

Experimental simulation of the formation of fibrous veins by localised dissolution-precipitation creep

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Abstract

Fibrous veins are generally interpreted in terms of the crack-seal mechanism. Several aspects of fibrous veins (fibrous structure, curved fibres, symmetry of antitaxial veins) are however better explained by vein formation without fracturing. Mass transfer to such veins would be by diffusional transport rather than by fluid flow through the veins. Deformation by dissolution-precipitation creep can provide the driving force for the necessary mass transfer. Veins form when mass transfer is heterogeneous and precipitation is localised.

Experiments were performed which enforced a chemical potential gradient, acting as the driving force for diffusional mass transfer. These experiments resulted in fibrous growths in aggregates of soluble salts (NaCl and KCl) saturated with brine. The experimental results support the theory that fibrous veins may form without fracturing and that rather than providing evidence for major fluid pathways, fibrous veins may instead represent localised precipitation during diffusional material transfer.

KEYWORDS: fibrous veins, dissolution-precipitation creep, mass transfer, deformation.

Introduction

VEINS are ubiquitous in upper and mid crustal rocks, but are also found at deeper levels. They provide a valuable source of information about the geological history of their host rocks (e.g. Ramsay and Huber, 1983). The shape, orientation and composition of veins may provide information on, for instance, stress state, pressure and fluid composition. Many veins have delicate internal structures that may record details of the whole history of vein formation. Furthermore, the scale of veins (cm to dm) often results in their preservation during ongoing or subsequent deformation and metamorphism, unlike many of the smaller grain-scale structures that are generally continuously reset by recrystallisation.

The correct interpretation of veins relies on a correct understanding of their formation. In this paper we discuss the formation of *fibrous* veins, which we define as those veins where the vein-filling is composed of extremely elongate parallel mineral grains (Fig. 1a and b). The length to width ratio of fibres can be more than 100:1. The fibre shape of grains is unrelated to the crystallographic orientation

and the mineral forming the fibres must not normally grow in a fibrous habit other than in veins. There is no or little increase in mean fibre width in the growth direction.

Elongate-blocky veins (after Fisher and Brantley, 1992) form another class of veins (Fig. 1c). In such veins the grains are elongate, but with moderate length/width ratios, usually less than ten. There is a distinct increase in mean grain width in the growth direction. Trails of fluid inclusions and wall-rock fragments can often be found parallel to the vein wall. Such trails often occur at regular intervals of a few to several tens of μm , suggesting incremental growth.

Both types of veins are generally referred to as being fibrous veins. They are however texturally sufficiently different to warrant the classification into two types. Moreover, the two types may form by distinctly different mechanisms. In accordance with Fisher and Brantley (1992) we therefore use the term fibrous in the strict sense and advocate the distinction in terminology.

The most generally accepted explanation for the formation of fibrous and elongate-blocky veins is the

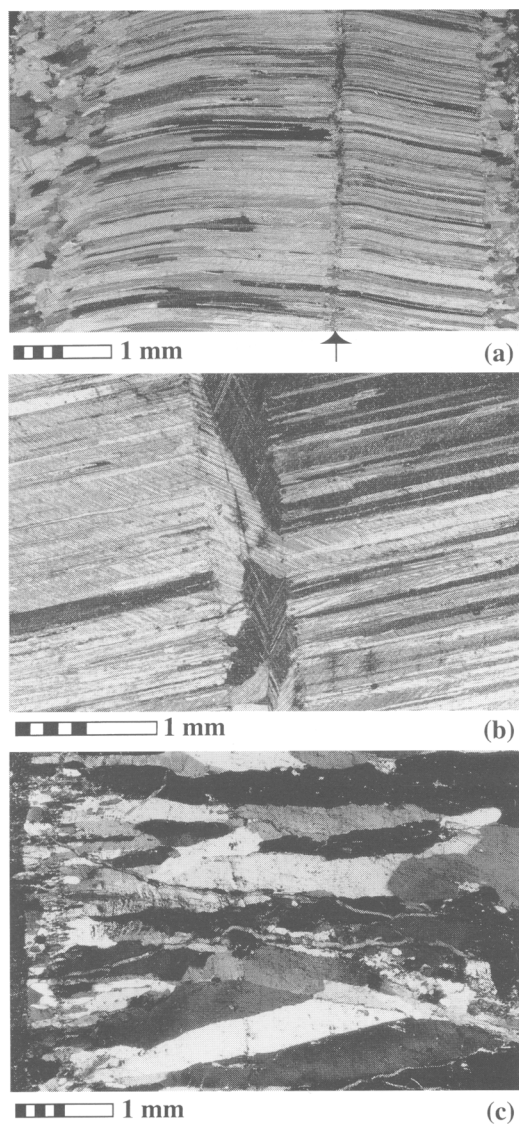


FIG. 1. (a) Fibrous antitaxial calcite vein from Lower Adelaidean shales, Opaminda Creek, Northern Flinders Ranges, Australia. The median plane, where growth initiated is clearly visible (arrow). The fibre width is constant with growth. (b) Central part of a fibrous antitaxial calcite vein from the same location as (a). Vein growth started with blocky calcite precipitation in a crack and was followed by growth in a fibrous texture. (c) Elongate-blocky quartz vein from the Otago Schists, Taieri Mouth, south of Dunedin, New Zealand (thin section courtesy of Dave Gray). Growth started at the left edge of the vein. Grain width increases in the growth direction. Wall rock inclusion trails indicate growth in small increments. All photo micrographs were taken with cross-polarised light.

crack-seal theory originally proposed by Ramsay (1980), by which the veins form by incremental opening or cracking events. After each such opening event, the narrow crack is filled with precipitate derived from either a percolating fluid or by diffusional transport. Earlier it was argued by Durney and Ramsay (1973) that fibrous textures are characteristic of growth without fracturing and that material transfer to a vein is by diffusional mass transfer related to pressure solution creep. More recently, Fisher and Brantley (1992) reiterated Durney and Ramsay's arguments for the formation of fibrous veins without fracturing. They did show evidence for crack-seal vein growth, but only for elongate-blocky veins.

