



Abstract 1

Veins form in the earth's crust, when a rock fails due to local extension. Fluids are attracted by a fracture, which is a low pressure environment, and dissolved matter precipitates. A group of veins with strain-free microstructures and pronounced elongate or even fibrous crystal morphologies is of special interest for geologists, because these veins are thought to develop during progressive deformation of the host rock. The long axes of the crystal tend to follow the opening trajectory of the vein walls and arrays of inclusions may indicate a process of episodic fracture opening and filling, defined as crack-seal mechanism. Yet little is known about abnormal crystal growth and the evolution of polycrystalline aggregates in syntectonic veins. In our analogue experiments we try to mimic conditions of the crack-seal mechanism.

Abstract 2

The kinematics of crystal growth in syntectonic veins are usually described by a classification into 5 growth directions: syn-, anti-, ataxial, uniaxial and composite. Their corresponding crystal morphologies are termed elongate, fibrous and stretched. Certain growth conditions are assigned to these vein classes, as can be depicted from table 1. However, our experimental study indicates that growth processes in opening veins are much more complicated than the system of table 1 might suggest. The experiments show that many mechanisms can act during the microstructural evolution of a vein. The most important process is the trend to minimise surface energy by area reduction (see explanation below). Area reduction involves mechanisms of growth competition and probably the formation of grain boundary attractors as crystals try to fill the optimal way of filling available fracture space (figs. 2, 3, 4). Our observations show additional mechanisms, which are outlined below (figs. 5, 6, 7, 8). These involve a displacement of the fracture plane, which seems to be likely when space is scarce and mechanical coupling becomes evident. In general, these processes show how material can be transferred from one side of the vein to the other. According to our experimental results, it seems that quite often veins grow by multiple mechanisms.

Table 1: Vein classes

Glossary

vein classes	syntaxial	antitaxial	ataxial	uniaxial	composite
kinematics	crystals grow from wall rock into the vein	crystals grow from centre of the vein against the wall rock	no localized growth surface, crystals break inside and heal	growth from one side of the vein to the other, here from the upper to the lower wall	an antitaxial calcite vein is surrounded by a syntaxially growing selvage of quartz crystals
crystal morphologies	elongate	fibrous	stretched	elongate	fibrous and elongate
crystal growth conditions	a) growth into open cavities b) vein opening > average growth rate of the crystals	continuous opening, slower average growth rate of the crystals	episodic opening in small steps equal to crystal growth rate	opening slower than or equal to average crystal growth rate	continuous opening, slower average growth rate of the crystals

Experimental procedure

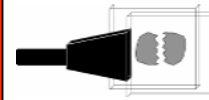
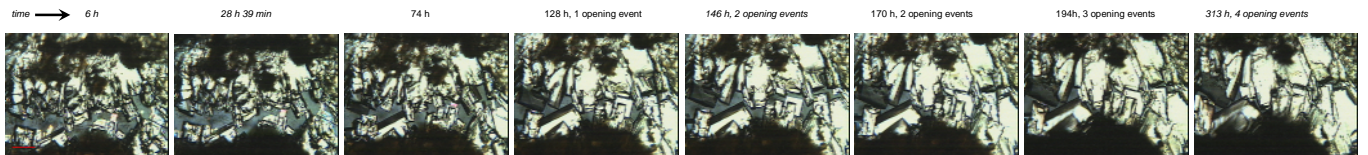


Fig. 1: Experimental set up. A sample is sandwiched between two glass slides. A piston pushes the upper glass plate forward, and moves two grips within the specimen apart, by which fracturing is localized.

A sample consisting of a partially molten benzamide-granite powder mixture is sandwiched between two glass slides with fixed grips. Granite powder is added to the sample to obtain a degree of anisotropy within the specimen, which promotes rough fracturing. The impurities also seem to catalyse nucleation. The sample is allowed to condense before it is placed in a linear deformation rig and heated up to 199 °C. A see-through window in the middle of the heating element serves for in-situ observation under the microscope and induces a temperature drop inside the sample, which drives crystallization. The sample only melts at its periphery. Tensile stress is applied by a motor that pushes a piston against the upper glass plate of the sample. When a fracture becomes visible the engine is stopped until the fracture is almost sealed, then opening is repeated.

