PERGAMON

Journal of Structural Geology 23 (2001) 857–863

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.nl/locate/jstrugeo

A laboratory simulation of fibrous veins: some first observations

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Received 22 January 1999; accepted 23 November 1999

Abstract

Following work by Stephen Taber 80 years ago, we describe vein-like arrays of parallel, fibrous crystals that grow evaporatively between pairs of brine-soaked, porous ceramic substrates. Crystals of solute grow antitaxially from fixed sites on the substrate, forcing older parts of the crystals away from the growth site, without benefit of any long-range cracking parallel to the substrate. The nutrients for growth are fed to the growth site advectively or diffusively through the substrate blocks themselves, not along the plane of the vein. We call such crystallization Taber growth and suggest, as Taber did, that it might be an important mechanism for non-evaporative fibrous vein development in nature. The Taber growth model provides a ready explanation for the ability of fibers to track vein opening directions, and tracking is indeed the rule in our samples, though exceptions are also seen. Our results lend support to ideas already in the literature that fibrous veins are not necessarily products of a crack-seal process and that fibrous veins are not necessarily syntectonic. Our observations also raise questions about criteria for recognition of syntaxial fibrous veins and underscore the importance of finding new criteria for recognition of the younging direction along fibers.

1. Introduction

Structural geology leapt forward when it was recognized that fibrous crystals in veins can record displacement histories during vein opening (Wickham and Elliott, 1970; Durney and Ramsay, 1973; Wickham, 1973; Ramsay and Huber, 1983). Though new to structural geologists in the 1970s, most of the essentials of this idea had been suggested decades earlier by Stephen Taber (e.g. Taber, 1917), a mineralogist at the University of South Carolina. The essentials are: (1) that the fibers in such veins grow *during* vein opening, (2) that the fibers extend as they grow in the direction of current vein opening, and (3) that earlier-formed fiber segments maintain their growth orientations relative to the vein walls during subsequent vein widening, thus locking-in a record of successive vein opening directions. Taber wrote about fibrous crysotile veins in particular (Taber, 1916a, 1917), but he was also aware of fibrous gypsum and calcite veins (Taber, 1918). He believed the material for fiber growth in such veins reached the growth-site by what he called 'lateral secretion' (Taber, 1918, p. 64), delivery *through* the vein walls, rather than along the plane of the vein.

Taber's ideas were based partly on laboratory experiments in which he grew fibrous crystals of water soluble salts from porous porcelain substrates, by evaporation of salt solutions in pore spaces in the substrates (Taber, 1916b, p. 546). Most of Taber's products were fibrous encrustations on free surfaces of the porcelain, but in a few experiments he also noticed vein-like structures where fibers grew from both sides of a crack in the porcelain, forcing the crack open as they grew (Taber, 1916a, p. 660).

In this paper we describe some new Taber-type experiments. They can be done by anyone with a minimum of equipment and may shed light on several questions concerning fibrous veins and pressure shadows in nature, for example: (1) Are fibrous veins necessarily syntectonic? (2) Is a cyclical cracking and crack-filling process necessarily involved in forming fibrous veins (e.g. the crack-seal process of Ramsay, 1980)? (3) Do the fiber axes in fibrous veins necessarily parallel or 'track' successive vein opening directions? (4) Can fibrous veins form by growth of the fibers *either* at the vein center *or* at the vein walls, as proposed by Durney and Ramsay (1973)?

It is a pleasure to have this contribution included in a volume honoring Paul Williams. Paul has, as much as anyone we know, exemplified and encouraged constructive skepticism in structural studies, and promoted the use of scale-inclusive field work to study the evolution of structure in rocks.

2. Experimental procedure

In our first runs we followed Taber, growing fibrous

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PII: S0191-8141(00)00158-9

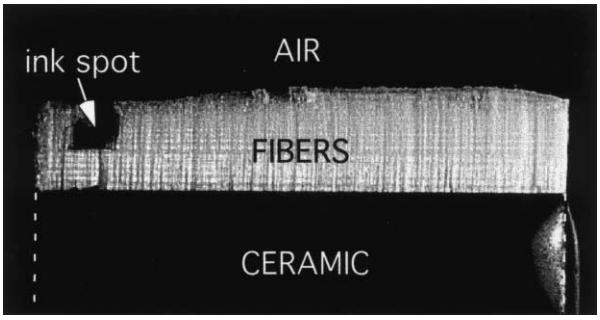

Fig. 1. Sample TB-6b showing fibers of ammonium thiocyanate (vertical) grown over a period of 88 h from a single block of porous ceramic. Width of ceramic block (between dashed lines) is 12 mm. Growth took place at room temperature in a dessicator at a relative humidity ≈ 10%. Horizontal stratigraphy results from fluctuations in growth conditions, for example humidity changes when the sample was removed from the dessicator for photography. An ink spot was placed *across* the fibers/ceramic interface after the first 49 h of growth, then rifted away from the ceramic by (anti-taxial) growth of younger fiber segments at the fiber/ceramic interface.

