



Experiment and modeling to evaluate the effects of proppant-pack diagenesis on fracture treatments

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ABSTRACT

Observed reductions in the permeability of propped hydraulic fractures are examined by considering the role of mechanical stresses and the chemistry of pore fluids at elevated temperatures as agents of proppant diagenesis. Stress-enhanced dissolution of proppant increases the density of grain packing and reprecipitation of mineral matter further occludes pores – together these mechanisms additively reduce porosity and permeability. Experiments and analyses are presented which explore the evolution of porosity and permeability in proppant packs subjected to reservoir conditions of stresses to 65 MPa and temperatures to 177 °C. Experiments are completed in two modes: in flow-through reactors absent intergranular stresses to evaluate rates of dissolution and reprecipitation on proppant surfaces, and in uniaxially stressed reactors with stagnant fluids to evaluate the relative role of stress in mediating dissolution and porosity reduction. Lumped parameter models are used to evaluate rates of dissolution and chemical compaction in a range of proppants. Mechanisms include mineral dissolution, transport, and reprecipitation of the resulting products in the particle interstices, resulting in a loss of intergranular porosity. The model uses thermodynamic data derived from the reactor experiments to constrain the projected loss of permeability for the mineralogical composition of available proppants. Evaluated silica dissolution rates vary with temperature but are of the order of 1.1×10^{-11} to 3.1×10^{-4} mol/m² s in the range of 100 °C to 288 °C. Experimental results show chemical compactions of the order of 10 millistrains over 40 days and these project modeled reductions in porosity of the order of 25% over 1000 days. Rates of porosity loss increase both with an increase in temperature and a decrease in mean grain size of the granular proppant although ultimate porosities at the conclusion of compaction are similar. Rates and magnitudes of ultimate reductions in porosity map directly onto reductions in permeability and for proppants in the range 100 to 600 μm, result in permeability reductions in the range of 25% (163 °C) to 75% (191 °C). Such magnitudes (75%) of permeability loss over short periods (1000 days) are consistent with many field observations, with the mechanistic models providing a rational method of scaling such observations.

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1. Introduction

Hydraulic fracturing is a common method of stimulating wells to efficiently recover hydrocarbons from low permeability reservoirs. As the hydraulic fracture is widened by the injection of fluids, sized particles (i.e., proppants) mixed with fracturing fluids are injected to hold fractures open. The ultimate goal of this treatment is to create a high-permeability and high-surface-area conduit that may access the fluids within the reservoir (Palish et al., 2007). These stimulations are expensive, and investors typically desire that the fracture treatment should remain a high-permeability conduit throughout the lifetime of

the reservoir. However, recent evidence suggests that the performance of such treatments may be degraded early within the lifetime of production. These effects include multiphase, non-Darcy flow effects, gel damage, proppant pack damage by the fracturing fluid, proppant flowback, fines intrusion, proppant crushing, and proppant diagenesis (Weaver et al., 2005). Moreover, the internal or innate effects of the proppants utilized, such as types of proppants, proppant concentration, also control the fracture conductivity (Barree et al., 2003). These factors influence the overall effectiveness of the fracture treatment.

Fracture diagenesis, which is a physicochemical phenomenon, may exert a long-term influence on the fracture permeability among the identified external factors. In this work we address mainly this phenomenon that may be a dominant mechanism influencing a long-term change in the fracture permeability (i.e., the workability and

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Table 1
Flow-through experiments on synthetic proppants and reservoir rock mixtures.

Column	Sample	Experiments
1	Ohio sandstone	Fluid-pressure-only furnace experiments
2	20/40 Brady sand	
3	20/40 HSP 1	
4	20/40 HSP 1	
5	20/40 Brady sand	
6	Ohio sandstone + 20/40 Brady sand	
7	Ohio sandstone + HSP 1	Ambient-stress quadcell experiments
8	Ohio sandstone + 20/40 Brady sand	
9	Ohio sandstone + HSP 1	
1	20/40 HSP 2 + Ohio Sandstone	
2	20/40 ISP 2 + Ohio sandstone	

durability of wells). One of the main mechanisms of diagenetic compaction and deformation in sedimentary rocks is pressure solution¹ (e.g., Weyl, 1959; Rutter, 1976; Revil, 1999). Pressure solution, controlled by gradients of chemical potential differential between stressed-sites and free pore spaces, involves three linked processes of dissolution at the stressed interfaces of grain contacts, diffusive transport of dissolved mass from the interface to the pore space and finally reprecipitation at the less stressed, free-face of the grains (Yasuhara et al., 2003). This process results in temporally prolonged compaction and the concomitant reduction in bulk porosity and related permeability which has been shown to operate over engineering timescales (Yasuhara et al., 2003).

In this work we report flow-through experiments on synthetic proppants. We use a range of high strength proppants (HSP) through intermediate strength proppants (ISP) and sandwich these between coupons of reservoir rock mixtures (Table 1) to represent the walls of the fracture. These experiments are completed at temperatures in the range 121 to 177 °C and at confining stresses in the range 55 to 65 MPa. Experiments run over durations of up to 34 days to examine the intermediate-term evolution of permeability. These observations are fit to contemporary models of permeability reduction in granular aggregates where precipitation and pressure solution may influence mechanical and chemical compaction.