It follows that there are essentially two opposing theories for the formation of fibrous veins: one includes fracturing as an essential step (Ramsay, 1980) and the other proposes that fibre growth takes place at an unfractured surface (Durney and Ramsay, 1973; Fisher and Brantley, 1992). Below, we briefly discuss five aspects of fibrous veins and their formation in the light of the two opposing theories. As the crack-seal theory is the most widely accepted, we begin each discussion with the assumption that fibre growth takes place in a narrow open crack, and then consider the alternative hypothesis.

1. What is the actual driving force for precipitation in the open crack? This question can be subdivided into (i) how and why are vein-forming components transported to the crack? and (ii) why do they precipitate inside the crack? There are two end-member transport mechanisms: passive mass transfer with a moving fluid and diffusional mass transfer through a stagnant fluid. Complete filling of a crack by a fluid flowing through the crack is problematic, since it requires a large volume of fluid to percolate towards and through the crack compared with the volume of precipitate required to fill it. If the pathways for this fluid are themselves cracks, the question immediately arises why precipitation occurs only in some and not all of these cracks? Furthermore, precipitation reduces the permeability of the system, thus inhibiting complete filling of the crack. Diffusional mass transfer does not require relatively large volumes of fluid to percolate through the system. One must, however, find a driving force for the diffusion towards and precipitation in the growing vein. This point will be further discussed in the next section.

2. Why are fibrous veins fibrous? According to the crack-seal theory, the fibres grow into a narrow, but open, fluid-filled crack. Crystals growing into an open fluid usually exhibit an anisotropy in growth rate with some crystal faces growing faster than others. For fibrous growth to occur, growth must be isotropic, i.e. independent of lattice orientation. It has

been suggested by Urai *et al.* (1991) that isotropic growth could be due to a rough crystal surface, which could be the case after each cracking event. However, a rough surface tends to become smooth with growth. The transition from rough (isotropic growth) to smooth (face-controlled growth) probably takes place within a few (tens of) nm of growth, whereas crack widths are at least in the order of μm to tens of μm (Fisher and Brantley, 1992; Gratier, 1993). On the other hand, if growth is at uncracked grain boundaries and growth is therefore not in a free fluid, fibrous growth could be expected because growth is largely determined by the stress state and to a lesser extent by crystallographic orientation of grains (Durney and Ramsay, 1973).

3. The microscopic process that determines the direction of growth of fibres is still uncertain. Fibres often track the opening trajectory, but not always (Cox and Etheridge, 1983; Cox, 1987; Williams and Urai, 1987). When fibres do track the opening trajectory, the question arises: "How do fibres know which way the opposite side of the crack has moved?" So far the most appealing theory (but no evidence?) has been put forward by Urai *et al.* (1991) who argue that the ratio between the aperture of the crack and the wavelength of the roughness of the crack surface determines the tracking capability of the fibres. In vein formation without fracturing, the actual growth path is the same as the opening trajectory (Durney and Ramsay, 1973).

4. Fibrous veins are often antitaxial with outward growth occurring at the two surfaces of the vein. These antitaxial veins generally show a striking symmetry. It is enigmatic how repeated cracking can occur with such a symmetry at either side of the vein. In vein formation without fracturing, growth is expected to be symmetric on either the median plane of a vein or at its surface, as again pointed out by Durney and Ramsay (1973). Indeed, the elongate-blocky crack-seal veins described by Fisher and Brantley (1992) are asymmetric in most cases.

5. The Mohr-Coulomb type (tensile) failure implied by the crack-seal mechanism necessitates a fluid pressure of the same order as the mean stress which is applied to the rock (Hubbert and Rubey, 1959; Engelder, 1993). Measurements of fluid pressure in fluid inclusions in fibrous veins show that fluid pressures can actually be much lower than the mean stress (Meere, 1995). Proposed explanations for the apparently too low fluid pressure range from leaky inclusions (O'Hara and Haak, 1992) to stress and fluid pressure heterogeneities (Meere, 1995). A lower fluid pressure in fluid inclusions could also be the result of a fluid-pressure drop after failure. However, if vein growth takes place without fracturing, the concept of Mohr-Coulomb type failure cannot be applied to constrain fluid pressure. It is

then possible that vein growth occurs at a variety of fluid pressures relative to the mean stress.

The authors are not aware of any published successful attempts to experimentally simulate the formation of fibrous veins by the crack-seal mechanism. Attempts have been made (Post and Urai, unpubl. data), but both their and our own experiments were mainly thwarted by problems number 1 and 3: material precipitates in the pathways towards the artificial 'crack' and thus blocks further fluid flow. This in turn inhibits the complete sealing of the crack. Any growth that did take place in the crack was in an open fluid filled space and was therefore euhedral.