Observations



Sequence 1: Crystals grow in a melt filled crack of a benzamide granite powder mixture. See the microstructural evolution of the vein filling from left to right. Scale bar in the first picture is 0,5 mm.

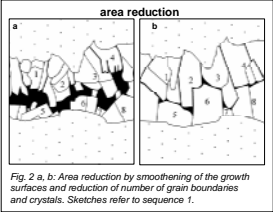


Fig. 2: a, b: Area reduction by smoothening of the growth surfaces and reduction of number of grain boundaries and crystals. Sketches refer to sequence 1.

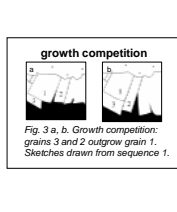


Fig. 3: a, b: Growth competition: grains 3 and 2 outgrow grain 1. Sketches drawn from sequence 1.

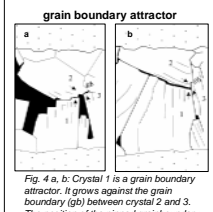


Fig. 4: a, b: Crystal 1 is a grain boundary attractor. It grows against the grain boundary (gb) between crystal 2 and 3. The position of the pinned grain boundary is determined by growth of the edge of crystal 1. Compare sequence 2.

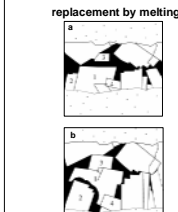


Fig. 5: a, b, c, d: Replacement by melting. Crystal 2 grows on top of crystal 1 that starts melting. This seems to favour growth of crystal 4, which in turn drives melting of crystal 2. Crystal 1 and crystal 2 have lost contact to the fracture wall and start growing again. c) While crystals 1, 2 and 3 merge to form a crystalline unit, the position of the crack changes and crystals 1 and 2 now belong to the opposing growth surface. d) Also see sequence 2.

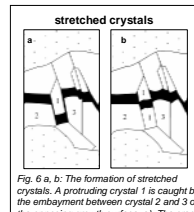


Fig. 6: a, b: The formation of stretched crystals. A protruding crystal 1 is caught by the embayment between crystal 2 and 3 of the opposing growth surface. a) The crack opens again and the crystal breaks inside. b) See sequence 2.

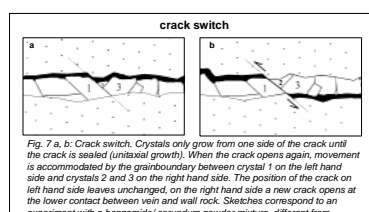


Fig. 7: a, b: Crack switch. Crystals only grow from one side of the crack until the crack is sealed (uniaxial growth). When the crack opens again, movement is accommodated by the grain boundary between crystal 1 on the left hand side and crystals 2 and 3 on the right hand side. The position of the crack on left hand side leaves unchanged, on the right hand side a new crack opens at the lower contact between vein and wall rock. Sketches correspond to an experiment with a benzamide/corundum powder mixture, different from sequences 1 and 2.

Area reduction:

Initially, a wide crack is opened and crystals start growing syntaxially from the rough fracture planes (sequence 1, fig. 2: a). Crystals protrude into the open cavity with different angles. The tips of the crystals tend to point inward into embayments of the fracture surface and spread out from asperities of the fracture wall. At this stage of free growth, the roughness of the growing surfaces is enhanced by growth anisotropy of randomly oriented crystals. As the opposing fracture plane is almost a template of the other side, the spreading crystals from the convex shaped wall unit meet the merging crystals from the concave opposite. When crystals get in contact, they impede each other. In consequence, the roughness of the growth surfaces is smoothened, because protruding crystals are blocked and slower growing crystals keep on growing. The roughness of the median line, in which the two growth surfaces meet, may then reflect a wavelength of the fracture wall, which could be transmitted by syntaxial crystal growth.

