The formation of veins and their microstructures

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Abstract

An overview is presented of the various vein types, their microstructures and the processes that lead to vein formation. Vein types and their structures are divided into three categories:

1. macroscopic morphology (e.g. sigmoidal vein),
2. microscopic morphology (e.g. fibrous, blocky, etc.),
3. growth morphology (e.g. syntaxial, antitaxial, etc.).

The formation of veins involves two steps: (a) transport of vein forming material (nutrients) to a vein and (b) precipitation of the vein forming mineral(s). Main modes of transport are diffusional transport, advective or Darcian fluid flow and mobile hydrofractures. Causes for precipitation range from local supersaturation in, for instance, pressure shadows, which is mostly associated with diffusional transport to, often large, supersaturation in externally derived fluids. Variations in fluid pressure between hydrostatic and lithostatic can also cause precipitation of vein material.

In general, fibrous textures form due to diffusional transport to low pressure sites, such as pressure shadows. Fibrous textures can form without brittle fracturing. Elongate blocky and stretched crystal textures form in case of repeated fracturing and sealing (crack-seal mechanism). Nutrient transport can be by diffusion or by advective fluid flow. Rapid fluid flow, especially in mobile hydrofractures, can bring fluids quickly from their source region to the sites of vein formation, allowing large supersaturation and precipitation of massive amounts of vein material. Resulting veins are often blocky, although elongate blocky / stretched crystal textures can also be found if repeated crack-sealing occurs.

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1.0 Introduction

Veins occur in many forms, are composed of many different minerals and occur at all levels of the Earth's crust and mantle. Their morphology, petrology and chemistry is a valuable source of information in a range of geological disciplines. The association of many ore deposits (particularly gold) with veins makes them even more relevant to geology. It is therefore not surprising that veins have been studied extensively. Yet, the formation of veins is still not fully understood. One surprising aspect of veins is that no one has been able to successfully and consistently simulate the formation of the variety of vein types - not in real rocks, nor in rock analogues. Attempts with varying degrees of success have certainly been made (Post 1989, Li & Means 1995, Means & Li 1995a&b, Bons & Jessell 1997, and probably many more which never have been published).
(Fig. 1)

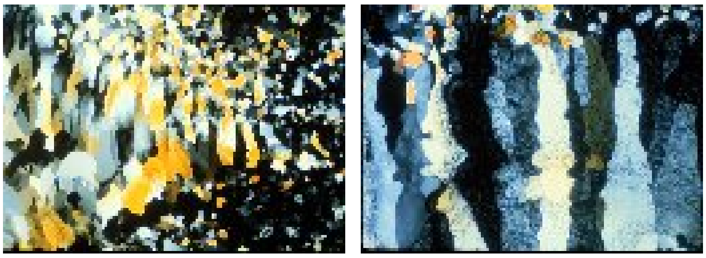

Figure 1. Vein like textures in a thin sheet of octachloropropane (OCP, C_3Cl_8) between glass plates. OCP is an organic material, that has been used to simulate microstructural developments in crystal-plastically deforming rocks (Means 1989). Here, a sheet of fine-grained OCP was heated on a hot plate to its melting point (160°C) and immediately taken off when melting started, to prevent melting of the whole sample. Sliding of the top glass plate relative to the lower plate, caused extension between different parts of the partially molten sample, with immediate crystallisation out of melt occurring within the extension zones, resulting in vein-like structures. The whole process took place in a few seconds. **(a)** Whole "vein" with a curved stretch-crystal type texture. Width of view 5 mm, crossed polars. **(b)** Detail of a "vein" with an elongate blocky / stretched crystal texture and serrate ("radiator") grain boundaries, typical for stretched crystals, but possibly due to recrystallisation. Width of view 1.2 mm, crossed polars.

It is a pleasure to be able to state in this volume, that probably the most interesting and real-life-looking vein simulations were done under the supervision of Win Means (Li & Means 1995, Means & Li 1995a&b). However, these experiments and those by others, have not yet resulted in full understanding of the formation of veins. This paper will therefore focus on what is known about vein formation. First, the various types of veins and their (micro-) structures are discussed. Secondly, the modes of transport of vein forming material are reviewed, followed by the third and last section that deals with the processes and circumstances that lead to precipitation of vein forming minerals. The processes that lead to vein formation are linked with the structures that are found in veins. It is impossible to go into detail of each individual aspect of vein formation within the limited space of this paper. Some topics are therefore only dealt with briefly, especially when much literature on the topic is available (e.g. veins and fluid flow through fractures). Other topics are discussed in more detail, especially if relatively little is published on these topics, such as the two end members of vein forming processes: vein growth without fracturing and veins formed out of mobile hydrofractures.

Before proceeding to discuss the formation of veins, it is important to define veins. In this paper, I define veins as "distinct polycrystalline mineral volumes that formed within a rock and that are filled with one or more minerals that precipitated from an aqueous fluid". The term "polycrystalline" figures in this definition to exclude individual metamorphic porphyroblasts. "Formed within a rock" is added to exclude evaporitic precipitates, although such precipitates can also form within sediments. Definitions of veins often include a description of the shape of veins, typically planar or lenticular. I do not do so, as veins have many shapes and I specifically want to classify pressure fringes as veins. Finally, small igneous bodies are also often termed "veins", but these are excluded in the definition given here as their melt origin is different from that of the veins discussed in this paper.

One could say that veins are structures that reveal a deformation history for structural geologists (e.g. Ramsay & Huber 1983), while veins are principally indicators of past fluid flow for metamorphic petrologists and geochemists (e.g. Thompson 1997). This difference in approach has not helped the issue. We will only achieve real understanding of veins if we combine all of these aspects and also if we consider the full range of vein-forming processes and the resulting vein types. In this paper I review the terminology of veins (traditionally mostly the domain of structural geologists) and the processes that lead to vein formation (more the field of metamorphic petrologists), with the aim of clarifying how different vein types form and how to recognise the processes that led to vein formation.

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2.0 Terminology

A proper terminology is very important to describe the many shapes of veins and the many different microstructures within veins. The terminology for veins that is currently in use, is mostly derived from Ramsay & Huber (1983) and Passchier & Trouw (1996). I use this terminology, with only minor refinements. Terms for the description of veins can be grouped in three categories. the first two relate to the structure of veins at different length scales, namely:

- macroscopic morphology (e.g. sigmoidal vein)

- microscopic morphology (e.g. fibrous)

The third category, termed "growth morphology" here, relates to the symmetry of the structures (e.g. antitaxial).

Ideally, the geometry and structure of a vein can be fully described by three terms, one from each category (e.g. antitaxial fibrous sigmoidal vein). We will see that not all combinations of terms occur and that some veins have a combination of features (e.g. partly blocky and partly fibrous).

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2.1 Macroscopic Morphology

Terms relating to macroscopic morphology, i.e. the shape of veins, are the least consistent, or well defined. Broadly speaking, we can divide veins in two categories:

a) veins that are directly related to some hard object as are pressure fringes (Fig. 2)

b) veins with shapes that are not primarily defined by a relatively hard object, but by fractures or other factors.

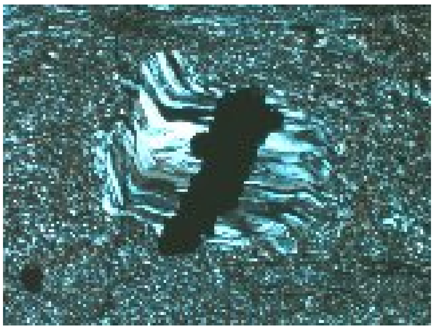

Figure 2. Pressure fringe of fibrous quartz around a concretion of iron ore in a BIF-chert from the Hamersley ore province, Pilbara, West Australia. Width of view 2.3 mm, crossed polars.

2.1.1. Pressure fringes

Pressure fringes are veins that form on the two low pressure sides of hard objects, usually ore minerals, but also other objects, such as crinoid stems (Durney & Ramsay 1973, Ramsay & Huber 1983, Selkman 1983, Beutner & Diegel 1985, Etchecopar & Malavieille 1987, Aerden 1996). They are termed pressure fringes if they have sharp edges and usually also if their internal structure (see below) is fibrous (Fig. 2). If not, they are termed pressure shadows (Fig. 3), which usually have diffuse boundaries and not a fibrous internal structure. One should however note, that recrystallisation can destroy the high grain boundary energy fibrous internal structure of a pressure fringe, making it appear like a pressure shadow.

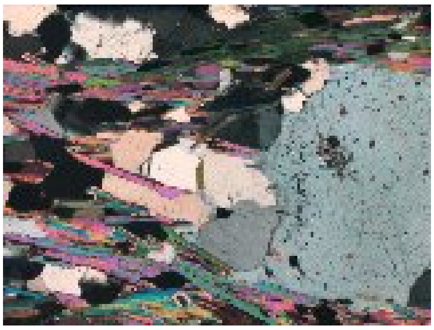

Figure 3. Quartz + mica pressure shadow adjacent to a quartz porphyroclast (on right, grey grain with inclusions) in a quartz-mica schist from Nooldoonooldoona Waterhole, S.W. Mount Painter Inlier, Arkaroola, South Australia. Width of view 3.2 mm, crossed polars. Note the sharp boundary of the pressure fringe (Fig. 2) in contrast to the vague boundary of the pressure shadow.

2.1.2. General veins

Most veins have the shape of lenses, tabular bodies or blobs. A variety of names (especially in mining; e.g. Barton 1991, Dong et al. 1995) exist for different shapes and positions within the rock. It is impossible to go into details here of every name or term that has been used in the literature, instead, I delineate three broad categories: tension veins, shear veins and breccia veins.

Many veins have their shape and orientation determined by structures such as fractures, faults or bedding (Fig. 4). The formation of fractures is favoured by high fluid pressures (P_f), as the differential stress needed to create fractures is reduced by high fluid pressures (Fig. 5). At sufficiently high differential stress ($\Delta\sigma = \sigma_1 - \sigma_3$) and P_f, shear fractures form at angles less than 45° to the maximum stress (Fig. 5.c). Although some dilation must occur on slip along such fractures, the main mode of displacement is parallel to the fracture plane and such fractures provide limited space for vein formation. If the fluid pressure is very high ($P_f > \sigma_3 + T$, T = tensile strength), extensional fractures can form where the main mode of displacement is normal to the fracture plane (Fig. 5.b) (Secor 1965). Such fractures provide more space for vein minerals to grow into and indeed, many veins appear to have grown in such extensional fractures (tension gashes). As tensional fractures provide the best opportunity for vein formation, it is not surprising that "tension veins", also called "tension gashes", "tension fissures" or "gash-veins" are common (Ramsay & Huber 1983, Rickard & Rixon 1983). These veins are usually lenticular is shape. Their size can range form mm-size to kilometres (Hippertt & Massucatto 1998) (Fig. 6). As can be inferred from Fig. 5.b, the formation of tensional fractures not only requires a high fluid pressure, but also limits the maximum possible differential stress (Etheridge 1983). Tensile strengths of rocks are generally in the order of 10 MPa, with values reaching several tens of Mpa at the most (Lockner 1995). This limits the differential stress during tensile fracturing to usually about 20-40 MPa.

Figure 4. Fibrous antitaxial calcite veins in carbonaceous shales. The veins form fracture-like sets with side splays where the interaction between two veins caused a local disturbance of the stress field. Tapley Hill Formation, Opaminda Creek, Arkaroola, South Australia.

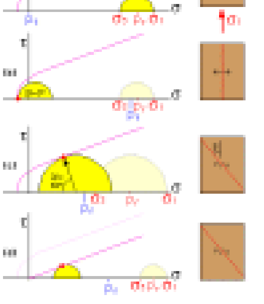

Figure 5. Mohr failure envelope representation (after Lockner 1995) in a graph of the shear stress (τ) against principal normal stresses (σ_1 and σ_3, with the rock pressure $P_r = (\sigma_1+\sigma_3)/2$). The Mohr-circle is a circle with its centre on the horizontal axis. Points on the circle represent normal stress / shear stress conditions on all possible planes. The angle β is the angle between the failure surface and the direction of maximum principle stress (σ_1). **(a)** When the Mohr-circle does not touch the Mohr-envelope, stresses are too low to induce failure. **(b)** Fluid pressure (P_f) reduces the effective pressure, which moves the Mohr circle to the left. Fluid pressure can rise until the Mohr-circle touches the Mohr envelope, at which point failure occurs. In the given case, with $P_f > \sigma_3$, failure is tensile (β=0°). **(c)** Shear failure (β=40°) can occur at relatively lower fluid pressure, but at a higher differential stress. **(d)** Tensile strength of an existing fracture is close to zero, which shifts the Mohr-envelope down. Less differential stress and fluid pressure is needed to reactivate such an existing fracture.

Figure 6. Massive tension vein on Poolamacca Station, Broken Hill Inlier, New South Wales (Australia). The vein is approximately 50 metres wide and a few hundred metres long and consists of pure milky white quartz.