The theoretical considerations listed above and the lack of experimental support for the crack-seal mechanism to produce fibrous veins led us to consider the alternative theory of fibrous vein growth without fracturing and to set out to experimentally simulate such vein growth. Before proceeding to describe the experimental technique and results, we first discuss the conditions under which vein growth could take place without fracturing.

Diffusional mass transfer and the formation of veins

Dissolution-precipitation creep is an important deformation mechanism in the upper crust and possibly also at deeper levels (see e.g. review by Gratier, 1993). It involves dissolution of material at certain sites and precipitation of that material elsewhere. The principal means of transport of material from one site to another is by diffusional mass transfer of dissolved matter in a pore or grain boundary fluid. Diffusional mass transfer is driven by concentration gradients, which in turn arise from chemical potential variations. Let us therefore consider chemical potentials and concentration gradients in a wetted granular aggregate of a soluble solid under an applied stress field. The chemical potential (μ_{eq}) of the dissolved solid in the grain boundary fluid is approximately proportional to the normal stress (σ_n) acting on the grain boundary (when grain boundary curvature effects are neglected) (Durney, 1976; Rutter, 1976; Lehner, 1990; Spiers *et al.*, 1990). Grain boundaries oriented normal to the maximum compressive stress (σ_1) have the highest chemical potential (μ^+) and those normal to σ_3 have the lowest chemical potential (μ^-). Dissolution and precipitation work towards local equilibration between concentration and chemical potential, whereas diffusion works towards equalisation of concentrations. The kinetics of the three processes (dissolution, diffusion and precipitation) determine the actual concentration distribution along

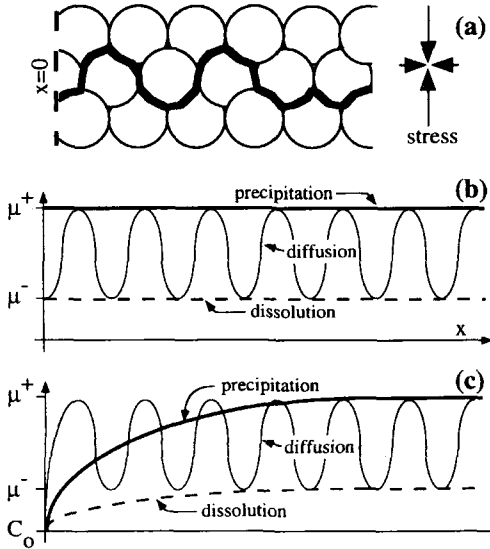


FIG. 2. (a) pathway (bold line) through a schematic grain boundary network along relative high and low normal stress sites, where the solubility is respectively high (μ^+) and low (μ^-). (b) Concentration profiles along this path (taken as x -axis) for dissolution (dashed line), precipitation (bold line) and diffusion (thin line) as the rate controlling step. (c) Concentration profiles along the same path for the case that the concentration at $x = 0$ is kept at C_0 (a lower value than μ^-), again for diffusion, dissolution and precipitation as the rate-controlling step.

the grain boundaries. A potential pathway for mass transport through the grain boundary network passes through relative compressive and relative extensional sites (Fig. 2a). The concentration profile along such a path (straightened and taken as the x -axis) is shown in Fig. 2b for the cases that dissolution, precipitation and diffusion are rate controlling. If diffusion is rate controlling, the concentration at any point along the path is approximately equal to the local solubility. However, concentrations are approximately constant along the path if dissolution or precipitation are rate controlling.

Heterogeneities in chemical potential may and most probably do occur in rocks. Such heterogeneities affect the local concentration (Fig. 2c). A heterogeneity in the chemical potential does not have an influence at a distance exceeding half the grain diameter, if diffusion is rate controlling. However, the influence of a heterogeneity can reach much further away if dissolution or precipitation are rate controlling. Possible heterogeneities in chemical potential that may lead to localisation can be variations in fluid content, grain size, composi-

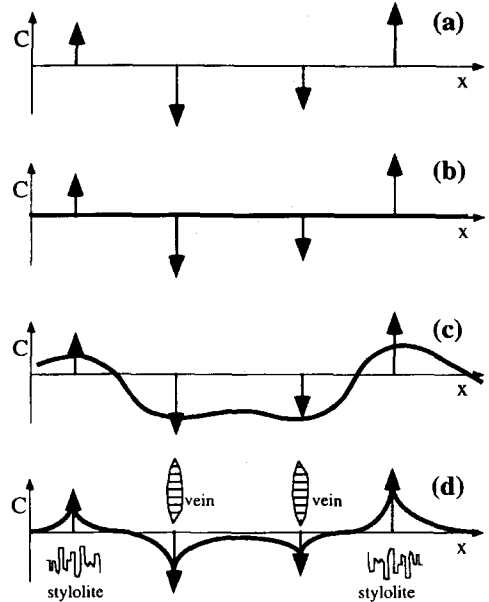


FIG. 3. Schematic one dimensional concentration profiles through a granular aggregate. (a) Arrows indicate local perturbations from the mean equilibrium concentration. The resulting concentration profile can be: constant (b), smoothly varying (c), which result in enrichment and depletion zones, or peaked (d), resulting in localised dissolution (stylolites) and precipitation (veins). This is a 1-dimensional example and in 3-dimensions positive and negative perturbation are most likely to occur in different orientations.

tion, (micro) cracks and even pre-existing veins themselves (Fig. 3a). No localised dissolution or precipitation occurs when the actual concentration at any point is unaffected by these heterogeneities (Fig. 3b). Net enrichment and depletion zones develop if the variations in concentration remain smoothly varying (Fig. 3c). Distinct veins and stylolites develop if these heterogeneities develop into sharp or peaked variations in concentration of dissolved solid (Fig. 3d).

