Quartz-driven fracture healing and its impact on fluid flow

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ABSTRACT

Fluid flow in healing fractures was simulated based on phase-field models (PFMs) for the growth of two dissimilar quartz morphologies (compact and needle growth). Results of the simulations indicate that flow in healing fractures highly depends on these morphologies. Growth of needle quartz favours an early formation of bridge structures that initially quickly inhibit fluid flow by creating tortuous flow channels, but also facilitate increased fluid flow at almost closed conditions (>90% healing) due to the formation of rather porous structures. In contrast, compact quartz uniformly heals the fracture due to it contiguous growth, however provides more effective flow paths under partially healed conditions (20 to 75 % volume fraction) due to the later formation of bridges. This study provides an initial stage for an improved empirical approach predicting fluid flow in fractures considering distinct growth morphologies.

1. INTRODUCTION

In geoscientific applications, fracture flow plays a crucial role to estimate the potential of subsurface according to its applicability (e.g. cap and reservoir rocks). Typically, fracture flow is mainly controlled by the geometric properties of the fracture such as aperture and roughness. Frequently, it is assumed that these properties remain constant during fluid flow, which however is not the case when considering changes in the stress field (e.g. Huo and Benson 2015) or reactive transport such as (often coupled) dissolution and precipitation processes (Singurindy and Berkowitz 2005). Hence, in this study, healing of fractures (i.e. precipitation on fracture surfaces) and its influence on fracture flow are investigated. In deep geothermal energy generation healing can particularly play an important role considering (a) the estimation of permeability for pre-existing, partially healed fractures (veins) in the reservoir and (b) the induced healing of open structures due to oversaturation of the fluid due to exploitation.

Typically, fracture geometries caused by healing depend on several factors such as mineralogy of the host rock and fracture fillings as well as reservoir and fluid conditions during the crystallization process (e.g. Okamoto et al. 2010, Moncada et al. 2012, Wendler et al. 2015). Thus, a variety of possible minerals and geometries can occur in natural fractures. Hence, this study focusses on quartz precipitates representing prominent hydrothermal features in rocks (Dong et al. 1995, Fischer et al. 2003, Moncada et al. 2012). However, experimental studies highlighting quartz growth in fractures are still rather sparse (Hilgers and Tentheroy 2004, Okamoto et al. 2010, Okamoto and Sekine 2011, Saishu et al. 2014) so that there is only limited information on natural, time-dependent development of quartz healing and related morphologies.

Thus, numerical models provide a useful tool to simulate these dynamic processes. In the past, fracture healing were simulated using different approaches such as purely kinetic front tracking methods (Bons 2001), cellular automaton models (Lander and Laubach. 2015), continuum-based reactive models (Li et al. 2008) and phase-field models (PFMs) (Ankit et al. 2013, 2015, Wendler et al. 2015). PFMs excel by sophisticated thermodynamic implementations capturing the transition between multiple phases and enable a three-dimensional depiction of the simulated structures and complex geometries (Moelans et al. 2008). Hence, Wendler et al. (2015) applied PFM to reproduce syntaxial healing of a fracture according to a hydrothermal quartz growth experiments performed by Okamoto and Sekine (2011). The authors found that PFM are in good agreement with experimentally derived morphology and that simulated quartz morphologies highly depend on the supersaturation of the fluid. While high supersaturations (S=3.6) tend to form rather compact and contiguous quartz morphologies, and low supersaturations (S=1.8) favor a more isolated needle-like growth.

The objective of this study is to evaluate how different quartz morphologies affect fracture flow with increasing healing. Thus, pre-existing phase-field models (Wendler et al. 2015), favoring compact and needle quartz growth, are coupled with computational fluid dynamics (CFD). The results are expected to provide further information about intrinsic flow conditions and hydraulic properties in fractures under progressive, chemically induced closing.

2. METHODS

In order to determine fluid flow in healing fractures two simulation steps are applied. In the first step, potential fracture morphologies are reproduced by using PFM. Then, the geometric data are used to apply CFD to simulate fluid flow.

2.1 Phase-field modelling (PFM)

In the last years, phase-field models (PFMs) became a useful tool to capture dynamics of crystal growth for various geoscientific issues concerning crystallization processes (e.g. Wendler et al. 2015). PFMs consider a physically profound scenario including interface kinetics and thermodynamic driving forces such as supersaturation.