2. Proppant pack diagenesis by physiochemical compaction

Artificial proppants are complex mixtures of ceramic phases made by processing kaolin or bauxite at temperatures approaching 1450 °C. During this processing, proppants are engineered based upon the desired mechanical strength and durability to withstand ambient stresses, temperatures and chemical characteristics of the fluid, encountered in situ. When the formation is exposed to different pressure and temperature conditions, the rate of transformation is controlled by these pressure and temperature conditions. The chemistry-associated metastability of such engineered proppants is the key to understanding the related processes of pore compaction, grain-interpenetration, mineral redistribution, and extreme loss of permeability. Similar transformations and the rapid loss of permeability have been observed to participate in the diagenesis of reservoir rocks.

Proppants emplaced within hydraulic fractures are subject to an evolving stress field and to changes in chemical composition of the pore fluids. Immediately upon emplacement, the local in-fracture intergranular stresses will grow as the fracture treatment fluid

pressures diffuse into the wall-rock or back to the wellbore. These stresses will be of the order of the pre-stimulation minimum in situ stress. These bulk stresses are amplified at the grain–grain contacts of granular proppants elevating the potential for stress-corrosion cracking and the chemical potential (manifest as an increase in the reactivity or dissolution rate) at the contacts. Together, these effects have been shown to promote immediate mechanical compaction and to drive chemical compaction which may evolve over periods of years to millions of years. In this work we invoke such mechanisms of chemical compaction to describe the loss of function in-fracture treatments as chemical compaction proceeds and porosity and related permeability is degraded in the process.

One mechanistic model involves the action of elevated chemical potential at the grain–grain contacts which drive the compactive process. This process involves the action of three serial processes; dissolution at the grain–grain contacts, diffusion along the interfacial water film separating the grains, and precipitation on pore walls. This is illustrated in Fig. 1. First, dissolution at the contacts provides a source of mass into the pore via the interface, and is defined in terms of the dissolution mass flux, dM_{diss}/dt , the rate of addition of dissolved mass into solution at the interface, given by Yasuhara et al. (2003),

$$\frac{dM_{diss}}{dt} = \frac{3\pi V_m^2 (\sigma_a - \sigma_c) k_+ \rho_g d_c^2}{4RT}, \quad (1)$$

where, V_m is molar volume of the solid, σ_a is the disjoining stress (e.g., Heidug, 1995) which is equal to the amount by which the pressure acting at grain-to-grain contacts exceeds the hydrostatic pore pressure, k_+ is the dissolution rate constant of the solid, ρ_g is the grain density, d_c is the diameter of the contacts, R is the gas constant, T is the temperature of the system, and σ_c is the critical stress, which defines stress state where the compaction of grain aggregate will effectively halt.

Secondly, based on Fick's first law, diffusion along the interface of the grain contacts is defined in terms of the diffusive mass flux, dM_{diff}/dt , as (Yasuhara et al., 2003),

$$\frac{dM_{diff}}{dt} = \frac{2\pi\omega D_b}{\ln(d_c/2\varepsilon)} (C_{int} - C_{pore}), \quad (2)$$

where, D_b is the diffusion coefficient, ε is infinitesimal length (1/1000, initial diameter of contact area), d_c is the diameter of the grain-to-grain contacts, and $(C_{int})_{x=\varepsilon}$ and $(C_{pore})_{x=d_c/2}$ are concentrations in the interface and pore space, respectively. ω is the thickness of the water film trapped at the interface.

Finally, precipitation of solute to the free faces of pore wall is defined in terms of the precipitation mass flux, dM_{prec}/dt , the rate of deposition of solute from the pore space onto the free-walls, is defined as (Yasuhara et al., 2006; Yasuhara and Elsworth, 2006; Elsworth and Yasuhara, 2006),

$$\frac{dM_{prec}}{dt} = k_- A_{pore} \rho_g V_m \left(\left(\frac{C_{pore}}{C_{eq}} \right)^m - 1 \right)^n, \quad (3)$$

where, A_{pore} is the nominal area of the void, k_- is the precipitation rate constant of the dissolved mineral, and C_{eq} is the equilibrium solubility of the dissolved mineral. m and n are two positive numbers normally constrained by experiment. In this work the constants are set to be unity because the dissolution kinetics of the proppants of interest are not be fully constrained and those of quartz, which may be considered a proxy of the proppants, have been identified to be unity (Rimstidt and Barnes, 1980).

At the applied stress and temperature condition, concentration of the material strongly influences compaction process, and the concurrent calculation to obtain the concentration is significant. Concentrations may be defined at the interface between grain

¹ We use the term pressure solution – in standard usage – to represent the process of stress-enhanced dissolution resulting from the elevated chemical potential of mineral at stressed contacts.

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