Experiments

Experiments were designed to simulate the heterogeneous dissolution and precipitation system described in the previous section. The aim was to impose a concentration gradient on a wet granular aggregate of soluble material and to study the ensuing mass transfer and resulting microstructures. The formation of fibrous vein-like structures would

support the theory of Durney and Ramsay (1973) that fibrous veins may grow without fracturing.

To complete experiments in practical time-spans and with simple equipment, two analogies were employed. The first was to use very soluble salts with high precipitation and dissolution rates at low temperatures. Such salts are NaCl (halite) and KCl (sylvite). The second analogy was to use temperature rather than stress to enforce a chemical potential gradient. As the solubility of salts is temperature dependent, one can impose a chemical potential gradient on a sample by applying a temperature gradient. This is much more convenient and can be achieved with a much simpler apparatus than that required if stress was used. If a granular aggregate is under stress, normal stresses at grain boundaries and hence equilibrium concentrations of the dissolved salt vary along grain boundaries. If there is a significant porosity, this may have an altogether different equilibrium concentration. Reducing the porosity in artificial samples is difficult and a low porosity and hence low permeability reduces the rate of material transport and thus slows down experiments. The variability of equilibrium concentration around grains and in fluid pockets means that mass transport only occurs over large distances when diffusion is relatively fast compared with precipitation and dissolution (Fig. 2). In an unstressed sample however, the equilibrium concentration at any site in any region with a particular temperature is the same, whether at grain contacts or in fluid pockets. Under an imposed temperature gradient mass transfer always occurs, irrespective of whether dissolution, diffusion or precipitation is rate controlling. The presence of a significant porosity only influences the rate at which mass transfer takes place. Another advantage of using temperature rather than stress is that the resulting microstructure is not affected or changed by possible deformation.

Samples were made of mortar-ground powder (unsorted, grain size $< 100 \mu\text{m}$) of salt. Two samples were made for each salt: one with pure ground salt and one where the salt was mixed with about 5–10% ground shale of equivalent grain size. The powder was then poured into a test-tube (10 mm diameter, 150 mm long) filled with an approximately saturated solution of the same salt (at $\approx 70^\circ\text{C}$). The saturated solution was heated for some time prior to adding the powder, to release dissolved air and to ensure saturation. Care was taken to minimise trapping air bubbles in the powder-solution mixture during preparation and most trapped bubbles were removed by putting the samples in a vacuum chamber. The wet sample was subsequently compacted with a rod and then sealed with a rubber cap. The test-tubes were then partly (45 mm) submerged in a hot-water bath kept at 72°C and left

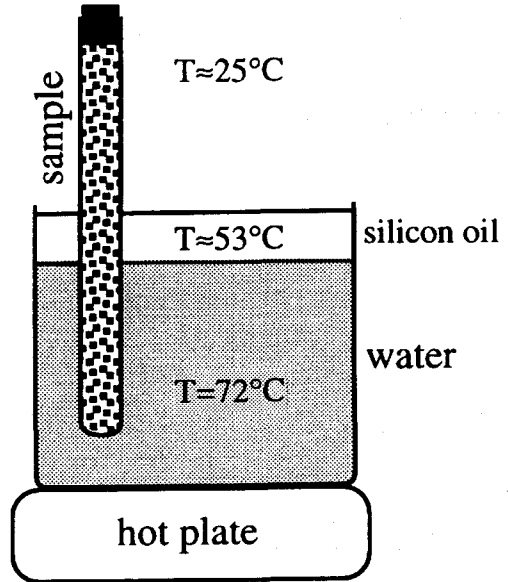


FIG. 4. Experimental set-up. A test-tube filled with compacted fine-grained salt and a saturated solution of the salt is partly submerged in a hot-water bath kept at a constant temperature (72°C). A 1 cm thick layer of silicon oil floating on top of the water is added to avoid evaporation and thus keep the hot fluid level constant.

to stand for several weeks (Fig. 4). The water level in the hot-water bath was kept as constant as possible by reducing evaporation with a floating layer (about 10 mm thick) of silicon oil and replenishing lost water every 2–3 days.

The temperature was 72°C at the bottom of the column. Temperature then rapidly decreased upwards from the hot-water level to reach approximately 30°C at the top of the column (Fig. 5a and b). Consequently, there was a concentration gradient of dissolved salt in the column, leading to diffusional mass transfer through the pore-fluid and the development of under- and over-saturated regions in the sample (Fig. 5c–e). The general mass flux through the fluid was upwards. Solid was lost (net dissolution) at the bottom just below the hot fluid level and was gained (net precipitation) further up in the column (Fig. 5f). Initially this took the form of an increase in porosity where there was net dissolution and a decrease in porosity where there was net precipitation. In the upper part of the column this porosity reduction was accompanied by a volume increase. As the column was capped at the top, this volume increase resulted in a downward movement of the solid grain aggregate in the lower part of the