Tension veins are often found in en échelon arrays (Fig 7.a). In such arrays they often have a sigmoidal (S or Z) shape (Durney & Ramsay 1973, Hanmer 1982, Rickard & Rixon 1983, Selkman 1983, Nicholson 1991, Olson & Pollard 1991, Passchier & Trouw 1996, Becker & Gross 1999, Smith 1999). The classical interpretation of such arrays is simple shearing parallel to the vein array in the direction opposite the way the vein tips point. The veins originally formed parallel to the maximum shortening direction (135°) and subsequently rotate. Vein propagation remains in the 135° direction, resulting in the development of the sigmoidal shape (Fig. 7.b). New veins may form cutting existing ones and these veins also initially form in the 135° direction. Continuing deformation at the en échelon array and formation of new veins in the deformed zone may eventually lead to the formation of one through-going vein (Fig. 8) (e.g. Wilkinson & Johnston 1996).

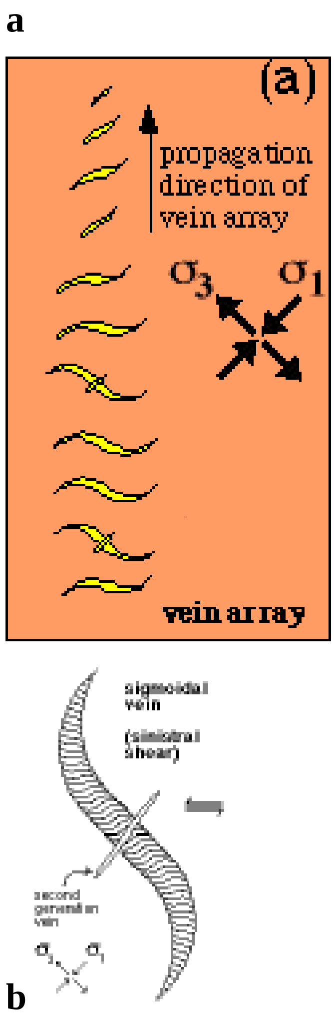

Figure 7. (a) En échelon array of veins in a dextral simple shear, resulting in a Z-shape of the tension veins. **(b)** Movie showing the development of a sigmoidal tension vein in sinistral shear. See text for discussion.

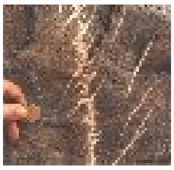

Figure 8. Set of sigmoidal en échelon veins that have amalgamated into a single dextral shear vein. Heavitree Quartzite, Ormiston Gorge, Central Australia. Photograph courtesy Alice Post.

Whereas tension veins tend to have at least their initial displacement direction normal to the fracture surface, fault related veins show evidence for a dominant fault-parallel displacement. Even then, some dilation is needed to provide space for vein growth. Slickenfibres (Passchier & Trouw 1996) occur on shear fractures (Fig. 9), but most vein growth is usually found on more dilatant pull-aparts (Peacock & Sanderson 1995, Brown & Bruhn 1996). Shear fractures can form, in intact rocks, at lower P_f than for tensional fractures, but a higher differential stress is needed (Fig. 5.c). However, existing planes of weakness (faults, bedding contacts) can reduce the tensional strength and hence the necessary differential stress and fluid pressure needed to induce fracturing (Cox & Paterson 1989, Sibson & Scott 1998) (Fig. 5.d). Veins thus tend to form along fault planes or parallel to bedding and there particularly in structures such as folds (e.g. "saddle reefs") and releasing bends (Raybould 1975, Cox *et al.* 1986, Henderson *et al.* 1990, Cosgrove 1993, Jessell *et al.* 1994, Glen 1995, Windth 1995, Fowler 1996, Fowler & Winsor 1997, MacKinnon *et al.* 1997). Another case where mechanical heterogeneities play an important role in the shape of veins is that of veins in boudinage necks (Lohest 1909, Cloos 1947, Platt & Vissers 1980, Mullenax & Gray 1984, Malavieille & Lacassin 1988, Smith, 1998).

Figure 9. Photograph looking down on slickenfibres in Heavitree Quartzite (Ormiston Gorge, Central Australia). diameter 1 A$ coin approx. 2 cm. Photograph courtesy Alice Post.

Breccia or net veins form a matrix between clasts in a breccia (Fig. 10). These typically occur in hydrothermal (ore) deposits. True breccia veins formed in one event of extensive fracturing, without significant preferred orientation. However, abundant veining of other types and/or the activity of multiple veining events with different cross-cutting orientations may produce breccia-like veins (Valenta *et al.* 1994).

Figure 10. Hydrothermal breccia of altered (haematised and silicified) wall rock pieces in a matrix of white quartz. Hammer on right edge of photo for scale. Mt. Gee, Arkaroola, South Australia.

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2.2 Microscopic Morphology

The microscopic morphology relates to the texture or the shape and arrangement of crystals inside a vein. Here I distinguish four primary categories:

1. Blocky
2. Elongate blocky
3. Fibrous
4. Stretched

This list is not exhaustive: especially shallow hydrothermal systems can produce a variety of textures and the reader is referred to Dong *et al.* (1995) for a review.

2.2.1. Blocky texture

A blocky texture is a texture in which grains are roughly equidimensional and randomly oriented. The texture in most granites could for instance be termed 'blocky'. Blocky textures can be primary, if, during vein growth, nucleation of new grains continues. Blocky textures can, however, also be secondary and due to recrystallisation of a primary texture.

2.2.2. Elongate blocky texture

Crystals in an elongate blocky texture (Fisher & Brantley 1992) are typically moderately elongate (length/width ratio generally in the order of 10) and the long axes of crystals are aligned (Fig. 11). This texture forms when nucleation of new grains does not occur during vein growth, and all growth is by crystallographically continuous overgrowths on existing grains and growth occurs at the tips of existing crystals. The 'seed grains' can be pre-existing grains in the wall rock of a vein, or grains formed during an initial nucleation stage. Elongate blocky textures show evidence for crystallographically controlled growth competition between grains (Mügge 1928). Crystals growing into a fluid typically show faceted morphologies as some crystal faces grow faster than others. Some grains, which are crystallographically oriented favourably with respect to the general growth direction, will outgrow unfavourably oriented grains. The faster growing 'winner' grains not only grow faster, but also wider, at the expense of the 'looser' grains. This leads to a gradual increase in grain width in the growth direction and the development of a crystallographically preferred orientation for the 'winner' grains (Mügge 1928, Cox & Etheridge 1983) (see Appendix B).

Figure 11. Photomicrograph of elongate blocky texture in a quartz vein. Vein crystals grew out from quartz grains in the sandstone wall rock (below), towards the centre of the vein (top). Growth competition reduced the number of grains away from the vein margin. Approximately horizontal dust and fluid inclusion trails suggest step wise crack-seal growth. Folded Palaeozoic turbidites, East Gippsland, Victoria (Australia). Width of view 8 mm, crossed polars.

2.2.3. Fibrous texture

In a fibrous texture, the rod-shaped grains can achieve a much higher length/width ratio than in elongate blocky textures (Fig. 12). As in an elongate blocky texture, the grains’ long axes are aligned. The distinguishing feature is that fibrous veins hardly show any growth competition. All grains have approximately the same shape. As with elongate blocky texture, a fibrous texture can only develop if no nucleation takes place after growth started.

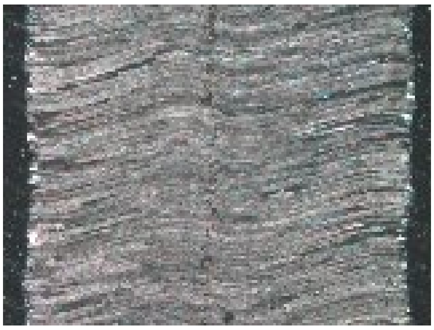


Figure 12. Photomicrograph of an antitaxial fibrous calcite vein. Fibre growth was outward from the median line, which is marked by a string of inclusions of the calcareous shale host rock. Outward growth can be determined by the slight increase in average fibre width away from the median line. Small blade-like quartz crystals precipitated at the vein margin, possibly onto existing small quartz grains in the shale. Tapley Hill Formation, Opaminda Creek, Arkaroola, South Australia. Width of view 4 mm, crossed polars.

It should be noted here, that I support the distinction between elongate blocky veins and fibrous veins as used by Fisher & Brantley (1992). This distinction is currently not usually made by other workers, who tend to call both categories 'fibrous'. However, until the seventies, it was recognised that the two are different (Durney & Ramsay 1973). The popularity of the 'crack-seal' mechanism, first proposed in the paradigmatic paper by Ramsay (1980) is perhaps the cause for the grouping together of the two categories. Although a crack-seal origin for all "fibrous veins" is favoured by some (e.g. Cox & Etheridge 1983, Cox 1987, Urai *et al.* 1991), different vein forming mechanisms may operate and therefore a distinction in fibrous and elongate blocky textures should be made.

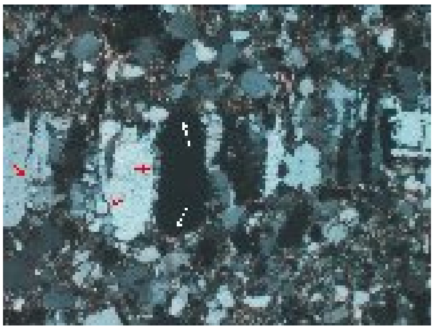
2.2.4. Stretched crystals

In the previous textures, additional vein material formed by precipitation on the surface of existing grains. The primary distinction between the previous textures and stretched crystals is that in stretched crystals, additional growth took place inside the grains (on the surfaces of the half grains), with the space for new-growth provided by (micro-) fractures that cut through the grains (Fig. 13). Fluid inclusions, dust rims or cathodo-luminescence images may reveal this. Stretched crystals often have jagged boundaries ("radiator" structure) and sometimes the two halves of the original grain can still be recognised at both ends of a stretched crystal.

a

b

Figure 13. Photomicrograph of stretched quartz crystals in a sandstone hosted vein in **(a)** plane polarised light and **(b)** cross polarised light. The vein material was formed by adding material to existing grains in the sandstone. White arrows indicate parts of a stretched vein crystal that formed two halves of one grain before the vein formed. Vein wall parallel dust trails and wall rock inclusions (black arrows) indicate that this vein formed by repeated crack-sealing, which can also



produce characteristic serrated grain boundaries ("radiator" structure, red arrows). Folded Palaeozoic turbidites, East Gippsland, Victoria (Australia). Width of view 2.3 mm.

2.2.5. Combinations of textures

Not all veins display only one texture. It is not uncommon for veins to be partly fibrous and partly (elongate) blocky as in figure 14. 'Polytextured' could be a possible term for such veins, but it is more important that the different textures for such a vein are described than to define a new and less meaningful single term for the many different possible combinations of textures. Two types of polytextured veins can be distinguished: (1) sequential growth of different textures as in fig. 14a&b, where first one texture forms and then another one, and (2) simultaneous growth of different textures at different sites within one vein (Fig. 14c). Veins of the second type occur in at Opaminda Creek, Arkaroola, when veins cut shales and carbonaceous silt stone layers. Fibrous textures form in the shale, but stretched crystals develop where the vein transects silt stone. Different mechanical properties probably play a role here, with fractures only forming in the silt stone layers and vein sections in the shale growing without any fracturing (see Ch. 3.2.2).

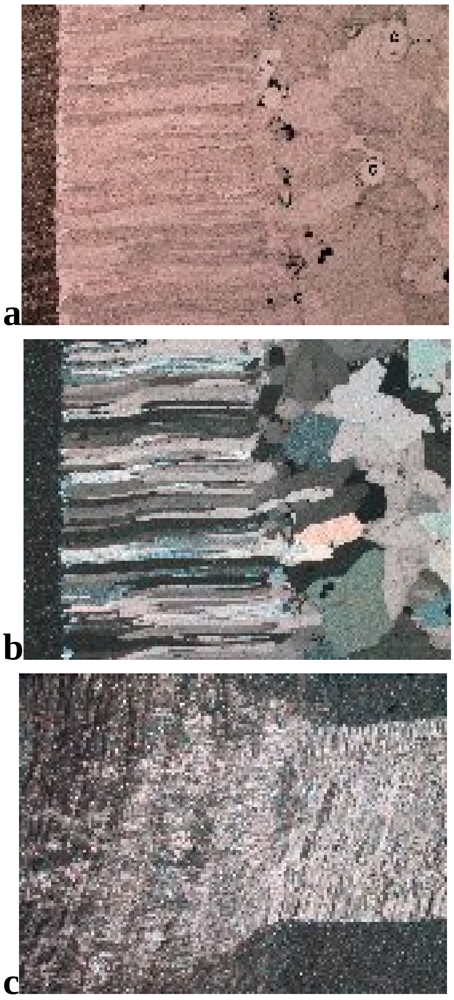


Figure 14. Photomicrograph of a polytextured, fibrous and blocky calcite vein in **(a)** plane polarised light and **(b)** cross polarised light. The initial veins is marked by a thin line of wall rock inclusions (S) and a line of quartz crystals (Q). Subsequently, two stages of vein growth occurred: (1) antitaxial fibrous growth towards the left and (2) open cavity growth on the right. The cavity infill took place by overgrowth of the first vein material (at line Q), but also by nucleation and growth of new crystals, resulting in a dominantly blocky texture. Infill of the cavity was not complete as cavities with faceted grain surfaces remained (C). This indicates that the blocky growth was probably the last growth event, post-dating leftward antitaxial fibrous growth from line S (right half of vein not shown). Width of view 10 mm. **(c)** Antitaxial fibrous calcite vein in shale (right) grading into stretched calcite in silt layer (left). Crossed polars; width of view 12.5 mm. Tapley Hill Formation, Opaminda Creek, Arkaroola, South Australia..