The interface morphology is captured on a regular grid by a time dependent indicator field $\phi(x,t)$, which passes a steep but smooth transition from $\phi = 0$ in the exterior to $\phi = 1$ in the interior of the respective solid phase, where each differently oriented quartz grain is treated as individual phase. The governing (phase-field) equation is derived from a Helmholtz free energy functional describing bulk thermodynamics, interface energy and kinetics, and is coupled to a diffusion-advection equation to provide a numerical solution. The realization of the PFM, also used in this study, is comprehensively discussed by Wendler et al. (2015). Geometrically, the initial fracture is simplified as parallel plates, where both sides of the fracture are composed by a random tessellation of N = 150 grains with random orientation for each fracture. Due to the pronounced growth of crystals at higher supersaturations, as an artefact of the boundary conditions, the initial parallel plate simulation box for compact quartz is much more voluminous (600 × 600 × 310 µm³) than for needle quartz (150 × 150 × 80 µm³) to provide a idiomorphic crystallization of proper quartz morphologies.

2.2 Computational fluid dynamics (CFD)

Fluid flow simulations are carried out to predict potential fracture flow behaviour under both, needle and compact quartz healing. For this purpose, the commercial, voxel-based software GeoDict (Math2Market GmbH) is applied using the same grid resolution as in the PFM (Voxel dimensions: 1³ µm³). Fluid flow in the open regions of the fracture is described applying an explicit finite volume method (FVM) solving the incompressible, stationary Navier-Stokes equation. No-slip boundary conditions on the fluid-solid interfaces are applied. For the flow simulation the fluid is treated as water at 20° with respective density and dynamic viscosity (fluid pressure = 31 MPa). Pressure drops across the fracture length are set to 0.1 Pa for compact quartz and 2.8 Pa for needle quartz so that Reynold's numbers are about 1.0 for the initial fracture and even lower for further healing stages to maintain laminar flow conditions. These fluid conditions are chosen to most widely represent fluid flow under shallow crustal conditions in pre-existing partially and completely healed fractures. According to the given conditions, GeoDict predicts the flow velocity pattern (and the mean flow velocity) over the sample for the predefined pressure drop (Figure 1). The simulation termination criteria are defined by accuracy (current iteration step/previous iteration step < 1×10^{-5}) or reaching 10^5 iteration steps. CFD are performed with a 32-core, 64-bit Intel Xeon server with 512 GB of shared RAM (Time per simulation < 30 min).

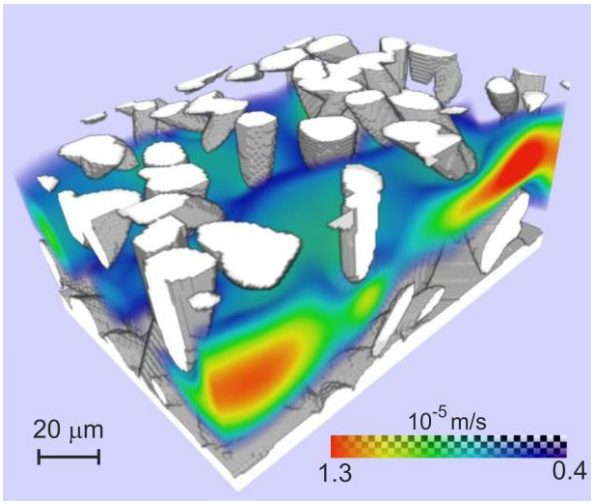

Figure 1: Formation of tortuous flow paths in the fracture healed by needle quartz at an intermediate stage of healing. Colors represent the magnitude of velocity within the open fracture space.

3. RESULTS AND DISCUSSION

Here, our results are presented for both healing morphologies considering the general fluid flow behaviour, hydraulic properties and their progressive changes.

3.1. Fluid flow

As might be expected, the flow simulations show a clear trend of decreasing conductivity (at constant pressure gradient gradient) with increasing healing time for both fractures (Figure 2). Although, both fractures have different widths and host different crystal morphologies they are nearly completely closed at the same time indicating a good comparability. Hence, for needle quartz growth the fracture is closed by 50% after 200 numerical time-steps, while compact quartz requires about 100 time-steps longer. This phenomenon can be perhaps explained by the different growth characteristics of the crystal habits. Due to the more pronounced growth in

lateral direction (parallel to the fracture plane), more dominant compact quartz crystals hinder the growth of some neighbouring crystals, so that at an early stage healing is dominated by lateral displacement processes until the remaining crystals finally close the fracture. In contrast, needle quartz crystals with variant main growth orientations directly grow towards each other favouring faster initial healing until contacting crystals ("bridges") slowly inhibit the growth of remaining free crystals (Figure 2).

