.A., Verhoosel, C.V., Remmers, J.J.C. & Smeulders, D.M.J.: Toward an improved fluid model for hydraulic stimulation. Poster – Twentieth Engineering Mechanics Symposium, Arnhem, The Netherlands, 23-25 October 2017
23. Bergkamp, E.A., Verhoosel, C.V., Remmers, J.J.C. & Smeulders, D.M.J.: Toward and improved fluid model for hydraulic stimulation. Poster – Eurotech/EMI workshop: Advanced School on Immersed Methods, Eindhoven, The Netherlands, 6-9 November 2017
24. Bergkamp, E.A., Verhoosel, C.V., Remmers, J.J.C. & Smeulders, D.M.J.: Toward an improved fluid model for hydraulic stimulation. Poster – Twenty-first Engineering Mechanics Symposium, Arnhem, The Netherlands, 23-24 October 2018

25. Bergkamp, E.A., Verhoosel, C.V., Remmers, J.J.C. & Smeulders, D.M.J.: Finite element simulation of a coupled fracture flow problem. Poster – Twenty-second Engineering Mechanics Symposium, Arnhem, The Netherlands, 22-23 October 2019
26. Bergkamp, E.A., Verhoosel, C.V., Remmers, J.J.C. & Smeulders, D.M.J.: Coupling fracture flow and porous media. Poster – Twenty-fourth Engineering Mechanics Symposium, Arnhem, The Netherlands, 26 October 2021
27. de Hoop, S., & Voskov, D.: Fast And Robust Scheme For Uncertainty Quantification In Naturally Fractured Reservoirs. Poster – SPE Reservoir Simulation Conference, Galveston, TX, USA, 4-6 October (2021c)

Public data set

28. de Hoop, S., Prabhakaran, R., Bertotti, G., Bezerra, H., Pontes, C., Lima, R., Audra, P, Auler, A: LiDAR Dataset for Hypogenic Morro Vermelho Cave in Bahia, Brazil (2018). Dataset. Link. – 2021d
29. de Hoop, S., Prabhakaran, R., Bertotti, G., Bezerra, H., Pontes, C., Lima, R., Audra, P, Auler, A: LiDAR Datasets for Hypogenic and Epigenic Caves in Bahia, Brazil (2018). Dataset. Link. – 2021e
30. de Hoop, S., Prabhakaran, R., Bertotti, G., Bezerra, H., Pontes, C., Lima, R., Audra, P, Auler, A: LiDAR Datasets for Hypogenic and Epigenic Caves in Bahia, Brazil (2019). Dataset. Link. – 2021f