2.2.6. Partially filled veins

Veins may contain voids or cavities. Such cavities may be a result of incomplete filling of the vein. One form of incomplete filling is where a continuous crust of crystals lines the wall rock, with the vein crystals often having euhedral crystal faces facing the remaining cavity. Another form is where individual crystals span the entire vein width, but have open space in between (Henderson *et al.* 1990). These voids can later be filled by side-ways overgrowth of the first crystals (Fig. 15). If the vein is completely filled, the original existence of such voids is sometimes only visible with cathodo-luminescence.

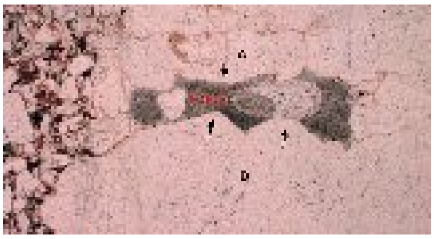


Figure 15. Photomicrograph of quartz vein with a void between elongate crystals. Crystals grew from left to right in many increment as indicated by repeated vertical dust trails. The void between crystals A and B is being partially filled by side-ways growth (arrows) of grains A and B. Folded Palaeozoic turbidites, East Gippsland, Victoria (Australia). Width of view 3.2 mm, plane polarised light.

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2.3 Growth Morphology

The third class of terms that are commonly used for veins is grouped here under the name 'growth morphology'. Growth morphology terms relate to where the site(s) of progressive growth are located in the vein, which determines the direction of growth of the vein forming crystals.

2.3.1. Syntaxial veins

In syntaxial veins (Durney & Ramsay 1973) (Fig. 16.a), growth occurs on a single plane: the median plane. On this plane, usually a thin fracture, material is added by overgrowth on vein crystals on both sides of the growth plane. Hence, the latest precipitated vein material is located at the median plane, while the first and oldest precipitate is found at the outside of the vein: at the vein - wall rock contact. Syntaxial veins can be symmetric, but often the growth plane is closer to one side of the vein, which produces a marked asymmetry in the vein (Fig. 16.b) (Fisher & Byrne 1990, Fisher & Brantley 1992). Syntaxial growth usually occurs when the vein forming mineral is a major constituent of the host rock. Vein crystals then grow epitaxially off grains in the wall rock.

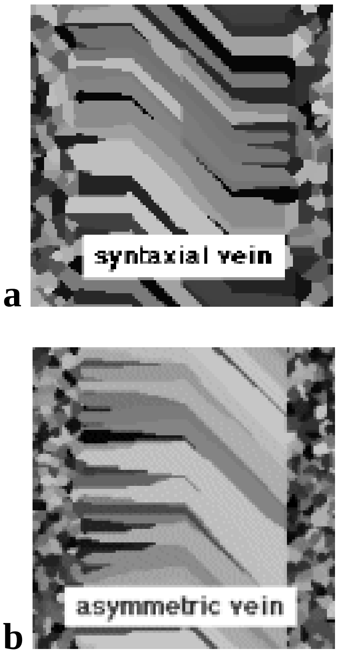

Figure 16. (a) Movie illustrating the growth of a syntaxial vein. The single growth surface is marked by a flashing white line. A record of the oldest part of the opening history can be found at the vein margins (horizontal opening, normal to the vein), while evidence for the youngest oblique opening direction is found in the centre. **(b)** Movie of the growth of a one-sided asymmetric vein, where growth is completely on one side of the vein.

2.3.2. Antitaxial veins

When the vein forming mineral is not a major constituent of the host rock, antitaxial veins (Durney & Ramsay 1973) commonly form (Fig. 12 & 17). In antitaxial veins there are two growth surfaces: one on each outer surface of the vein, between vein and wall rock. New vein material is added simultaneously at both these surfaces (Fig. 18). Hence, the youngest material is located at the outside of the vein, while the first precipitate is situated in the middle, on the median plane. The median plane in an antitaxial vein is clearly of a different nature than the median plane of a syntaxial vein. In antitaxial veins, which are usually (always?) fibrous, the median plane is marked by a string of wall rock inclusions (Fig. 12 & 17) or by a thin zone of differently textured vein material. Figure 19 shows a case where a zone of elongate blocky textured calcite occurs in the middle of a fibrous antitaxial calcite vein.

Figure 17. Tips of two parallel en échelon antitaxial fibrous calcite veins. Mean fibre width increases slightly from the median line outwards, which indicates that growth was outwards (antitaxial). Fibre shape is symmetric around the median line, except near the tips. Growth and propagation of the veins caused bending if the shale "bridge" in between. Tapley Hill Formation, Opaminda Creek, Arkaroola, South Australia. Width of view 13 mm, crossed polars.

Figure 18. Movie illustrating growth of an antitaxial fibrous vein, which typically contains a mineral different from those dominant in the wall rock. Growth occurs on the two outer margins of the vein. A record of the oldest part of the opening history can be found at the vein centre (horizontal opening, normal to the vein), while evidence for the youngest oblique opening direction is found in the margins. Note that not all crystals keep growing all throughout the growth history, but competition is usually not strong in antitaxial fibrous veins.

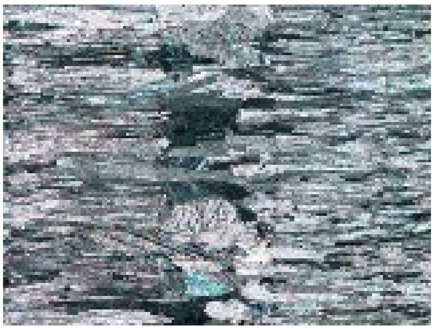

Figure 19. Median zone in a dominantly fibrous antitaxial calcite vein. The median zone has an elongate blocky texture with growth mainly from the right to the left. Small wall rock inclusions and quartz crystals mark the edge of the median zone. Antitaxial growth took place after formation of the median zone, with fibres growing out of median zone grains. The fibre width is much smaller than the grain size in the median zone, but comparable in size to the deformation twins in these grains. This indicates that the initial (median zone) vein was deformed before the onset of fibre growth. Tapley Hill Formation, Opaminda Creek, Arkaroola, South Australia. Width of view 6.4 mm, crossed polars.

2.3.3. Composite veins

If a vein is composed of two minerals (e.g. quartz and calcite), it can occur that one mineral shows syntaxial growth, while the other grows simultaneously with an antitaxial growth morphology. The syntaxial mineral started growing from the wall rock inwards, while the second mineral grew from the inside outwards. In this case there are two growth surfaces. Such growth morphologies are called "composite" by Durney and Ramsay (1973). It is suggested here to also use the same term for pressure fringes, and not "complex fringes" as used by Passchier and Trouw (1996). The term composite should be reserved for veins where both morphologies and minerals occupy similar proportions of the vein. Many antitaxial calcite veins, for instance, have a thin rim of syntaxially grown quartz crystals (Fig. 12 & 17) (Williams & Urai 1987, Urai *et al.* 1991), but these rims are too thin compared to the vein to warrant classification as composite veins.

2.3.4. Syntaxial & antitaxial pressure fringes

The terms syntaxial and antitaxial are also used for pressure fringes (Durney & Ramsay 1973) (Fig. 20). The convention for pressure fringes is somewhat confusing as it seems to be inconsistent with the convention for veins. 'Syntaxial' is a term from crystallography and denotes overgrowth on a crystal in crystallographic and mineralogical continuity. Syntaxial veins are called such, as these veins usually form by crystallographically syntaxial overgrowth of wall rock grains. 'Antitaxial' (not a crystallographic term) then signifies the opposite. In an antitaxial veins, the new precipitate is not in crystallographic or mineralogical continuity with wall rock grains. Instead, growth occurs by crystallographically syntaxial overgrowth of vein crystals. The terms syntaxial and antitaxial are therefore defined with respect to a reference material: the wall rock in case of veins.

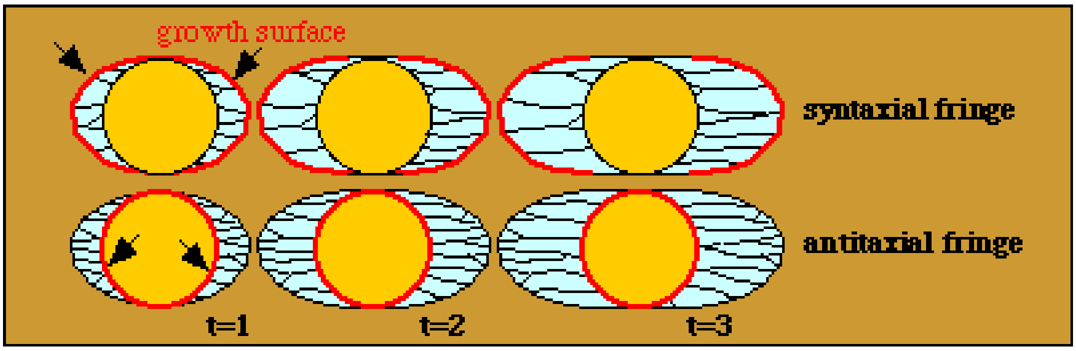

Figure 20. As with veins, the difference between syntaxial and antitaxial pressure fringes is determined by the position of the growth surface. Syntaxial fringes (crinoid-type) have their growth surface between fringe and wall rock, while the more common antitaxial or pyrite-type fringes have the growth surface between the object and the fringe.

It is somewhat confusing at first sight that for pressure fringes, the object was chosen as the reference material and not the wall rock. In a syntaxial pressure fringes, growth occurs on the outside of the object + fringe system and the fringe crystals are syntaxially (or sometimes epitaxially) overgrowing the object. Calcite fringes on a crinoid stems are classical examples of syntaxial pressure fringes (hence the "crinoid-type" of Ramsay & Huber 1983). In an antitaxial pressure fringe, the opposite occurs: the fringe crystals are crystallographically and mineralogically unrelated to the object (and possibly to the wall rock as well). New growth occurs at the contact between object and fringe, with the object often being pyrite ("pyrite-type" of Ramsay & Huber 1983). An excellent overview of the use of pressure fringes for tectonic analysis is given by Passchier & Trouw (1996), who, incidentally, use the term "strain fringe" instead of "pressure fringe". Also note that they use the term "complex fringes" and not "composite fringes" (which would be consistent with Ramsay & Huber 1983) for fringes that exhibit both antitaxial and syntaxial growth.

2.3.5. Ataxial or stretched veins

In the previous cases we saw growth on one or two surfaces. These surfaces remained the same throughout the growth history. A different class of veins is formed when the position of the growth surface changes through time (Fig. 21). This happens when a vein forms from a succession of fractures that fill with vein material. These fractures can cut the host rock and vein at different locations and multiple fractures can be present at any given moment. As such veins are neither syntaxial, nor antitaxial, the term ataxial is used (Passchier & Trouw 1996). The term 'stretching veins' (Durney & Ramsay 1973) is also appropriate, as the resulting grain morphology is that of stretched crystals. One can recognise two end-member cases of stretching veins: one where all fractures occur within the growing vein (Fig. 22.a) and one where fractures occur randomly and it becomes difficult to distinguish between a vein and the wall rock, as in fact there are multiple veins (Fig. 22.b).

Figure 21. Stretched calcite veins in carbonaceous shale. It is clear from the wall rock slivers and thin crack-like veins outside the main veins, that the veins grew by many crack-seal events, each crack being up to a few tens of microns wide. It is difficult to impossible to determine the sequence of fracturing. Individual stretched crystals span the whole width of veins. Tapley Hill Formation, Opaminda Creek, Arkaroola, South Australia. Width of view 3.8 mm, plane polarised light.

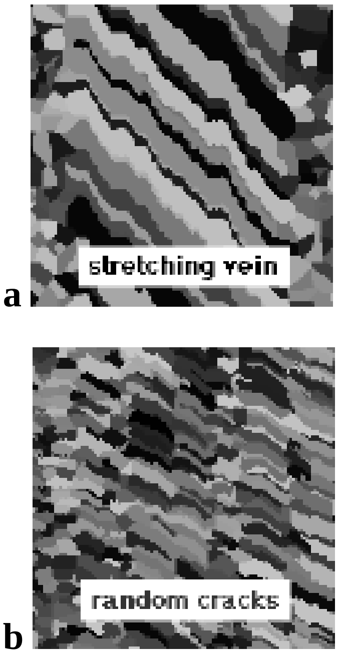

Figure 22. Movies illustrating the formation of stretched veins. **(a)** Fully localised fracturing end member. All fracturing occurs within the growing vein. The margin of the vein is distinct. **(b)** Completely random position of parallel fractures. A distinction between wall rock and veins is difficult to make. In both movies, opening is initially horizontal and then oblique. This opening history cannot be determined from the shape of the stretched crystals, which only reveal the average opening direction over the whole growth history.