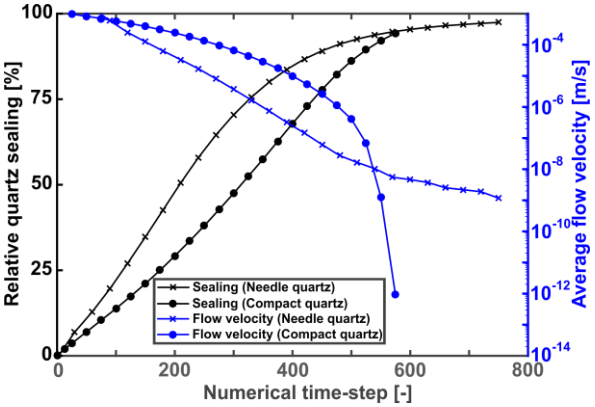

Figure 2: Relative evolution for healing for both fractures starting from a parallel plate (0 %) until maximum closure (~98 %). The blue graphs represent the respective changes in fluid flow based on flow simulations.

Differences between both healing scenarios due to different crystal growth characteristics become clearer when considering the behaviors of fluid flow with increasing healing. In Figure 2 fluid flow is represented by the simulated average flow velocity of the fluid along the entire fractures at the certain healing stages. Both parallel plate fractures start with similar flow velocities at the initial stage (1 to 6 × 10^{-3} m/s). According to the growth kinetics, needle quartz growth causes a nearly exponential decrease in velocity. Once the healing rate of the process decreases with progressive closure, also the changes in flow velocities become smaller resulting in a final velocity of 1.2 × 10^{-9} m/s. In contrast, flow velocities of compact quartz growth also decrease, however still reveals higher velocities than for needle quartz growth, which coincides with the healing behaviors. However, with increasing healing, velocities undergo a significant drop by reaching a final flow velocity of 8.7 × 10^{-13} m/s. This significant gap and respective different flow behaviors can be explained by dissimilar structures formed by the healing. While compact quartz form two contiguous healing fronts that grow towards each other until the fracture is finale closed, needle quartz bridges rather form fabric-like structures favoring partially connected, slowly closing pores within the fracture and, hence, increased fluid flow.

3.2. Hydraulic properties

Typically, fluid flow in fractures depends on three cornerstones (Hakami and Larsson 1996): Hydraulic properties (relating to fracture geometry), fluid property and hydraulic boundary conditions. Since the last two are predefined constant values in this study, hydraulic properties become the focus of attention by highlighting apertures (mechanical, hydraulic) and contact areas (Figure 3 and 4). Average mechanical apertures (a_m) are derived by integrating entire non-solid volume of the single PFMs and dividing it by the lateral area of the simulation box. The hydraulic apertures a_h are computed by using the common cubic law where the volumetric flow rate is derived from the integration of all fluid velocity components and the cross-sectional area the simulation domain. Contact areas are represented here as absolute numbers of contact voxels where opposite crystal grains touch.

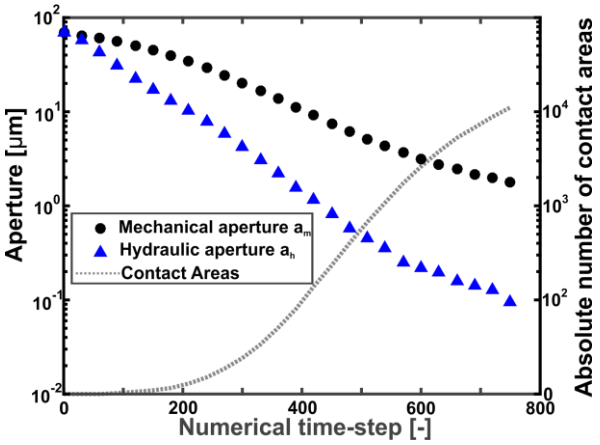

Figure 3: Changes in mechanical and hydraulic apertures for the fracture with progressive needle quartz healing. Additionally, the dotted line represents the absolute changes of detected contact points due to the formation of crystal bridges.

