Abstract

Microstructures grown experimentally from advective supersaturated solution and their implication for natural vein systems

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Abstract

See-through experiments in transmitted light microscopy allow detailed analyses of fracture-sealing processes on the grain scale. In this study, we grew syntaxial veins in an open fracture with a solvent transported by advection along the crack. Using highly soluble alum as an analogue material, epitaxial overgrowths of polyhedral seed grains can be obtained within 24 h. Flow experiments at constant fluid flux indicate that the channel first seals at the inlet, independent of the flux rate. An increase in fluid flux leads to a more homogeneous growth along the fracture, until fluid flow will be stopped due to a closure of two opposing grains at the inlet. Large voids remain open in the vein microstructure. Our experiments suggest that fracture-sealing processes caused by advection along fracture networks result in vein systems containing numerous cavities, and a gradient in grain size decreasing along the flow direction. They do not explain vein systems completely sealed over long distances, which are often observed in nature.

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1. Introduction

Vein systems can be studied in a wide range of geological settings. Although they are of great economic importance in mineral exploration and hydrocarbon industry, the relationship between microstructural evolution, mass transport mechanisms and rock deformation is only poorly understood. Two different types of overgrowth microstructures are known from natural veins. If fractures have been filled by grains grown from the wall rock towards the centre of the vein, they are called syntaxial (Durney and Ramsay, 1973). More recently, these microstructures were called elongate-blocky (Fisher and Brantley, 1992; Oliver and Bons, 2001), because the grain boundaries are not parallel to each other. Rapid growth competition takes place next to the vein—wall interface, with only a few favourably oriented grains surviving (Fig. 1a). The second type of microstructure also appears as overgrowth from the wall rock, but grains continue across the vein and connect formerly fractured grains on the opposing walls. The grain’s aspect ratio hardly changes across the vein, which results in an overall fibrous morphology (Fig. 1b). It is assumed that these stretched crystals...
Fig. 1. (a) Thin section of a quartz vein grown syntaxial from a surface into an open void. Rapid growth competition at the beginning results in the survival of a few large grains. (b) Stretched quartz crystals are also epitaxial overgrowths, but grains located in the vein connect wall rock grains on either side of the fracture. The transition from elongate-blocky to stretched crystal (fibrous) microstructures is gradual, as can be seen in the upper part of the vein.

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The mass transport mechanism ranges from diffusion to advection, acting on different length scales (Oliver and Bons, 2001). Many ore deposits and mass balance calculations indicate that the vein material has been transported over long distances by advection in many geological settings. This has been simulated quite successfully applying different numerical methods (Heimrich et al., 1996; Steefel and Lasaga, 1994; Matthäi and Roberts, 1997).

Various authors described the coupling of syntectonic deformation and vein growth (Mügge, 1928; Hulin, 1929; Durney and Ramsay, 1973; Ramsay, 1980). They suggested that multiple small crack increments lead to a final vein microstructure with an overall fibrous morphology. However, it has been shown that crack increments larger than approximately 10 µm can result in an elongate-blocky microstructure (Koehn et al., 2000; Hilgers et al., 2001). This means that an elongate-blocky vein microstructure does not exclude syntectonic growth.

To date, any relationship between the microstructural evolution of a vein, transport mechanisms and deformational events is unknown. This study tries to contribute here. Using a newly developed see-through apparatus for growth experiments under the microscope, we present syntaxial veins grown from advective supersaturated solution.

2. Methods

Constant fluid flux (0.05–0.5 ml/h) experiments were carried out in a machine, which can be attached under a transmitted light microscope. The experimental set-up consists of three units: a micro-pump containing saturated solution, a transparent reaction cell with seed crystals and a discharge container (Fig. 2). All units are accurately temperature controlled up to 0.01 °C. Saturated solution is pumped along a small channel about 2–3 mm wide and 15 mm long, whose walls consist of the same material as the solute. The reaction cell is 0.35 mm high in order to avoid grains growing on each other, and to force the microstructure to grow in an almost two-dimensional manner. Alum (KAl(SO$_4$)$_2$ × 12H$_2$O) has been chosen as analogue material because (i) it is highly soluble in water and thus reasonable amounts of solute precipitate within an experimental run of up to 24 h, and (ii) it grows as polyhedral crystals under the conditions applied. While being pumped out of the reservoir, the solution becomes supersaturated due to a temperature decrease of approximately 3 °C. Measurements assured that the solution was supersaturated before it reached the seed crystals in the reaction cell. Supersaturation was kept low (10% above the equilibrium concentration) to avoid spontaneous nucleation of solute, but favours secondary nucleation on existing seed crystals. During the experiments, images were regularly grabbed with a
Hitachi HV20 3CCD video camera and stored on a computer hard disc.