2.3.6. A-syn-anti-bi-uni-taxial?

The terms "syntaxial" and "antitaxial" (Durney & Ramsay 1973) gained common use in geology thanks to popular text books such as Ramsay & Huber (1983) and Passchier & Trouw (1996). Passchier & Trouw (1996) added the term "ataxial" veins for what Ramsay & Huber called "stretching" veins. They also extended the use of syntaxial and antitaxial to pressure fringes or strain fringes (see Ch. 2.3.4). More recently, Urai (*pers. comm.*) and Hilgers *et al.* (*in press*) proposed additional -taxial terms: "unitaxial" and "bitaxial" (Fig. 23). All these terms may be confusing if they are not fully and accurately defined and consistently used by different authors.

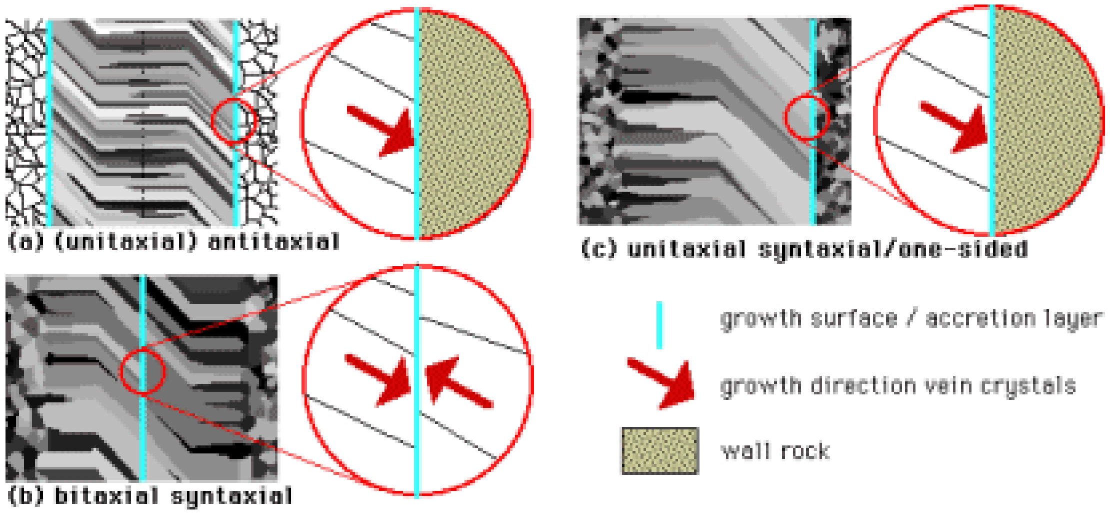

Figure 23. Unitaxial and bitaxial refer to the directions (red arrow) of growth at the growth plane or accretion plane (blue line). **(a)** In unitaxial growth, growth is in one direction only at the growth plane, which is the case in antitaxial veins with two unitaxial growth planes. **(b)** With syntaxial growth, there is only one growth plane on which bitaxial growth takes place. **(c)** One sided veins have a single unitaxial growth plane between vein and wall rock and could be termed "unitaxial syntaxial".

Antitaxial was defined by Durney & Ramsay (1973), Ramsay & Huber (1983) and Passchier & Trouw (1996) for veins in which the crystals inside the vein do grow towards the wall rock, from a median line. In their figures (fig. 13.9 & 13.24 in Ramsay & Huber (1983) and fig. 6.6 in Passchier & Trouw (1996)), antitaxial veins have two growth planes, as in Fig. 12, 17 & 23a. Syntaxial veins grow from and in continuity with the wall rock inwards. Syntaxial veins have only one growth plane (Fig. 16.a and 23.b). At the growth surface of an antitaxial vein, growth is in one direction only and hence they can be termed unitaxial, while growth in syntaxial and stretching veins is from both sides of the growth plane and these veins thus show bitaxial growth.

Whereas the terms "syntaxial", "antitaxial" and "stretching/ataxial" veins refer to the whole vein, the terms "bitaxial" and "unitaxial" refer to growth at one single growth plane. This terminology would normally not cause any problems and one may even argue whether the introduction of the terms "bitaxial" and "unitaxial" is necessary as all antitaxial veins would appear to be unitaxial and all syntaxial and ataxial veins are bitaxial. Problems however arise with completely asymmetric or one-sided veins, that have only one growth plane between the wall rock and one side of the vein (Fig. 16.b and 23.c). Such veins are described by Fisher & Byrne (1990) and Fisher & Brantly (1992) and the "antitaxial fibrous" veins of Cox (1987) could also be such, although it is not fully clear from his figures or text. Are such veins antitaxial because growth is towards the wall rock, albeit only on one side of the vein? Or are they syntaxial, because growth is seeded on the wall rock, albeit only on one side? What is clear, is that these veins are unitaxial, as growth is only in one direction at the growth plane. Ambiguity can be avoided if the terms antitaxial, syntaxial and stretching/ataxial are strictly used to describe a whole vein and unitaxial and bitaxial for the growth situation at a single growth plane:

- An antitaxial vein has two persistent growth planes on the outer surface of the vein, where simultaneous growth occurs unitaxially outwards (Fig. 23.a).

- A syntaxial vein has only one persistent growth plane. Normally growth is bitaxial at that plane and growth is inwards from the wall rock (Fig. 23.b). However, unitaxial growth can occur, in which case the growth plane is on one side between the vein and the wall rock and thus only one half of the syntaxial vein develops (Fig. 23.c).

- Stretching or ataxial veins do not have one or two persistent growth planes but alternating planes at different sites. Growth at the "jumping" growth plane is bitaxial.

2.3.7. Vein morphology and structural analysis

It is clear that syntaxial, antitaxial and composite veins can provide detailed information on the progressive sequence of conditions under which these veins formed. These veins are elongate blocky or fibrous and the direction and curvature of the crystals indicate the kinematics of deformation and the orientation of the stress field. Curvature of vein crystals is a result of progressive change of the vein orientation with respect to the stress field around the vein. Such a change in orientation can result from a change in orientation of the stress field (as for instance in multiple deformation events) and/or a change in orientation of the deforming vein. The correct growth morphology must be determined for any strain analysis. The direction of growth in fibrous or elongate blocky veins can usually be determined by an increase in average grain width in that direction. Careful analysis can reveal this (Durney & Ramsay 1973, Ramsay 1980, Winsor 1987, Passchier *et al.* 1996, Passchier & Urai 1988, Aerden 1996). It is important in such analyses that it is recognised that crystal shapes do not always fully reflect the displacement path of the vein wall rock, or 'opening trajectory' (Williams & Urai 1987, Urai *et al.* 1991). A full discussion of the use of veins for structural analysis is beyond the scope of this paper, but this point will be discussed in some more detail in Appendix B.

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3.0 Vein Formation

Vein formation essentially involves two steps:

A. transport of vein forming material (nutrients) to the growing vein,

B. precipitation of the vein forming mineral(s) in the growing vein.

As veins were defined as forming from precipitation from an aqueous fluid (possibly containing CO_2, but excluding melt), it is clear that material transport involves transport in solution and that precipitation involves supersaturation of a fluid. This section deals with how and why material can get transported in solution to veins and why at some stage the fluid may get supersaturated and precipitate vein forming mineral(s). Transport and the cause for precipitation are by no means always independent processes, but a division is attempted here for clarity.

3.1. transport mechanisms

3.1.1. Transport through a fluid: diffusional flow

Diffusional flow is the first of two basic transport mechanisms. This transport mechanism does not necessarily involve movement of a fluid: even in a completely stagnant fluid, there can be a net flux of dissolved material through the fluid if there is a gradient in chemical potential of that dissolved material and the fluid provides a connected pathway. Diffusion is a geologically very important transport mechanism. It is the primary transport 'vehicle' for dissolution-precipitation creep (Durney & Ramsay 1973, Durney 1976, Raj 1982, Rutter 1983) and metamorphic reactions. Although diffusion is a very effective transport mechanism on the small scale (< cm-dm), it is relatively ineffective for transport over larger distances.

3.1.2. Transport with a fluid: fluid flow

The second basic transport mechanism is fluid flow. When a fluid flows, it takes with it its solute. Aqueous fluid have a very low viscosity (compared to rocks) and can therefore move easily and quickly over large distances through rocks. Fluid flow is therefore the only effective mechanism for transport of dissolved material over large distances (>m-km) through rocks (see Jamtveit & Yardley (1997) for a recent review). Again, we can distinguish two types of fluid flow (Appendix A):

1) fluid flow through channels (e.g. fractures) or a permeable medium (Darcian or advective flow);

2) fluid flow with its containing fracture (mobile hydrofractures).

3.1.3. Darcian or advective fluid flow

In the first case, Darcian or advective flow, fluid flows down a gradient in hydraulic head, through interconnected pathways. These pathways can be distinct macroscopic channels, such as fractures, or the pores inside a solid permeable rock (pervasive flow). With localised or channellised flow, the fluid by-passes most of the rock volume, whereas with pervasive flow, the fluid comes in close contact with most of the rock. This of course has significant implications for the chemical interaction between fluid and rock (Rye & Bradbury 1988).

3.1.4. Mobile hydrofractures

In the second case, fluid is contained as a unit in a fracture and *both fracture and fluid* move at the same time and the same rate. This transport mechanism is known as hydrofracture mobility (Weertman 1971, Secor & Pollard 1975, Pollard 1977, Takada 1990) and is invoked to explain the rapid ascent of magmas (Clemens & Mawer 1992, Clemens 1998), but has received relatively little attention in metamorphic hydrology or hard-rock structural geology. Transport rates in case of hydrofracturing are not determined by Darcy's law. Transport is very rapid (in the order of metres per second), but intermittent: short bursts of mobility are followed by possibly long periods of stagnation (or other types of flow). Hydrofracture mobility is a mechanism for rapid long distance transport of fluids, without much interaction with the wall rock during transport (Davies 1999, Bons *in press b*)

The difference in rate controlling factors between Darcian flow and flow by mobile hydrofractures can be illustrated by the analogy of a gardener watering his plants. The Darcian flow case would be the case where the gardener uses a hose. The rate at which water reaches the plants is determined by the water pressure at the tap, the diameter of the hose and the length of the hose. The gardener using a bucket to carry the water would be analogous to mobile hydrofracture transport. The rate is now determined by the rate at which the bucket can be filled, the size of the bucket and the distance and walking speed of the gardener.

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3.2 Precipitation in a vein

3.2.1. The crack-seal mechanism

Before discussing the processes and causes for precipitation inside a vein, it is worthwhile to briefly discuss the crack-seal mechanism. The crack-seal mechanism was first introduced by Ramsay (1980) and has quickly become the accepted mechanism for the formation of fibrous/elongate blocky veins (Cox *et al.* 1986, Urai *et al.* 1991, Kirschner *et al.* 1993). The mechanism itself does not dictate any fluid or solute transport mechanism, nor a specific cause for precipitation inside a vein. The essence of the crack-seal mechanism is the repeated formation of a crack which is subsequently sealed by precipitation of vein forming material inside that crack. The crack-seal cycle can be repeated hundreds of times, typically adding about 10 µm to a vein each cycle (Fisher & Brantley 1992). The crack-seal mechanism can explain many parallel wall rock inclusion trails that are often found in veins (Fig. 13 & 21). The effect of the crack-seal mechanism on the morphology of vein forming crystals (stretched / elongate blocky / fibrous) and the tracking-capability of elongate crystals is further discussed in Appendix B.

3.2.2. Vein growth without fracturing

Probably the most clear-cut case of vein growth without fluid flow, but by diffusional solute transport is a pressure fringe adjacent to a rigid object (e.g. a pyrite grain). The presence of a rigid object in a deforming/stressed rock causes a perturbation of the stress and pressure field around the object (Durney & Ramsay 1973, Strömgård 1973, Durney 1976, Selkman 1983). The sides of the object facing the highest compressive normal stress experience the highest pressure, while the sides facing the lowest normal stress experience a relative low pressure (Fig. 24). This pressure difference can drive dissolution at the high pressure sides, diffusional transport to the low pressure sides and precipitation there to form the pressure fringes. This process can occur without the formation of a (thin) crack at the low pressure sides of the rigid object. Pressure fringes are usually fibrous and generally have no wall rock inclusions and therefore show no typical indicators for repeated crack-sealing. However, crack-sealing can occur, as has been shown by Lister *et al.* (1986) for biotite porphyroblasts where radiator structures formed in pressure shadows.

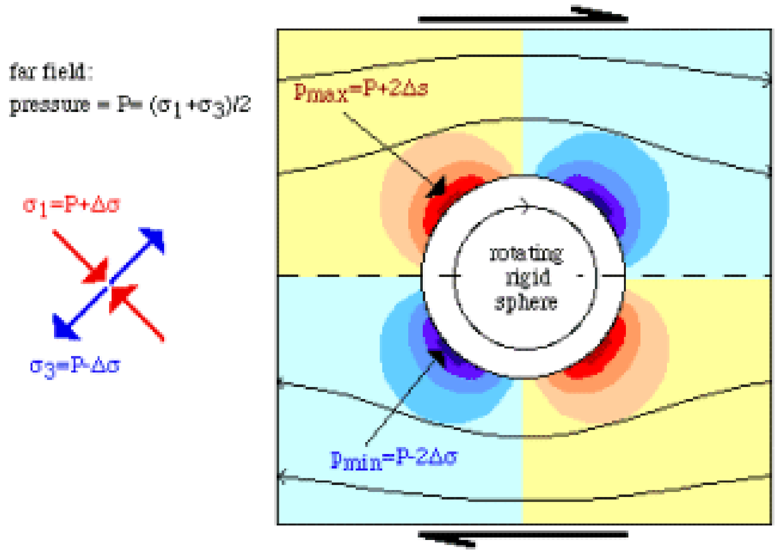


Figure 24. Flow lines (arrow lines) and pressure contours around a spherical object in a homogeneous linear viscous matrix deforming in horizontal dextral simple shear. Far away from the object the principle stresses are at 45° to the flow plane. If the far field pressure is P, then σ_1=P+Δσ and σ_3=P-Δσ and the differential stress is 2Δσ. The maximum stress perturbations occur on the surface of the rotating sphere, where stresses range from P-2Δσ (blue) to P+2Δσ (red). The difference in pressure can drive diffusional material transport from the red quadrants to the blue ones, where precipitation leads to the growth of pressure shadows (distributed precipitation) or pressure fringes (localised precipitation). The flow field and pressure contours were calculated with equations from (Chwang & Wu 1975), modified for simple shear.