crystals from free surfaces of single blocks of a fine-grained porous ceramic (Fig. 1). Our main ceramic has been a material known as 'P-C-3', with a nominal pore size of 1.5–2.2 μm, available from the Coors Ceramic Company of Golden, Colorado. The blocks were coated on all but one side (the intended growth surface) with wax or epoxy cement, and then filled with a saturated aqueous solution of ammonium thiocyanate (NH_4SCN) or sodium nitrate ($NaNO_3$). We filled some blocks with brine by vacuum impregnation but got no better fibers this way than when we filled the blocks by simple immersion in brine at atmospheric pressure, or by adding brine, drop by drop, to the uncoated surface until no more brine would soak in. For the samples illustrated here we blackened the surfaces of the ceramic that would face the camera, to set off the veins and make them look more like the common veins in dark pelites. Unknown to us until we finished the experiments described here, Zehnder and Arnold (1989) performed very similar single-block experiments, in a study of the salt efflorescence that damages wall paintings.

A large variety of porous materials and fluids can be used to grow fibers. Taber grew fibers of alum and copper sulphate from porous porcelain (Taber, 1916a, p. 660). Janos Urai (pers. comm., 1998) has grown sodium chloride fibers from an unglazed flower pot and other porous ceramics. Zehnder and Arnold (1989) grew fibers of many salts, including sodium nitrate and potassium chloride, from mortar and ceramic substrates. In addition, many will be familiar with the morphologically similar growth of ice fibers (needle ice) from moist soils (e.g. Washburn, 1980, p. 91). The advantage of ammonium thiocyanate over the other salts we have used is that it is exceedingly soluble in water (about 180 g/100 g of water at room temperature, Broul et al., 1981, p. 81). This allows growth of longer fibers from a block of a given depth, without refilling the block. A general requirement of the fluid is that it soaks into the

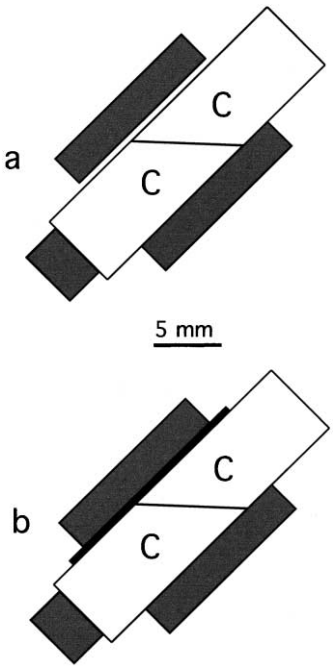

Fig. 2. Arrangement of ceramic blocks (C) and guide blocks (shaded) to impose change in vein opening direction over time. Guide blocks were cemented to base-plate (not shown). (a) Arrangement for vein-normal opening followed by vein-oblique opening. As fibers grow into the vein site (horizontal line between ceramic blocks), the upper ceramic block is pushed vertically (on the page) until it hits the upper guide. Thereafter it moves parallel to the guide and oblique to the vein. (b) Arrangement for vein-oblique motion followed by vein-normal motion. The gap between the ceramic blocks and the upper guide is now filled with a removable plate (black, thickness exaggerated). When this is removed, the vein opening direction changes from vein-oblique to vein-normal.

ceramic readily. A concentrated sugar solution, for example, would not wet our ceramic. The general requirement of the ceramic is that it has a pore size of the order of 10 μm or less. With pore sizes bigger than this, we get granular growth instead of fibers.

Fibrous growth of ammonium thiocyanate from our ceramic occurs by evaporation at ambient conditions, so long as the relative humidity is less than about 40–50%. We have usually accelerated growth either by keeping the samples in a reduced humidity chamber (a dessicator) or by placing them on a slightly warm surface. A typical controlled humidity was about 30%, maintained by a container of saturated $CaCl_2$ solution in the chamber. A typical warm surface was a hot plate set to 45°C. Fibers of ammonium thiocyanate grew to lengths of a millimeter or two in a few days to a week. Fibers of sodium nitrate grew about half this fast. The growth rate slowed toward the end of all experiments, as the blocks dried out. Photography was done in reflected light with a 35 mm camera or with a video camera mounted on a low power microscope.