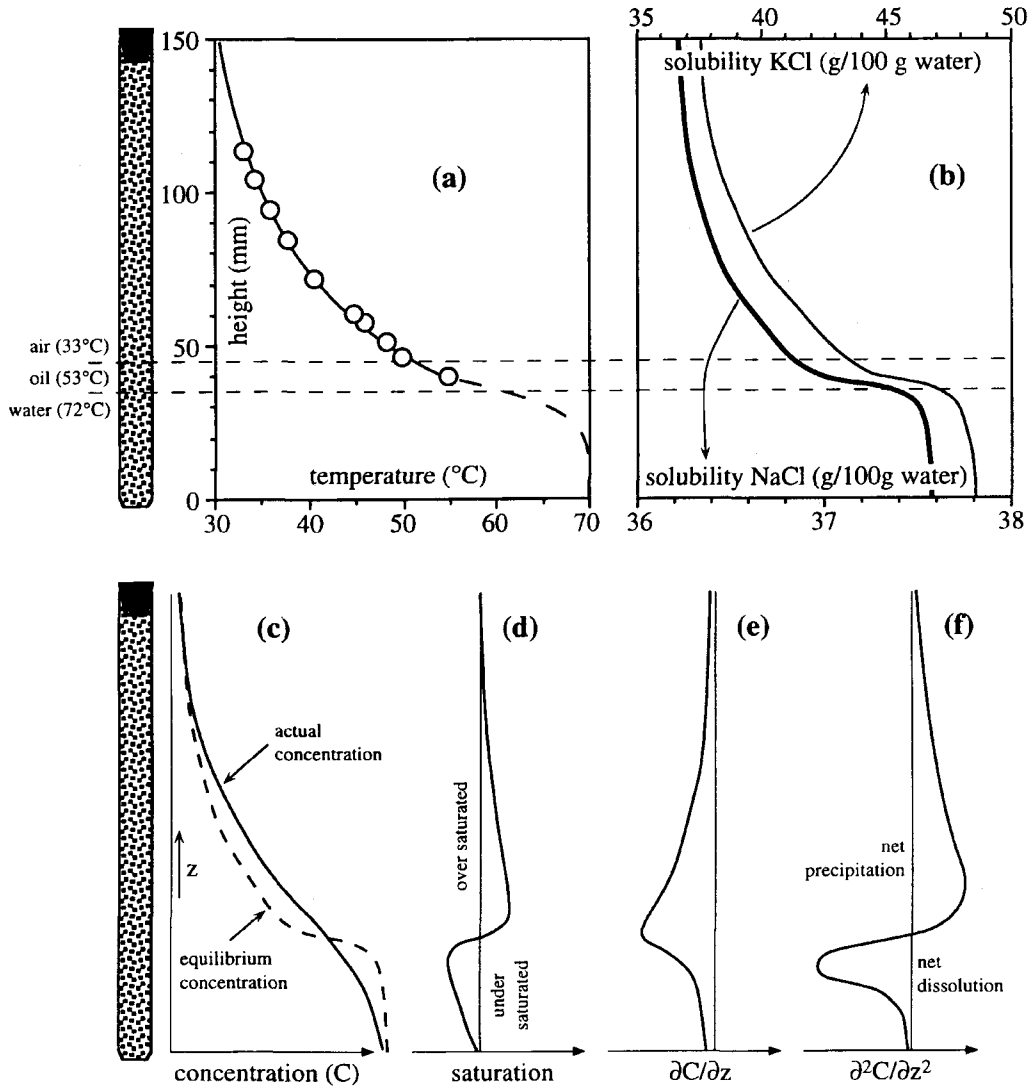


FIG. 5. (a) Graph of the temperature profile along the sample column. The temperature was measured with a K-type thermocouple probe inserted into a dummy sample of sand with water. The probe was too short to measure the temperature at the bottom of the column, which is therefore estimated. (b) The inferred solubility profile for NaCl (bold line) and KCl (thin line) along the sample column. Solubilities were calculated from data listed in Elvers *et al.* (1991). (c) Schematic drawing of the solubility profile compared with the actual concentration (C) profile, with the difference being due to diffusional transport. (d) Saturation profile (actual concentration minus equilibrium concentration) showing the under-saturated zone at the bottom of the sample and over-saturation in the upper part. (e) Profile of the first derivative of the concentration against z, where z is the height along the column. (f) Profile of the second derivative against z of the concentration. The negative second derivative in the lower part signifies net dissolution or material loss and the positive value in the upper part signifies net precipitation or material gain. The sketched profiles are schematic and idealised. In reality, the processes are affected by temperature dependent rates of dissolution, precipitation and diffusion, and developing variations in porosity and permeability in the aggregate along the sample.