It may be important that pressure fringes are usually fibrous (not elongate blocky) and appear to form without any brittle failure: there are no microstructural indicators for fracturing and the stress and pressure field around the object provide the driving force for material transport and precipitation in the fringe. This supports the hypothesis that the fibrous crystal morphology may form in the absence of fracturing, as was also proposed by Taber (1918) and Mügge (1928), and more recently by Durney & Ramsay (1973), Janssen & Bons (1996) and Bons & Jessell (1997). In the absence of fractures, diffusion is the only viable transport mechanism and we may infer that fibrous veins are indicative of diffusional material transport.

Taber (1918) argued that the base of fibrous crystals must be in contact with a supersaturated solution in pores in the wall rock. Fibres "grow out of" the pores, which means accretion of new material is at the wall rock - vein interface. The work of Taber has recently been replicated by Means and Li (1995a,b) and Li and Means (1995), who produced very natural looking fibrous textures, without any fracturing. Mügge (1928) argued that the absence of growth competition in fibrous aggregates indicates the absence of an open fracture in which the crystals grew. He delineated three cases:

(1) The opening rate of the vein (fracture) is faster than the maximum potential growth rate (on fastest growing crystal faces). Euhedral crusts of crystals form.

(2) The opening rate of the vein (fracture) is slower than the maximum, but faster than the minimum potential growth rate of crystals. Growth is partly constrained and elongate-blocky crystals would form with a crystallographic preferred orientation (CPO).

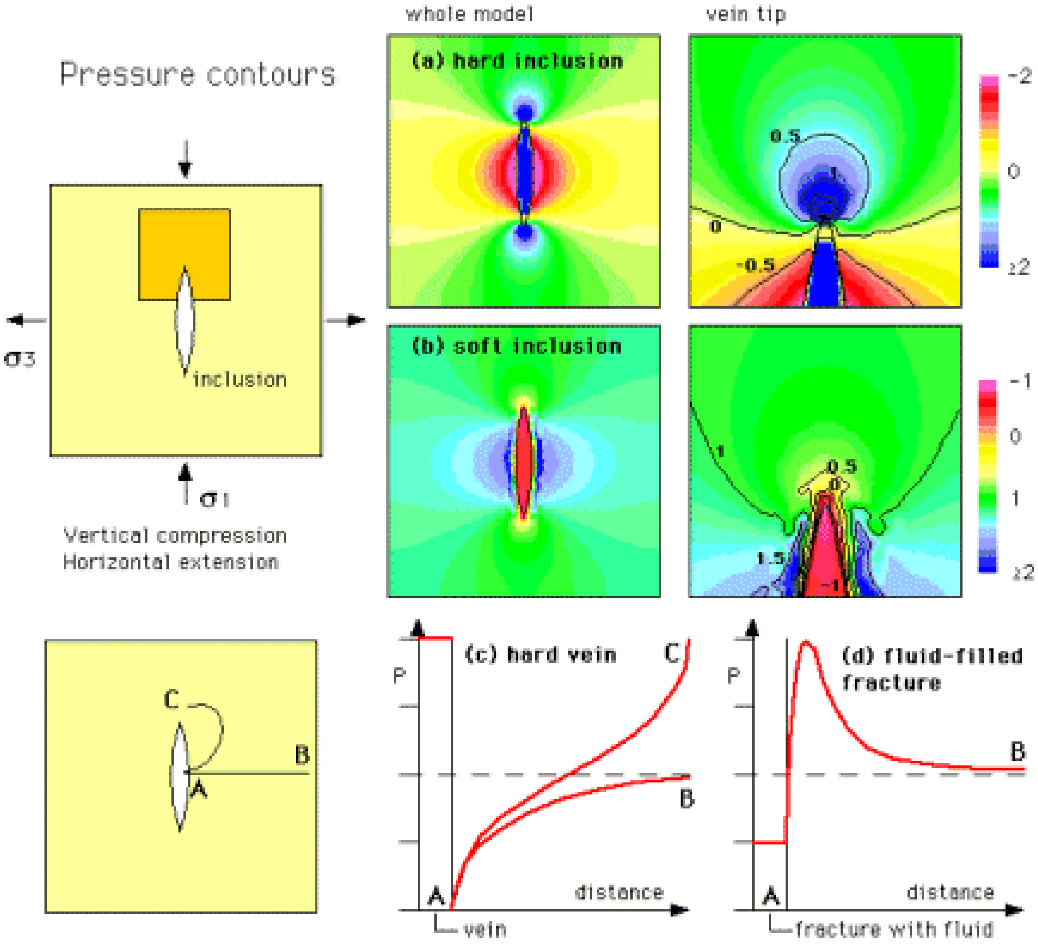
(3) The opening rate of the vein (fracture) is slower than the minimum potential growth rate. The surfaces of the growing crystals remain in contact with the opposite wall rock at all times and growth competition is therefore inhibited. Fibrous crystals form without the development of a CPO.

Pabst (1931) measured c-axes orientations in fibrous pressure shadows to test the hypothesis of Mügge (1928) and indeed found that the fibres did not develop any CPO. The stretched and elongate-blocky quartz veins of Cox (1987), on the other hand, did show a CPO, which is in line with Mügge's (1928) hypothesis that such veins fall into category (2), with the refinement by Ramsay (1980) that opening rates are not constant, but that space is created in distinct steps by repeated crack-events.

In the case of fibrous growth in pressure fringes, the driving forces for diffusional transport and precipitation are evident: the stress and pressure perturbation caused by the relatively rigid object. Can growth without fracturing in other fibrous vein types be explained, when the transport mechanism and cause for precipitation is less evident? Well developed antitaxial fibrous calcite veins in shales are found in Opaminda Creek (northern Flinders Ranges, South Australia). The Young's modulus of calcite is at least about double that of shale (Birch 1966). An isolated (lenticular) calcite vein therefore forms a hard object relative to the surrounding shale and, during deformation, would (as for rigid pyrite grains) develop a pressure gradient around itself (Fig. 25), which can drive further growth of the vein. Such veins can then be regarded as 'self-supporting' pressure fringes. Propagation at the vein tips, where a strongly localised stress perturbation occurs, lengthens the vein as it widens, which probably enhances the process.

Figure 25. Pressure contours for deformation of a lenticular inclusion in a linear viscous matrix. The model is shown on the left with the imposed vertical shortening boundary conditions (arrows). Contours for pressure are shown on the right for the whole model (yellow square) and for the area around the

inclusion tip (orange square). **(a)** Pressure contours for deformation around a hard inclusion (viscosity 100 x that of matrix). Pressure inside the hard lens is high, but the highest pressure is found at the inclusion tips. Lowest pressure is found at the sides of the inclusion. **(b)** Pressure contours for a soft inclusion (viscosity 0.01 x that of matrix), simulating an open fracture. Lowest pressure occurs inside the inclusion and highest pressures at the sides of the inclusion. Except for the singularity at the tip of the hard inclusion, the solutions for hard and soft inclusion are the inverse of each other. **(c)** Pressure profile along paths A-B and A-C for a hard inclusion. Any transport down the pressure gradient would bring material from the inclusion tip area (C), but also from the far field (B) to the surface of the inclusion. This could explain the growth of antitaxial veins without fracturing. **(d)** Pressure profile along profile A-B for a soft inclusion or fracture. The highest pressure occurs adjacent to the fracture, which would be the site of maximum dissolution if dissolution-precipitation creep operates. Material transport could be towards the vein, but possibly also away from



the vein, down the pressure gradient. Pressures were calculated with the finite-element package BASIL (Barr & Houseman 1992, Bons *et al.* 1997).

For this process to work, a ’seed’ vein must already be present. Many of the antitaxial fibrous veins at Opaminda Creek have a median zone that is actually blocky in texture and fibrous crystals started growing from the surface of this zone (Fig. 19). The veins may have thus started their life by another process than described above and subsequently grew wider and longer by material transfer and precipitation by a self-supported pressure gradient. It should also be noted that fibrous veins at Opaminda Creek occur as isolated lenses, but also as long (metres) and thin (cm’s) fracture-shaped veins, both of which are antitaxial and fibrous. The shape of these veins is probably related to fracturing, which may have only seeded these veins. However, the actual driving force for subsequent fibrous growth in fracture-shaped veins is not known.

3.2.3. Vein growth in fractures

Fractures are the most common sites for veins to form, as fractures provide space for precipitation and preferred pathways for fluids to flow through. Two main causes for precipitation inside fractures can be distinguished:

a) Vein-forming material is derived from a fluid that resides in both fractures and surrounding wall rock. The conditions inside the fracture and in the wall rock are different, such that a fluid that does not produce any (significant) precipitation in the wall rock does precipitate one or more minerals inside the fracture. Vein formation can then occur in the fracture by either diffusional transport in a possibly stagnant fluid or by flow of a fluid that brings local fluid from the wall rock into a vein. Again we can distinguish two cases:

> a1) The fluid is supersaturated with respect to the vein forming mineral(s) in both fracture and wall rock, but precipitation is inhibited in the wall rock. Taber (1918) and Putnis *et al.* (1995) argued that a low porosity can inhibit precipitation and therefore a pore fluid can remain significantly supersaturated until a fracture provides a possible site for precipitation. Material transport to such fractures can be by diffusional transport (Fig. 26.a) or by advective flow.
>
> a2) The difference in conditions between fracture and wall rock cause a difference in the chemistry of the fluid residing in fracture and wall rock (Fig. 26.b). This could, for instance, be due to a difference in fluid pressure in both reservoirs. Silica solubility is pressure dependent, and therefore, we may expect that at a constant concentration of silica, fluid may be undersaturated in a high fluid pressure wall rock and supersaturated in a low fluid pressure fracture, where precipitation then occurs. Veins are often associated with deformation by dissolution-precipitation creep or ‘pressure solution’ (Durney 1976, Rutter 1976; 1983, Raj 1982, Lehner 1990). This deformation mechanism involves dissolution at certain sites, transport of dissolved material and precipitation of that material at other sites. The redistribution of material produces a change of shape of the rock: deformation. Re-precipitation can occur pervasively in the rock, but can also be localised, in which case veins form (Beach 1977, Winsor 1984, Cox *et al.* 1986, Fisher & Brantley 1992, Gratier *et al.* 1993) (Fig. 27).

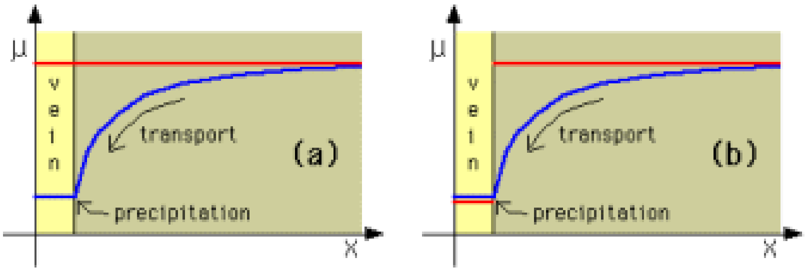


Figure 26. Two possible cases of diffusional transport towards a vein, illustrated by graphs of chemical potential of dissolved vein forming mineral (μ) against distance, x, from a vein. **(a)** Equilibrium μ (red line) is the same in vein and wall rock, but precipitation is inhibited in the wall rock. Precipitation in the vein is possible, which lowers the actual value of μ in the vein. This produces a gradient in actual μ (blue line), driving transport towards the vein. **(b)** Equilibrium μ is lower in the vein than in the wall rock (red line). This causes a gradient in actual μ (blue line), with again precipitation only inside the vein.

Figure 27. Stylolite and quartz vein combination in Heavitree Quartzite (Ormiston Gorge, Central Australia). A distinct stylolite dips shallowly to the right and truncates milky white vertical quartz veins. The jagged surface of the stylolite, common in limestones but relatively rare in quartzites, indicates vertical shortening, consistent with the horizontal stretching that is indicated by the quartz veins. Scale bar is 1 cm. Photograph courtesy Alice Post.

b) Vein forming material is derived from an extraneous fluid that enters the fractures, where it is/becomes supersaturated with respect to the vein forming mineral(s). Fractures, of course, provide high conductivity pathways for channellised fluid flow. The presence of fractures thus allows fluid to flow over long distances and, in the process, become over- or undersaturated in its solute, primarily due to changes in pressure and temperature.