Equivalent to the morphological observations concerning healing and flow, the same tendencies are reflected in the hydraulic properties. Mechanical apertures for needle quartz growth (Figure 3) also show an exponential decrease reaching a minimum value of 1.7 µm for the average mechanical aperture (a_m). However, this mechanical aperture represents a simplified representation of the actual void geometry, which rather resembles a porous medium. In addition, hydraulic apertures (a_h) immediately deviate from a_m, drop faster than expected and reach a final value of 0.1 µm before fluid flow stops. These immediate deviations are caused by the rapid formation of crystal bridges starting at time-steps (t) between 100 and 200. Hence, the growth of isolated quartz crystals and the occurrence of bridge structures cause a fast roughening of the initial parallel plate fracture favoring all factors for an significant decrease in fluid flow as described by Tsang (1984): fracture closure, a decrease in connectivity by forming fewer flow channels and an increase in tortuosity by forming additional barriers. Considering compact quartz growth (Figure 4), the evolutions of a_m as well as a_h rather follow an almost linear reaching a minimum value of 17.1 µm for a_m and 0.1 µm for a_h. In contrast to needle quartz growth, significant deviations

between a_m and a_h appear at a later healing stage (t = 350), where first contact areas appear. The collision of both contiguous crystallization fronts immediately forms large contact areas causing the formation of a flow channel network of short duration. Minor deviations before the onset of contact areas most widely can be attributed to predefined no-slip conditions defining zero fluid velocity along solid boundaries restricting the flow.

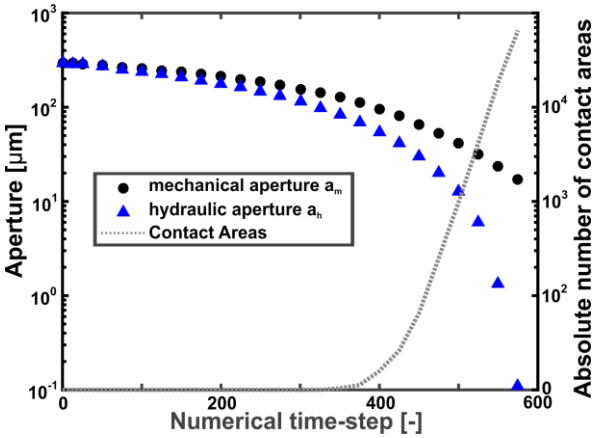

Figure 4: Changes in mechanical and hydraulic apertures for the fracture with progressive compact quartz healing. Additionally, the dotted line represents the absolute changes of detected contact points due to the formation of crystal bridges.

Comparing the apertures of both healing scenarios indicates that fracture closing due to healing (Figures 3 and 4) differs significantly from stress induced fracture closing, where aperture typically decrease exponentially (e.g. Huo & Benson 2015). While precipitation models most widely assume that fracture closure and, hence, the effect on permeability reduction can be explained by kinetic reaction models (e.g. Lowell et al. 1993) our observations in Figures 3 and 4 indicate that mechanical and particularly hydraulic aperture reduction also depends on the morphology of quartz crystals precipitating on the fracture surfaces. This can be an important aspect, when considering rather needle-like quartz healing, where even at lower healing stages crystal morphology and early crystal bridge formation has a significant impact on hydraulic apertures. Such distinct bridge structures are not uncommon in natural fractures (Lander and Laubach 2015) and, hence, can play an important role when assessing flow properties. However, it should be mentioned that in this study pure healing due to uniform precipitation along a small ideal fracture is considered. In natural, larger scales enhanced boundary conditions such as coupled dissolution, concentration and temperature gradients as well as the presence of initially rough fracture surfaces can cause variations from these results.

3. CONCLUSIONS

In this study, two crystal growth scenarios (needle and compact quartz) of progressive fracture healing based on a phase-field approach are coupled with computational fluid dynamics to assess how quartz morphologies can affect fluid flow in fractures. We found that flow behaviour of both scenarios significantly differ from each other. Needle quartz growth causes a fast formation of bridge structures, thus fracture flow rather resembles a porous setting compared to more pervasive growth of compact quartz, where these bridge-type structures still facilitate increased flow through at almost closed conditions (circa 90% healing). However, under partially healed conditions (25-75%) these bridge structures rather represent a constraint by affecting tortuosity and connectivity.

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