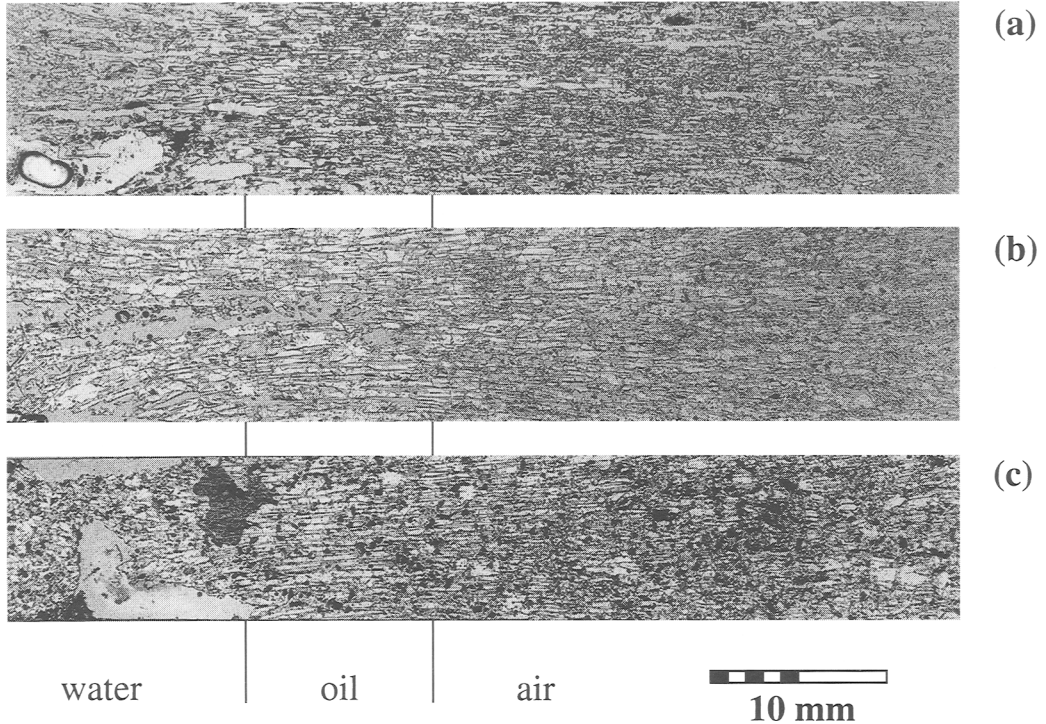


FIG. 6. Photo micrographs of samples in transmitted light. Thin sections ($100\ \mu\text{m}$ thick) were cut parallel to the long axis of the sample. Lines indicate the surface level of the oil layer (right) and the water layer (left); temperature decreased towards the right. Sample material is (a) pure KCl (after 34 days), (b) pure NaCl (after 21 days) and (c) NaCl mixed with ground shale, showing up as dark specks and grains (after 31 days). All samples show a distinct fibrous texture, most strongly developed at the oil layer level. The addition of inert particles in sample (c) shows that enrichment is pervasive over the zone above the hot fluids. It increases in intensity downwards where the sample is relatively depleted in ground shale. At the left of this sample, non-fibrous material can be seen, which resembles the starting material. This material has remained below the maximum depletion zone where voids have formed. Plane polarised light. Sections are 60 mm long.

column. In samples of salt mixed with shale, the effect of a local volume decrease or increase is a relative enrichment or a relative depletion of the shale respectively.

Figures 6 and 7 show micrographs of samples in which a fibrous texture has developed. The samples show the expected mass transfer and texture development. Net dissolution at the bottom of the column has led to the formation of voids in two of the three samples. A fibrous texture is most strongly developed at about the level of the oil layer and decreases upwards. Variation in concentration of insoluble shale shows that net enrichment of NaCl coincides with the strongest fibrous growth. Fibres are slightly curved (Fig. 7a), which is probably due to curved temperature gradients in the sample.

Mechanisms for fibre growth in the experiments

Our experiments produced fibrous textures without brittle failure or fluid flow. Several mechanisms may have produced the fibrous texture. The first mechanism is local net precipitation (Fig. 8a), if the addition is by syntaxial growth on existing grains and growth only occurs on grain surfaces normal to the temperature gradient. The addition of material then causes a stretching of the aggregate in one direction. The amount of stretching is related to the length of the fibres. Shale-free zones with fibrous crystals shown in Fig. 7b suggest that this mechanism of fibre growth may have operated as zones where salt is added will be free of shale particles. However, this mechanism alone cannot account for the extreme elongation which was observed in the samples.

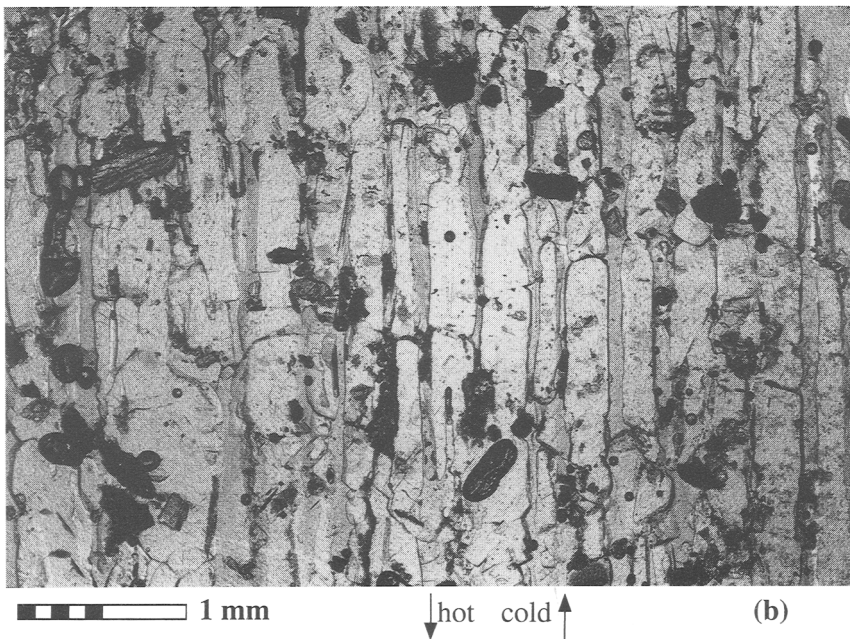
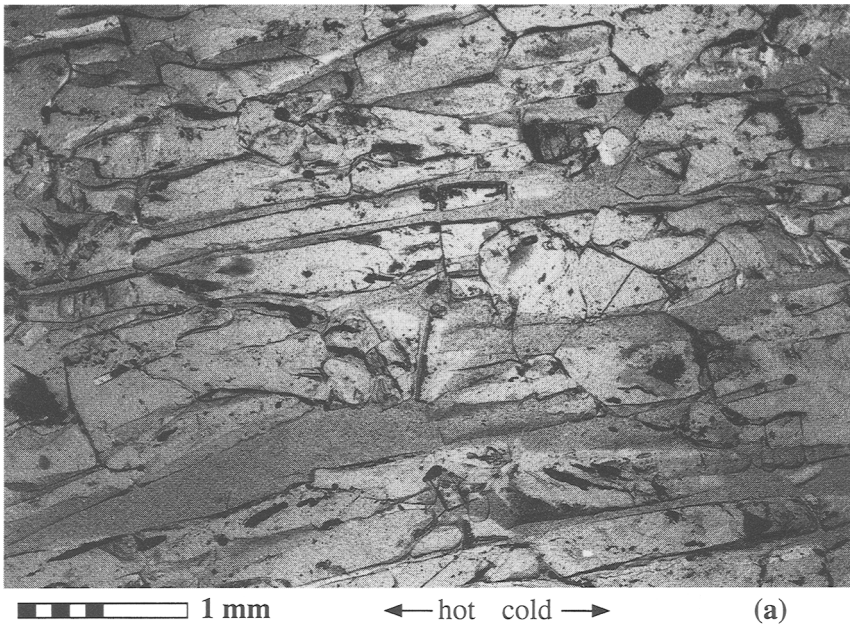