Minerals precipitating in a fluid filled fracture grow into an open fluid, even though there may only be a few microns of free space, before the other side of the fracture is encountered. The shape of the crystals is then determined by the growth competition of different minerals and the competition between crystals with different crystallographic orientations. The resulting texture in the vein depends on several factors (Urai *et al.* 1991):

- the morphology of the fracture surface (smooth, rough);

- the width of the fracture;

- the growth habit of the vein forming mineral(s).

The effects of the different factors are discussed and illustrated in more detail in Appendix B. Microscopic morphologies that result from crack-sealing are typically elongate blocky and stretched crystals. The first form when repeated fracturing occurs on the same fracture surface, while the second is the result of repeated fracturing along different surfaces.

3.2.4. Coupled fracturing and fluid flow

High fluid pressure, close to lithostatic, can only form in a low permeability regime which prevents rapid drainage of the overpressured fluid (Sibson *et al.* 1975, Nur & Walder 1992). Close-to-lithostatic fluid pressures therefore are generally found only at deeper levels in the crust, roughly below the brittle upper crust. As mentioned above, high fluid pressure can create high permeability through fracturing - especially when helped by deformation (Cosgrove 1993). The ensuing high permeability allows draining of fluid, which brings the fluid pressure down towards hydrostatic levels. Closure of dilatant fractures and sealing of fractures by precipitate reduces permeability and fluid pressures eventually rise again. This cyclical behaviour of rising fluid pressure until sudden fracturing, release of fluid ("burping") and reduction of fluid pressure is known as "fault valve behaviour" or "seismic pumping" (Sibson *et al.* 1975, Nur & Walder 1992, Thompson 1997, O'Hara & Haak 1992) (Fig. 28). It is generally used to explain extensive veining, such as the gold-bearing quartz veins in mesothermal gold deposits (e.g. Victorian and Yilgarn gold fields in Australia (Cox *et al.* 1986, Sibson & Scott 1998)).

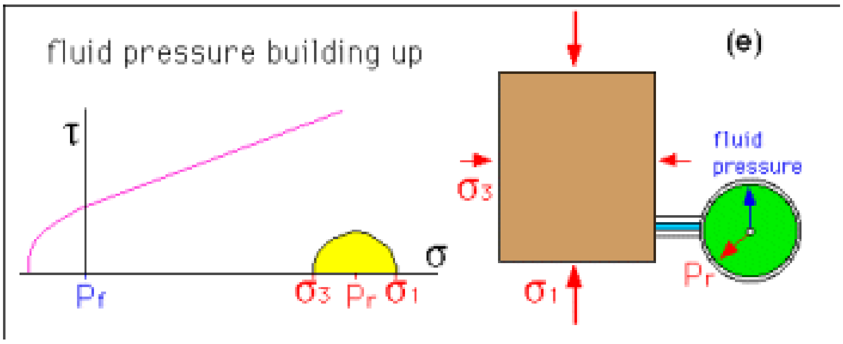
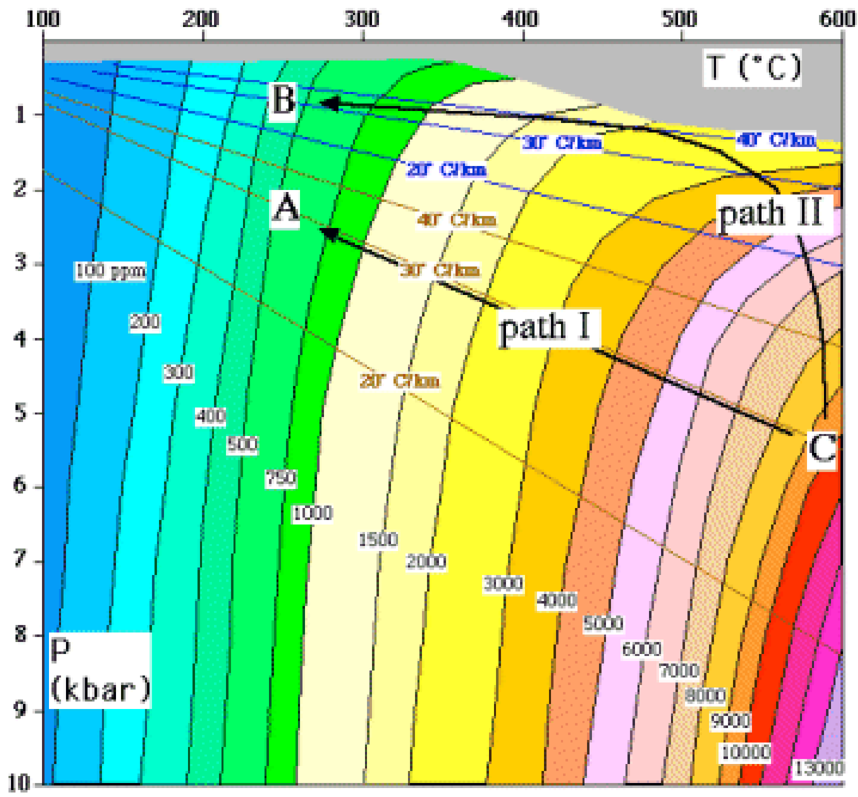


Figure 28. Movie illustrating the effect of an increase in fluid pressure (dial on right), which brings the Mohr-circle to the point of tensile failure. Drainage of the fluid through the newly created fracture, causes a decrease in fluid pressure again, bringing the situation back to the start of the cycle.

Changes in temperature (Eisenlohr *et al.* 1989) and pressure (Vrolijk 1987, Henderson & McCaig 1996) are the primary causes for precipitation of vein forming material from a fluid that is flowing through fractures. Chemical interaction with the wall rock and mixing of different fluids are other possible causes (Boullier *et al.* 1994), but as veins occur in almost any type of rock, these can not be the main reason for precipitation. As quartz is the main mineral in large fracture hosted vein sets, the discussion below focuses on the solubility of silica. Silica solubility is primarily dependent on temperature (Fig. 29), except at high temperature and low pressure, where the solubility becomes strongly pressure-dependent. The solubility of silica is about 500 ppm in pure water that is at a lithostatic pressure of about 200 Mpa at about 250°C (consistent with a depth between 5 and 10 km and a geothermal gradient in the order of 30°C/km, point A in Fig. 29). Dropping the fluid pressure to hydrostatic pressure (point B) reduces the solubility to about 400 ppm. The drop in pressure thus causes about 20% of dissolved quartz to precipitate and 10,000 kg of water is needed for every kg of vein quartz. The pressure sensitivity is even smaller at lower temperature. The large amount of fluid needed (fluid/rock ratio about 10,000 and at least 1000) is a problem. One source for the fluid can be metamorphic dewatering at deeper levels. Another possibility is recycling of water by pumping fluid in and out of the rock ("seismic pumping", Sibson *et al.* 1975) or convective flow, that allows the fluid multiple passes through the same veins (Etheridge *et al.* 1983; 1984).

Figure 29. Contours of silica solubility (in ppm) in pure water as a function of pressure (P in kbar) and temperature (T in °C). Solubility is strongly temperature dependent, with a strong pressure dependency only in the low P and high T domain. PT-lines are drawn for geothermal gradients of 20, 30 and 40°C for a lithostatic pressure-depth gradient (brown, $\rho=2.75\cdot10^3$ kg/m^3) and a hydrostatic pressure-depth gradient (blue, $\rho=1.0\cdot10_3$ kg/m^3). Contours are based on the equation for



silica solubility as a function of temperature and specific volume of pure water (Fournier & Potter 1982). Specific volume values are from tabulated data in Bowers (1995) (<2 kbar) or calculated with equations provided by Kerrick & Jacobs (1981) (>2 kbar). Reduction of fluid pressure (Pf) from lithostatic (point A) to hydrostatic (point B) leads to about 100 ppm (~20%) reduction in solubility at 250 °C and a geothermal gradient of 30 °C/km. Hot metamorphic fluid (point C) has a dramatically higher solubility (~10,000 ppm). Most silica would precipitate close to the source during slow ascent (path I) (Connolly 1997). Rapid mobile hydrofracture ascent (path II) would see silica precipitation much higher in the crust.

Metamorphic dewatering produces hot water at depth. Solubility of silica at source conditions of the fluid are high, in the order of >10,000 ppm (point C in Fig. 29). Cooling of the fluid as it flows upwards causes almost all of the dissolved quartz to precipitate at deep levels (Connolly 1997). One would thus expect most quartz veins to form just above the level of dewatering. However, extensive quartz veining is usually found at much shallower levels. It seems that metamorphic dewatering and normal advective (Darcian) upward flow of fluid cannot explain the formation of extensive vein sets at shallow levels: more than 90% of the dissolved quartz would have precipitated before reaching the veining level as flow is too slow to maintain any significant elevated fluid temperature.

Metamorphic dewatering can, however, produce extensive quartz veining at or just above the brittle-ductile transition, without significant quartz precipitation at deeper levels, if the fluid can rise fast enough not too cool (much) before reaching the brittle-ductile transition. Mobile hydrofracturing provides the mechanism for such a rapid rise (Appendix A). The rise of water filled fractures at rates in the order of metres per second allows the water to stay hot until arrest in brittle levels of the crust (Bons *in press b*). Upon arrest (point A & B in Fig. 29), the water then still contains several thousands ppm of silica, which is immediately dumped as the water cools to the much lower ambient temperature. As is explained in Appendix A, arrest occurs in the base of the brittle region, where the fluid can enter pre-existing fractures or where a low (hydrostatic) fluid pressure causes leakage of the fluid into the wall rock. In the latter case, one can expect significant wall rock alteration to occur.

Shear zones on small scales to crustal scales focus fluid flow, due to their enhanced permeability, either on the microscopic scale (dilatant grain boundaries or microfractures) or the macroscopic scale (fractures) (Connolly 1997, Thompson 1997). Many shear zones show evidence of enhanced fluid flow in the form of retrograde mineral reactions that involve hydration and/or the presence of veins (Rutter & Brodie 1985, Dipple & Ferry 1992, O'Hara & Haak 1992). Shear zones are also the preferred pathways for mobile hydrofractures, as they provide a relatively weak zone for hydrofracture propagation and, in case of crustal scale shear zones, provide a continuous pathway through the crust for ascending fluids. Many extensive vein systems are therefore associated with major fault and shear zone systems (Eisenlohr *et al.* 1989).

Veined fractures are usually regarded as the product of fluid flow. Hence, their study can provide insight in how fluid flows. This view should be reconsidered: veins that form from mobile hydrofracture arrest may tell us more about how fluid **failed** to flow. This philosophical point can perhaps best be explained with the analogy with granites: the shape and structures of granite bodies tell us most about the emplacement mechanism (stoping, ballooning, etc.) and much less about the mode of transport of granite melt (Clemens 1998).

Significant supersaturation, open fluid-filled fracture space and repeated fracturing are characteristic for both veins that form from extensive flow through fracture networks and by arrest of mobile hydrofractures. Elongate blocky textures and evidence for crack sealing can be expected. Significant supersaturation can cause ongoing nucleation of precipitating minerals, which produces a blocky texture.

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4 Conclusions

Veins can have a range of microscopic morphologies. Even a single vein can have different textures, such as polytextured blocky + fibrous veins (Fig. 14). There is not a clear one-to-one relationship between macroscopic and microscopic morphology. Fibrous crystals can be found in pressure fringes, lenticular veins and fracture-shaped veins. It is therefore not easy to make a simple link between morphology and conditions and processes of vein growth. Also, the processes that lead to vein formation are not sharply delineated. For instance, during seismic pumping, a single growing vein may experience periods of advective fluid flow between periods of dominantly diffusional nutrient transport. Such a variation in process can also occur in space: while at one spot fluid may flow through a fracture and deposit vein material, another fracture nearby may be dead-ended and not experiencing fluid flow, but only vein growth by diffusional nutrient transport. Despite this, an attempt can be made to correlate processes and vein morphology as much as possible (Fig. 30).

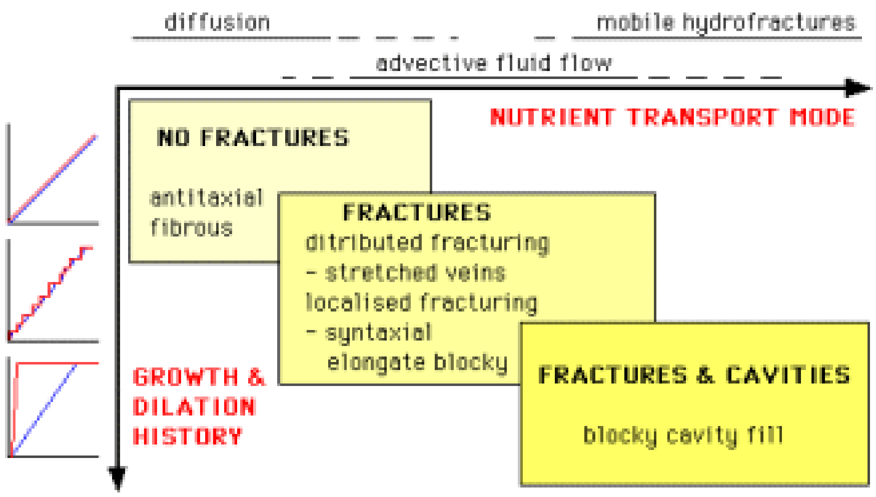

Figure 30. Schematic representation of the relationship of vein morphology, vein growth rate relative to dilation rate, and nutrient transport mode. Graphs on the vertical axis show the wall rock dilation (red line) and the width of the vein (blue line) as a function of time.