Another important aspect in this system is the effect of area reduction by growth selection, which is twofold. Either crystals outgrow each other and the fastest growing grain survives (fig. 3 a, b), or a grain with preferred growth orientation consumes other grains. Growth competition usually leads to the formation of crystalline units, which behave like a large single crystal (fig. 5 a-d). Within these units area reduction is predominant in the concave segments of the fracture walls. At some time spreading crystals from the convex fracture segments will probably meet there and merge. In this scenario large crystals will end up in the embayments of the fracture walls and grain boundaries are more likely to be situated at the asperities of the fracture walls. Crystals of the second growth surface grow against grain boundaries of the first growth front, see fig. 2b, crystal 6 faces the grain boundary of crystals 2, 3. This intercalated growth pattern can be found at selvages of antitaxial veins. Here, grain boundaries of the vein crystals also tend to lie at crystal tips spiking from the fracture walls, the so called grain boundary attractors (compare fig. 4a,b).

Sequence 2: Crystals grow in a vapour-filled crack of a benzamide granite powder mixture. Scale bar in first picture is 0,5 mm.

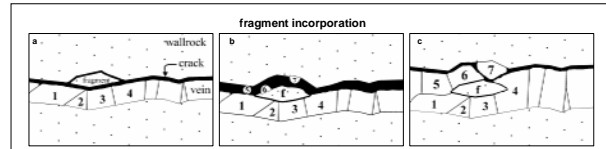
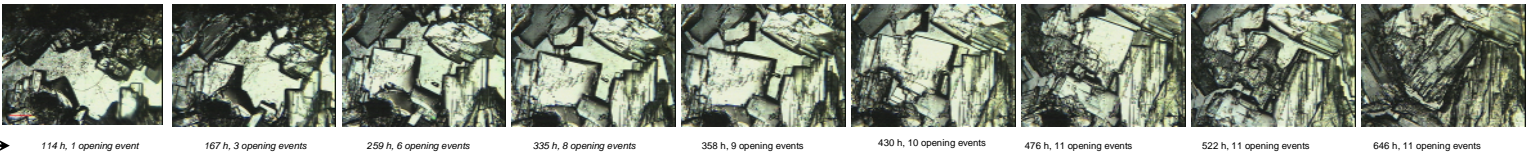


Fig. 8: a, b, c: Fragment incorporation. A wall rock fragment breaks off during crack opening. Crystals of the uniaxial vein take up the fragment and three nuclei form at the new fracture site: nucleus 5 within the melt filled space, nucleus 6 upon the fragment and nucleus 7 upon the newly exposed substrate surface. Further growth leads to a restricted area of bilateral growth, as crystal 1 grows against the other grains. Sketches stem from the same experiment as fig. 7.

Perspective

Some investigations of our laboratory study hint at special growth mechanisms that crystals assume, when space is restricted. Crystals of our experimental veins often subdivide into growing columns, similar to crystals from natural veins (fig. 9). Besides, we found in our experiments that growth velocities of individual faces undergo oscillations, while the overall growth rate of the crystalline aggregate along the vein stays constant (figs. 10, 11).

In addition to our experiments, we want to apply analytical methods:

- TEM for high resolution images of grain boundaries and contacts between an antitaxial vein and wall rock.
- EBSD to analyse orientations of crystals
- and 3-D tomography to obtain an idea of the dimension missing in thin sections and the planar samples of the experiments.

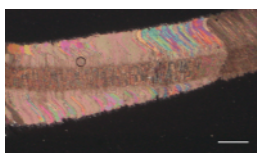


Fig. 9: Thin section of an antitaxial vein. Crystals show fibrous subcrystals or twins. Sestri Levante, Italy. Scale bar is 0,5 mm.

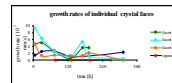


Fig. 10: Growth velocities of single crystal faces

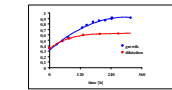


Fig. 11: Growth rate of the entire vein, which is dependent on opening rate, when crystal growth is faster than vein opening (flattening curve).