FIG. 7. Details of the micrographs shown in Fig. 6. (a) Pure NaCl just below the oil-layer. The fibrous habit of the crystals is clearly visible, as is the relatively large porosity. The fibres are slightly curved, which is probably due to curved temperature and hence concentration contours in the sample. Temperature decreases towards the right. (b) NaCl mixed with ground shale at the middle of the oil layer. The distribution of shale particles is variable, suggesting heterogeneous enrichment in NaCl in this zone (see also Fig. 8a). Temperature decreases upwards. Width of view is 5 mm for both micrographs. Plane polarised light.

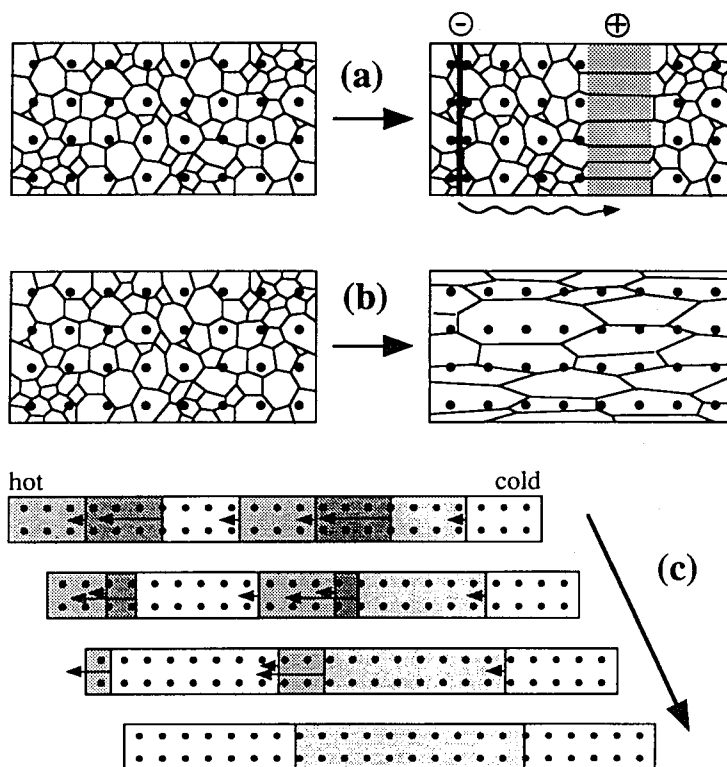


FIG. 8. Sketches showing three possible mechanisms for the formation of a fibrous texture. All three may operate simultaneously in the experiments presented in this paper. (a) Fibre-growth by localised net precipitation. Black dots represent passive inert markers. These markers are concentrated at zones of net dissolution (-), where stylolites may form (thick line) and diluted where mobile (soluble) material is precipitated (+): the grey area with elongate (fibrous) grains. (b) Anisotropic grain growth resulting in elongate grains. This process only involves grain boundary migration and passive inert markers are not displaced. (c) Formation of elongate grains by unidirectional grain boundary migration with variable migration rates (arrows). 'Overtaking' of grain boundaries results in the disappearance of some grains. This process does not involve material transport and passive inert markers are again not displaced.

A second possible mechanism is anisotropic grain growth (Fig. 8b). The average width of the fibres is about 250 μm , whereas the original grain size was less than 100 μm . Anisotropic grain growth may be responsible for a stronger increase in grain size parallel to the long axis of the sample than normal to it. Strong anisotropic recrystallisation, resulting in a fibrous texture, has also been observed in experimentally stretched calcite (Rutter 1995, pers. comm.). We do not know the underlying process for this second possible mechanism for the formation of a fibrous texture or whether it occurred.