As was discussed in this paper, fibrous veins may form without fracturing. This implies that nutrient transport is either by diffusional or by pervasive porous flow transport. Considering that pressure fringes are usually fibrous and are in their shape controlled by the local stress distribution, diffusion is the most probable nutrient transport mechanism for pressure fringes and therefore for fibrous vein growth. In case of pyrite-type (antitaxial) pressure fringes, the site of lowest pressure is at the surface of the object, which is the growth plane. In case of crinoid-type pressure fringes and solid relatively rigid veins, the lowest pressure lies on the outside of the fringe or vein, which is indeed the growth plane (antitaxial veins). In fracture-less growth, the rate of vein growth is at all times exactly the same as the dilation rate, which is the rate at which the wall rock on either side of the vein moves apart.

An important class of veins is formed by those veins that formed by repeated crack-sealing. In that case, the dilation rate is spiky, with the vein growth rate passively following to fill any dilation. Elongate blocky textures form when the growth plane remains a plane of weakness (localised fracturing), possibly due to imperfect sealing. Such veins are in principle syntaxial. If fracturing occurs at different sites in a vein throughout the dilation history (distributed fracturing), and thus cuts through previously grown vein material, stretched veins form. Both elongate blocky and stretched crystals form in the absence of ongoing nucleation, which precludes large supersaturation in the vein forming fluid. The nutrient transport mechanism can be diffusion and/or advective flow.

An interesting question is whether crack-sealing and fractureless vein formation are end members of a continuous spectrum or distinct processes. Macroscopic fractures and grain boundaries are distinctly different, but microcracks and wide grain boundaries as described by Drury & Urai (1990) may provide the link between the two end members. This question remains open.

Sudden extensive dilation leads to the formation of large cavities. Such cavities can only form at depth by excessive fluid pressures, which can arise from seismic pumping / fault-valve like processes or by the arrival and arrest of batches of fluid from rising mobile hydrofractures. Large cavity-fill veins usually have a blocky texture, indicating large supersaturation. Extremely large supersaturations can occur in fluids that very rapidly rose through the crust in mobile hydrofractures. The veins that formed from such fluids indicate arrest and sudden chemical equilibration of these fluids, not their passage.

In recent years, much emphasis has been put on crack-sealing and advective fluid flow. Although these processes are undoubtedly very important for the formation of veins, other processes should not be neglected. Fibrous veins and pressure fringes that formed by fracture-less vein growth are important for strain analysis, while mobile hydrofractures provide a mechanism to rapidly transport vein forming minerals (particularly quartz) and, more importantly, ore minerals such as gold, up through the crust.

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Acknowledgments

Without wanting to insult anyone else, I would like to say that Win Means has probably been the most inspiring scientist for me. His help and encouragement for my research are gratefully acknowledged. My study of veins would not have led anywhere without the guidance and many discussions with Mark Jessell and Janos Urai. Nick Oliver is thanked for introducing me to many of localities with fascinating veins and he, Alvar Soesoo, Marlina Elburg, Chris Janka, Michelle Robinson and others are thanked for their company and help in the field. Lynn Evans is thanked for her help with the numerical modelling with BASIL. Margaret, Doug, Griselda and the late Reg Sprigg are thanked for their hospitality and access to rocks at Arkaroola, as are Maurice and Jane Phillips for Poolamacca. Anne-Marie Boullier and Janos Urai are thanked for their careful review of the manuscript. Research was initially funded through an ARC Postdoctoral Fellowship and was subsequently funded by Monash University, through a Logan Research fellowship. Finally I would like to thank Mark Jessell and Janos Urai for giving me the honour to publish in this *CD-amicorum*.

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Appendix A. Darcian flow and mobile Hydrofractures

The basics of Darcian or advective flow through a permeable medium are described in Darcy's equation for one-dimensional flow:

$$Q = - A \cdot K \cdot \Delta\phi/\Delta x \qquad \text{(A.1)}$$

This equation states that the flow rate, Q ($m^3\ s^{-1}$), along a line in the x-direction, is linearly proportional to the cross-sectional area, A (m^2), through which the fluid flows, the hydraulic conductivity, K ($m\ s^{-1}$), and the gradient in hydraulic head, $\Delta\phi/\Delta x$ (m/m). A more general three-dimensional form of Darcy's equation is:

$$q = - K \cdot \delta\phi/\delta x \qquad \text{(A.2)}$$

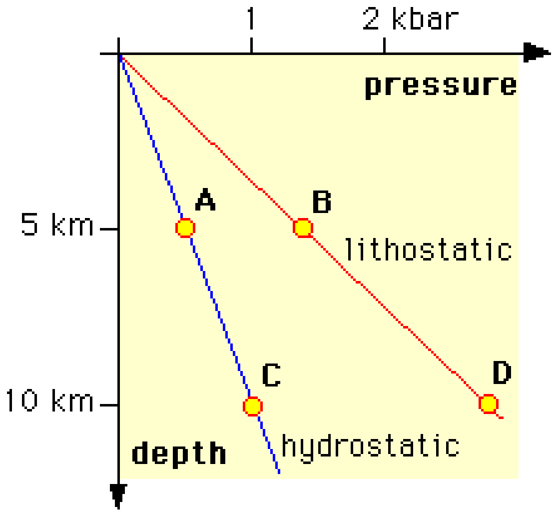
where the vector q ($m\ s^{-1}$) is the rate of flow, per cross-sectional unit area, in the direction x.

Hydraulic head is often confused with pressure when it is stated that "fluid flows from high to low pressure". Obviously, it is not so simple as water does not flow from the bottom of a glass (highest P) to the surface (lowest P). The hydraulic head (unit is metre) is given by:

$$\phi = P / \rho g + z \qquad \text{(A.3)}$$

The first part of the equation is the pressure head, determined by the pressure, P (Pa), the fluid density, ρ ($kg\ m^{-3}$), and the gravitational acceleration constant, g ($m\ s^{-2}$). The second term, z (m), is the elevation head, which is simply the elevation above some datum level. If the pressure is simply the hydrostatic pressure, then the hydraulic head is the same at any level. If fluid pressure increase with depth is equal to the lithostatic pressure gradient (say $2.75 \cdot 10^4$ Pa/m), then the hydraulic head gradient is 1.75 and fluid would flow upwards (Fig. A1).

Figure A1. Graph showing lithostatic (red line) and hydrostatic (blue line) pressure-depth gradients in pressure-depth space, assuming specific densities of $2.7 \cdot 10^3$ kg/m^3 for rock and $1.0 \cdot 10^3$ kg/m^3 for water and a gravitational acceleration constant of 10



HYDRAULIC HEAD (ϕ):

$\phi_{(A)} = 5\cdot10^7 / 10^3\cdot10 - 5000 = 0$ m

$\phi_{(B)} = 10\cdot10^7 / 10^3\cdot10 - 10000 = 0$ m

hydrostatic: $\Delta\phi/\Delta z = 0 / 5000 = 0$

$\phi_{(C)} = 13.75\cdot10^7 / 10^3\cdot10 - 5000 = 8750$ m

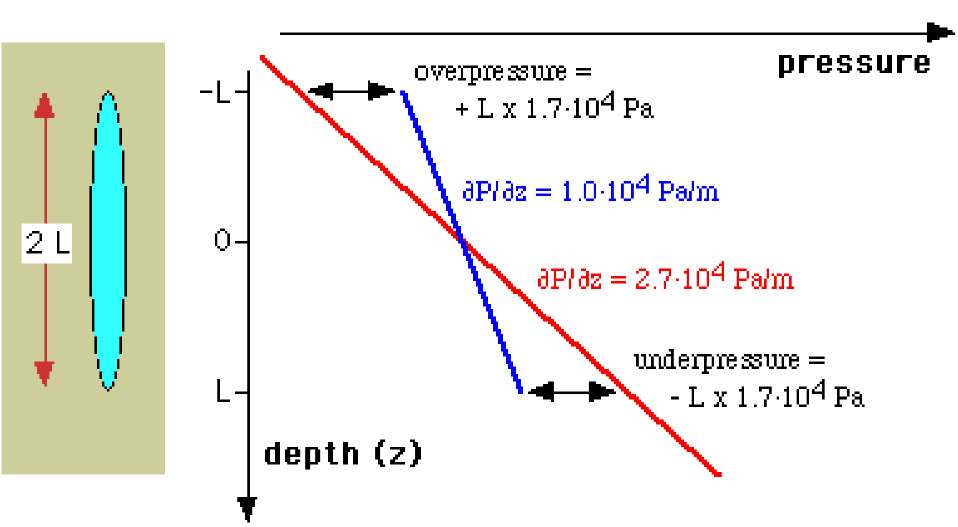
$\phi_{(D)} = 27.5\cdot10^7 / 10^3\cdot10 - 10000 = 1750$ m

lithostatic: $\Delta\phi/\Delta z = -8750 / 5000 = -1.75$

m/s^2. Hydraulic heads are calculated for points A to D, showing that the hydraulic head gradient is 0 (no flow) for the hydrostatic pressure gradient and -1.75 for the lithostatic case, which results in upwards fluid flow.

The hydraulic conductivity inside an open fluid reservoir is infinite and hence the hydraulic head inside a water-filled fracture is the same at any level in that fracture. As a consequence, the pressure inside such a fracture increases by about 10^4 Pa/m with depth. Suppose now that we have a vertical fracture of length 2L that is filled with water (ρ~$1\cdot10^3$ kg/m^3) in a surrounding rock with a density of $2.7\cdot10^3$ kg/m^3 (Fig. A2). It is clear that the vertical pressure gradient inside the fracture ($1.0\cdot10^4$ Pa/m) is different from the pressure gradient in the adjacent rock ($2.7\cdot10^4$ Pa/m). Suppose now that the pressures balance halfway the fracture, which level we take as a reference (z=0 m). At the upper tip of the fracture, the fluid pressure exceeds the rock pressure by L · $1.7\cdot10^4$ Pa. The fluid is underpressured with respect to the rock pressure by the same amount at the bottom end of the fracture. This puts a limit on the length of an open fluid-filled fracture. Above some critical length, the overpressure at the upper end of the fracture causes the rock to further split open, while the underpressure causes the fracture to be closed at the bottom end. If the fluid volume is to remain constant, opening and closure must occur in tandem and when this happens **the fracture moves upwards together with its fluid**.

Figure A2. Pressure state inside a vertical fluid filled fracture, shown in a pressure-depth graph. The density difference between fluid ($1.0\cdot10^3$ kg/m^3) and rock ($2.7\cdot10^3$ kg/m^3) causes overpressure at the upper end of the fracture and underpressure at the lower end. Over- and underpressure are proportional to the length (2L) of the fracture.



Secor & Pollard (1975) provided a simple equation to estimate the onset mobility of a vertical fracture:

$$L_{max} = 1.36 \cdot (K_c/S)^{2/3} \tag{A.4}$$

L_{max} is the maximum length of a stable fracture, K_c is the fracture toughness and S is the effective normal stress gradient ($S = \delta\rho / \delta z$, ~ 0.015 MPa/m). The fracture toughness is about 1-3 $\mathrm{Mpa} \cdot \mathrm{m}^{1/2}$ for intact crystalline rocks (granite, gneiss; Secor & Pollard 1975), but is probably lower for schists and low grade rocks, especially for fracturing parallel to schistosity. One should note that S is given here for a vertical fracture. The value of S is smaller for an inclined fracture, but can be significantly higher when a fracture is subject to a tectonic stress gradient, in which case S can possibly reach values of 0.1-1 MPa/m.

Figure A3 shows that vertical water filled fractures can reach lengths of about 5-100 m. Above that length, such fractures become unstable and rise rapidly, in the order of metres per second. A mobile fracture can thus easily ascend through the crust in a matter of hours. A mobile hydrofracture stops when the conditions of equation (A.4) are no longer satisfied. This can be because of rock type with a higher fracture toughness is encountered or when S decreases. The latter is probably the main reason for arrest. At any time it is easier for a fluid to enter pre-existing fractures than to propagate a fracture through intact rock. The presence of fractures thus causes the dispersal of fluid into these fractures, lowering S. For a hydrofracture to be mobile, the average pressure in the fluid must be lithostatic. Fluid is lost to the wall rock when a fracture reaches lower than lithostatic fluid pressures in the wall rock. Low fluid pressures and pre-existing fractures occur above the brittle-ductile transition and hence mobile hydrofractures are to be expected to get arrested at this level.