3. Results

Detailed observations in our reaction cell can be summarized as follows: at the conditions applied, dissolved material precipitates on the seed crystals. Most of the material accumulates on crystals located next to the inlet, while grains at the outlet grow at slower rates. Seed crystal facets also grow against the flow direction, toward the fluid reservoir. Growth rates measured normal to individual crystal facets along the channel reach values up to $3 \times 10^{-8}$ m/s, which concords with growth rates of alum single crystals (Garside, 1977; Mullin, 1993). During growth, the shape of seed grains changes due to two interfering
processes: similar to single crystal growth, a single seed crystal first takes shape of slow-growing low-index facets. During growth, they predominate over faster moving facets of this grain. However, once growing seed crystals get into contact with their neighbours, an overgrowth process starts. Now grains will outgrow their neighbours, if their fast-growing facets are oriented parallel to the channel-wall interface. This growth process is highly non-linear along the flow direction, showing an enormous growth competition at the beginning. Fig. 3 clearly indicates that only a few grains survive from an infinite number of seed crystals. Depending on the supersaturation and the fluid flux chosen, the overall growth rates change along the channel. At low fluid flux rates, dissolved material precipitates on grains located near the inlet (Fig. 3a). If the flux rate is increased by a factor of 5–10, the overall sealing process is more homogeneous at the scale of observation (Fig. 3b,c). In all cases, fluid flow and grain growth stop once two opposing grains touch.

4. Discussion and conclusion

In these experiments, we used highly soluble salt as rock analogue, rather than sparingly soluble material commonly observed in veins such as quartz, calcite or halite. Analogue experiments allow much faster growth rates and thus sealing of millimeter-wide veins within days at almost room temperature conditions. Sealing experiments of natural material require hydrothermal conditions with a highly sophisticated experimental set-up, which avoids precipitation in the tubing and failure of the high-pressure rig. In order to compare results with natural examples, a material was chosen which grows polyhedral crystals rather than skeletal or dendritic ones. Additionally, supersaturation was kept low to avoid spontaneous nucleation. Consequently, results can only be compared with polyhedral vein microstructures grown syntactically from the wall into the crack. Sunagawa (1984) pointed out that no significant difference exists between hydrothermal and surficial mineral growth, because both are precipitated from aqueous solution obeying the same growth laws. However, one has to consider the difference in solubility at high pressures and temperatures, and especially changes in reaction vs. diffusion-controlled growth rates. Thus, experimental results can only be extrapolated to polyhedral-grown hydrothermal syntactical veins.

Our experiments suggest that advection of supersaturated solution along a fracture network results in grains decreasing in size towards the downstream end. An increase of fluid flux leads to a more homogeneously sealed vein, but large voids remain open, and the vein is still sealed at the inlet. Additionally, the vein microstructure is a result of two interfering growth processes. Individual grains develop slow-growing low-index facets, but during growth compe-

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**Fig. 3.** Experimental results run at a supersaturation $\sigma$ of about 0.1. The channel is about 15 mm long and 2–3 mm wide, with fluid flux from left to right. At low flux rates, the channel will be sealed at the inlet only. Growth rates at the downstream end are very small. High flux rates result in a more homogeneous sealing, but still the inlet is sealed first. (a) Flux rate of 0.05 ml/h, experiment 0505. (b) Flux rate of 0.25 ml/h, experiment 0421. (c) Flux rate of 0.5 ml/h, experiment 0425. Scale bar: 2.5 mm.
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References