A third possibility is that the presence of the concentration gradient caused mass transfer from one grain to another along the gradient as in the

temperature-gradient-driven movement of fluid inclusions (Carter and Hansen, 1983, and refs. therein). If this transfer is variable from grain to grain, due to variations in the gradient or differences in crystallographic orientation, then grain boundaries may catch-up with others. This would lead to grain length increase in the direction of the temperature gradient (Fig. 8c). Whether this third possible mechanism for the formation of a fibrous texture did occur, or to what extent, also remains unknown.

The internal geometry of natural fibrous veins clearly indicates that there only the first mechanism operated. In our experiments, the precipitation was not localised in a plane as in natural veins, but was spread out over a few cm in the test tube. This makes

it difficult to ascertain the amount of material addition to this zone and to which extent this led to the formation of fibrous veins. It probably also led to the operation of the other processes which are not relevant to natural veins, such as anisotropic grain growth and temperature-gradient-driven grain boundary migration.

Discussion

The experiments produced mass transfer leading to local depletion and enrichment in the soluble phase and the development of a fibrous texture in the enrichment zones. The experiments were performed without fracturing or healing events. These results support the theory that fibrous veins may form without fracturing (Durney and Ramsay, 1973; Fisher and Brantley, 1992) and not necessarily by incremental fracture opening and sealing events as envisaged by the crack-seal theory (Ramsay, 1980). Our results are corroborated by Means and Li (1995) and Li and Means (1995) who experimentally produced fibrous growth in ammonium thiocyanate without fracturing.

Although cracks may not be necessary to form fibrous veins, they can of course play a role in the growth of fibrous veins. They can for instance initiate vein growth. Antitaxial veins sometimes start growing on a thin vein with blocky filling (Fig 1b). This suggests that the formation of the vein started with a fluid-filled crack in which the vein forming mineral was precipitated. The presence of this 'vein seed' could then have resulted in localised precipitation which caused subsequent vein growth with a fibrous texture, without further cracking.

The treatment of rocks deforming by dissolution-precipitation creep as self-organising (Ortoleva *et al.*, 1987) provides a framework to explain why and when precipitation and/or dissolution localise to produce veins and/or stylolites. It has been shown above that the rate of diffusional mass transfer, relative to dissolution and precipitation rates, is of prime importance. More work remains to be done on investigating the effect of existing and developing heterogeneities in rocks on the distribution of diffusional mass transfer. For instance, variations in mineralogical composition or grain size, as in layered rocks, must give rise to variations in stress (Treagus, 1983, 1988) and hence variations in equilibrium concentration of soluble minerals. Under conditions of relatively high diffusional mass transfer rates, this can lead to structures such as bedding-parallel veins. Alternatively, initially homogeneous materials may develop heterogeneities, which in turn may strengthen heterogeneous mass transfer. The positive coupling in such a process could lead to regular material segregation, such as found in cleavages and

metamorphic layering (Robin, 1979). The spacing and intensity of such structures are a function of the degree of coupling between developing structures, and resulting mass transfer, and the relative rates of diffusion, dissolution and precipitation.

The fact that fibrous veins may have formed without fracturing has two important implications for the interpretation of fibrous veins:

Fibrous veins are often oriented normal to the least principal stress. If these veins were formed by brittle failure, these veins would be tensional failure cracks (tension gashes). One can, in general, only produce such failure at a high lithostatic stress when the fluid pressure is also high. The Mohr-Coulomb failure criteria for tensional failure constrain the maximum differential stress at such elevated fluid pressures to a few times the tensional strength of the rock. The interpretation of veins as sites of tensional failure thus leads to important and far reaching conclusions on the stress state and fluid pressure during their formation. However, Mohr-Coulomb failure criteria cannot be used if brittle failure was absent. In such cases, the stress state and fluid pressure are less constrained. It follows from the above that care should be taken with the genetic term 'tension gashes'. It should only be used for veins for which it can be proven that tensional failure did occur.

Another consequence of the interpretation of veins as fractures is that veins constitute preferred pathways for fluid flow during their formation. The possibility that fibrous veins formed without fracturing implies that veins are not necessary such pathways. In fact, veins could in some cases even be barriers to fluid flow, if they are less permeable than the surrounding rock. One should note that open cracks do not necessarily constitute pathways for fluid flow. This is only the case if the cracks form a connected network. Non-connected open cracks can fill by diffusional mass transport as has been shown by Fisher and Brantley (1992). It is noteworthy that Fisher and Brantley (1992) proved a crack-seal mechanism of formation (with about 8 μm opening increments) for these veins, which are elongate blocky veins and not fibrous veins.

Conclusions

It is proposed that heterogeneous mass transfer and localised precipitation in a rock undergoing dissolution-precipitation creep can provide the mechanism for material transport to produce veins without fracturing. The rate of diffusional material transport, relative to dissolution and precipitation rates, is a prime factor in determining whether this mass transfer is heterogeneous or not.

Experiments were performed to test whether fibrous veins could form by diffusional mass transfer

without fracturing. A temperature gradient was imposed on samples of wet granular soluble salts to create a concentration gradient and hence diffusional mass transfer. The experiments resulted in material redistribution and strong fibrous growth in the salts in zones of net precipitation. The experiments thus support the theory that fibrous veins may form without fracturing. Fibrous veins may represent sites of localised precipitation (sinks) rather than sites of brittle failure and preferred pathways for fluid flow.

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