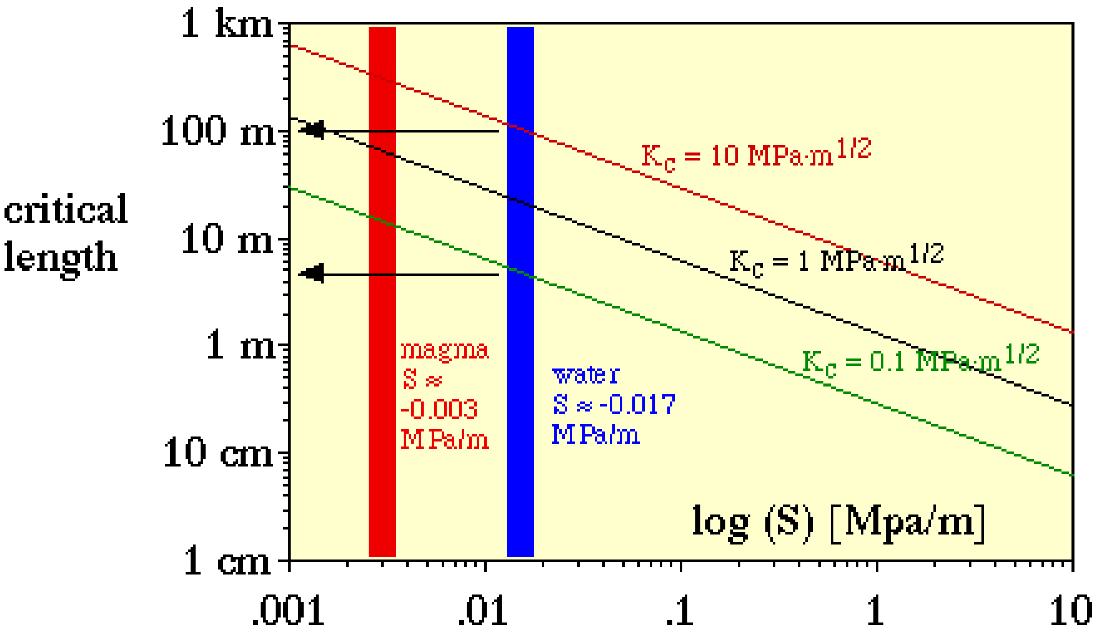


Figure A3. Graph of critical vertical length as a function of effective normal stress gradient (S) (after Secor & Pollard 1975). For fracture toughnesses between 0.1 and 10 Mpa·m$^{1/2}$, water-filled fractures are unstable due to their buoyancy above 5 to 100 m length. For comparison, granite magma-filled fractures become unstable when longer than 20 to 300 m. Tectonic stress gradients can give rise to much higher S-values

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Appendix B. Crack-Seal microstructures

The shape and orientation of elongate blocky and fibrous veins can provide information about the opening trajectory of a vein. The opening trajectory is the movement path taken by two particles that originally were adjacent to each other on either side of the vein. Elongate and, in particular, fibrous crystals can be curved and often seem to follow the opening trajectory (Durney & Ramsay 1973). However, crystals can become curved due to deformation (Williams & Urai 1987) or may not follow the opening trajectory in the first place (Urai *et al.* 1991). Urai *et al.* (1991) developed a model to explain the not always perfect "tracking capability" of vein crystals that form during repeated crack-sealing. Each time a fracture forms, the crystal tips start growing outward into the fracture space. The direction of growth is generally perpendicular to the local fracture surface. If the fracture is rough or wavy, this growth direction may not be parallel the opening trajectory. The result is that grain boundaries have a tendency to converge on protrusions and ridges on the fracture surface (Fig. B1). If the ridges are distinct and sharp, they may lock a grain boundary and this boundary will subsequently follow the ridge and hence the opening trajectory. If the fracture is smooth, grain boundaries do not get locked or to a lesser extent, and grain boundaries then do not or only partially follow the opening trajectory.

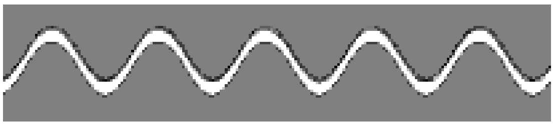

Figure B1. Movie of grains growing by repeated crack-sealing. Growth is isotropic as envisaged in the model of Urai *et al.* (1991). Grains grow outward from the surface and thus converge on each other in embayments between ridges. Eventually, only grain boundaries are left that are growing vertically towards a ridge on the opposite side of the crack.

To further investigate the model of Urai *et al.* (1991), a computer program was written to simulate the crack-seal process. The model is only briefly described here, and the reader is referred to the full description of the model and a first systematic investigation with the model that are given by Bons (*in press a*) and Hilgers *et al.* (*in press*). In the 2-dimensional model, grains are defined by nodes that are linked by straight boundary segments. An initial horizontal surface fracture is created with a user-defined roughness. Every N time steps, the lower fracture surface is moved a user-defined distance and direction to simulate a crack-opening event. All grain surfaces that are then exposed to the open fracture grow outward by repeatedly moving the boundary segments over small distances one at a time. The segments are moved until they reach the other side of the fracture space (Fig. B2). The rate of growth is a function of the angle (α) between the boundary segment and the c-axis of a grain, which defines the lattice orientation. The type of function defines the growth habit of the crystal and therefore different "minerals" can be defined. In the examples below, two "minerals" were used:

- "Square mineral". The growth rate is fastest in the directions parallel and perpendicular to the c-axis. The habit of this mineral is that of a square.
- "Prismatic mineral". Growth is fastest parallel to the c-axis and slowest normal to it. A secondary growth rate minimum occurs at 30° to the c-axis, which gives the mineral a

quartz-like prismatic habit.

Figure B2. Movie of crack-seal vein growth to illustrate the working of the program VEINGROWTH. Each crack-event, the lower wall rock is moved, in this case down and to the right. Exposed surface segments of grains grow into the crack. Their growth rate is determined by the relative orientation of the surface segment and the c-axis of the grain and the growth habit of the "mineral", in this case the prismatic "mineral". The orientation of the c-axes is shown by the shading: darkest for horizontal and white for vertical c-axes. The crystallographic control on growth rate leads to the development of faceted grain surfaces. However, if the crack is too thin, such facets may never fully develop before the crack is sealed again. In this example faceting is just forming before sealing.

Growth in an open cavity

Growth in an open cavity best illustrates the effect of different mineral types on the morphology of the vein fill. Figure B3.a shows the result of 800 growth steps of the prismatic mineral into a wide open fracture with a rough surface. The shading of the grains is a function of the c-axis orientation. One can see that the grains with a vertical c-axis (light) quickly outgrow differently oriented grains. Figure B3.b shows the same for 640 growth steps for the square mineral. Both grains with vertical (light) as well as with horizontal (dark) c-axes are now the "winner" grains.

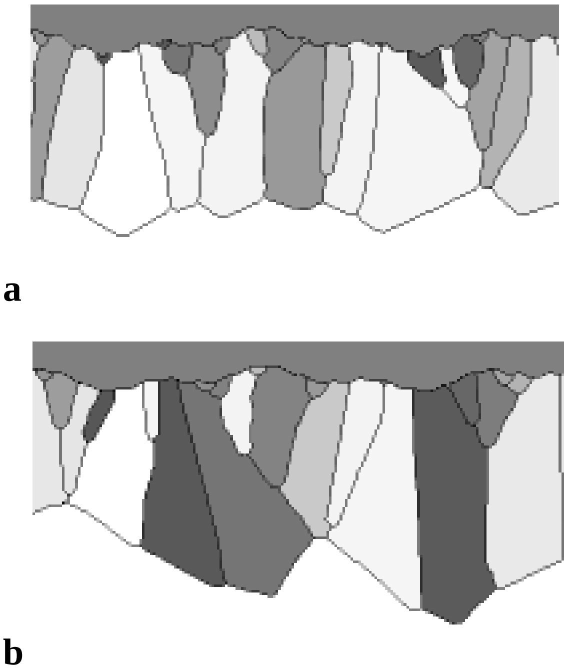

Figure B3. Movies of simulated vein growth into an open cavity. **(a)** Prismatic "mineral", growing for 800 time steps. Grains are elongate blocky in shape (no nucleation, except at beginning on wall rock) with faceted surfaces with the cavity. Growth is fastest in the direction of the c-axis and minerals with vertical c-axes (light) outgrow other grains (dark). **(b)** The same for the square "mineral". Growth is fastest parallel and normal to the c-axes and both grains with horizontal and vertical c-axes outgrow others.

Crack-sealing with a vertical opening trajectory - effect of crack-width

Three movies (Fig. B4) show the effect of the crack width. Figure B4.a shows growth in many (154), but small (2 pixels) vertical fracture opening events. Grain boundaries quickly get locked on ridges, resulting in little reduction in average grain width as growth progresses. The spacing of the ridges determines the width of grains. If, keeping all other parameters the same, the fracture opening is doubled to four pixels per event (Fig. B4.b), we see a decrease in locking capability of the ridges and a slightly larger average grain width developing. Increasing the fracture width to 16 pixels (Fig. B4.c) results in almost complete loss of locking capability of ridges. These simulations confirm the model of Urai *et al.* (1991), that the locking capability of ridges is a function of the width of the fracture relative to the roughness of the fracture. The rougher a fracture and/or the thinner the fracture, the better is the locking capability and hence the tracking capability of the vein crystals. The spacing between ridges determines the average crystal width when locking is strong.

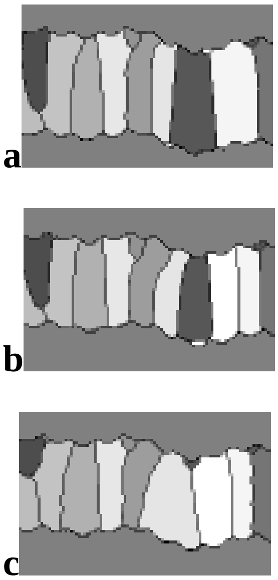

Figure B4. Movies showing the effect of fracture width on the vein texture for the prismatic "mineral". All parameters are kept the same, except the vertical opening distance, which is **(a)** 2 pixels, **(b)** 4 pixels and **(c)** 16 pixels. See text for discussion.

Crack-sealing with an oblique opening trajectory - effect of crack roughness

Figure B5 shows three movies of growth with an oblique ($\Delta x=-2$ & $\Delta y=4$) opening direction, while all other parameters are kept the same except the roughness amplitude. The fracture surface is too smooth in Fig. B5.a for any ridges to lock grain boundaries. The average grain width increases in the growth direction and there is no tracking whatsoever of the oblique opening direction. Doubling the amplitude of the roughness (Fig. B5.b) leads to locking of some boundaries, but not all. Therefore, some boundaries follow the oblique opening trajectory, while others grow vertically. The result is a specific microstructure with some strongly elongate grains, some large blade like crystals and many "looser" grains (see Fig. 1.c in Bons & Jessell 1997). A further increase in surface roughness (Fig. B5.c) produces a better locking capability of the ridges and hence better tracking of the opening trajectory.

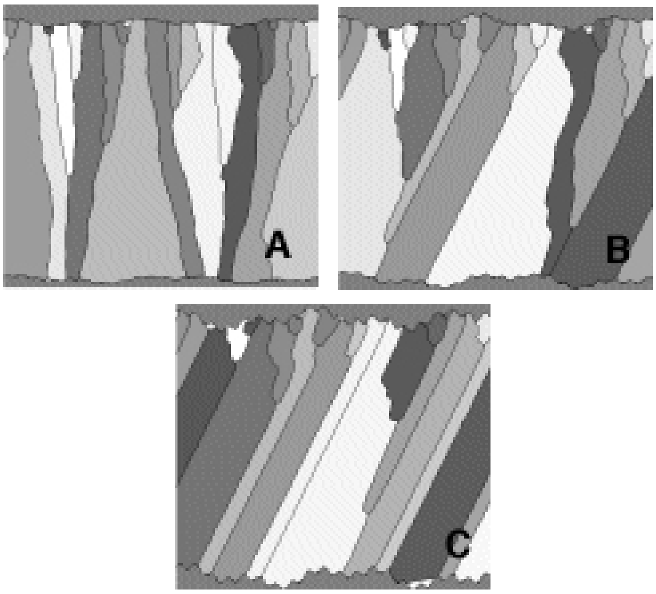

Figure B5. Movies showing the effect of fracture roughness on the vein texture for the prismatic "mineral". Opening direction is 2 pixels to the left and 4 pixels down. All parameters are kept the same, except the fracture roughness, which varies from **(a)** smooth, **(b)** medium rough and **(c)** rough. See text for discussion.

Crack-sealing - change of opening direction

Finally, a case of growth with an abrupt change of opening direction is shown in Fig. B6. The case shown is for isotropic growth with a rough fracture surface, resulting in perfect tracking of the opening trajectory in the first growth period. After an abrupt change in opening direction, perfect tracking is maintained, but several fibres get truncated soon after the change in direction. Such a sudden increase in average fibre width is often seen associated with a change in opening direction (Fig. 14.b). The change in opening direction causes a change in the points where grain boundaries are locked. Temporary unlocking during the transition period frees the grain boundary for lateral movement and possibly the truncation of the grain.

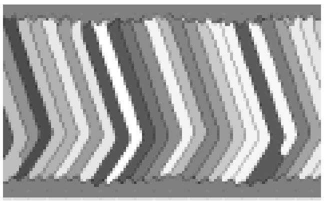

Figure B6. Movie showing the effect of a change in opening direction for an isotropically growing vein material. Opening direction is 2 pixels to the right and 4 pixels down first and then 2 pixels to the left and 4 pixels down. See text for discussion.

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