To simulate veins, we set two brine-bearing ceramic blocks with their growth surfaces face-to-face. As fibers grew out of the opposed 'wall rock' blocks, the blocks were pushed apart by the growth process itself, by the

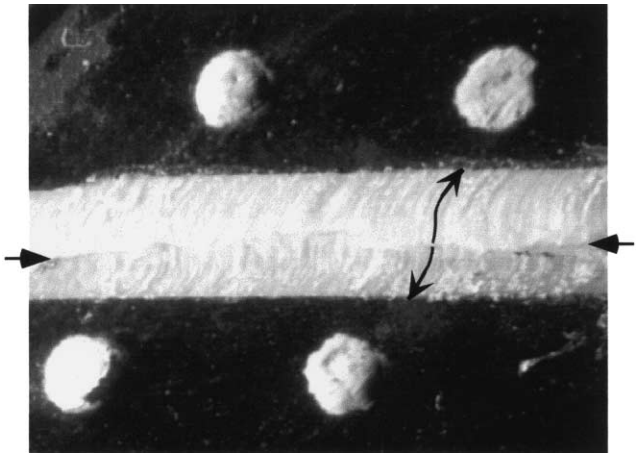

Fig. 3. Videomicrograph of sample TF-52 showing curved fibers of ammonium thiocyanate grown at about 45°C over a period of 49 h. Vein width on the right is 1.5 mm. White spots above and below the vein are paint spots, parts of which served as displacement markers. Arrows left and right indicate the position of a medial plane that wanders irregularly along the vein. Curved arrows indicate displacement trajectories of hangingwall and footwall blocks relative to the earliest formed fiber segments in the middle of the vein, as explained in the text and Fig. 4. Note approximate parallelism of trajectories with fibers, indicating fairly good tracking.

force of crystallization (see references in Durney and Ramsay, 1973, p. 73; Watts, 1978; Maliva and Siever, 1988). In some experiments, we allowed initial vein opening to be vein-normal, then constrained later opening to be vein-oblique, using the system of guide blocks shown in Fig. 2(a). In other experiments we constrained early opening to be vein-oblique and allowed later opening to be vein-normal using the slightly different system of guide blocks shown in Fig. 2(b). The plane of Fig. 2 was horizontal in the experiments of both kinds.

3. Taber growth

In all experiments we observed what Taber had observed, namely that the growth site is at the interface between the ceramic and previously-grown fibers (e.g. Taber, 1916b, p. 254). Moreover, growth of a given fiber occurs persistently at *one position* on the surface of the ceramic. There has been no slip at the fiber/ceramic interface in our experiments to date. These fibers grow as lawn grass grows from soil or hair grows from skin. The fibers are 'antitaxial' in the vein terminology of Durney and Ramsay (1973). Even in single-block experiments, a macroscopically cohesive boundary is maintained at the fiber–ceramic interface during the growth process. The force of crystallization does work against the cohesion at the growth site but does not produce long-range cracks there (cracks extending for many times the width of individual fibers). There are often wall-parallel, more opaque layers or narrow horizons extending across many fiber widths (see Figs. 1 and 5b), the Type I discontinuities of Means and Li (1995), but these were never long-range cracks. They are layers caused somehow by fluctuations in the growth conditions. So, the kind of long-range cracking brought to mind by Ramsay's (1980) crack-seal model or by what might be called the 'crack-seal dislocation model' of Fisher and Brantley (fig. 11 in Fisher and Brantley, 1992) is not present in our experiments so far. To distinguish this kind of *forceful growth of fibers at a macroscopically cohesive boundary between the fibers and a substrate through which nutrients are delivered*, from crack-seal growth, we call it Taber growth (Li and Means, 1997). We base the term on Taber's conception of how fibrous veins form in nature, not on his experiments themselves, which involved what might be called evaporative Taber growth. We are not the first among recent writers to suggest that growth may occur at a cohesive boundary between fibers and matrix. Durney and Ramsay (1973, p. 83) also suggested this, as have Fisher and Brantley, (1992, for pressure shadows), Bons and Jessell (1997), and Wiltschko and Morse (1998).

Although Taber growth and crack-seal growth are fundamentally different, there may yet be a *micro*-cracking process at work in our Taber growth samples. We refer to some cryptic, cloudy, planar features that extend across no more than a few fiber widths, the Type II discontinuities of Means and Li (1995). We do not understand how these features form, but local parting of slow-growing fibers, loaded by faster-growing neighbors, may be part of the process. We assume these Type II features were never parts of through-going cracks, however, because they do not line up across many fibers.

4. Tracking

In experiments like these, it is easy, at least in principle, to observe whether fiber segments track incremental vein opening directions, using markers on the ceramic blocks to record the actual sequence of opening increments and comparing this with the pattern of fiber orientations and lengths. In general, our fibers do track the current opening direction quite well when they crystallize, and they maintain their as-grown orientations relative to the vein walls during subsequent opening. So, in the final state, fiber axes and opening trajectories are about parallel (Fig. 3). Exceptions to good tracking have been observed, however, where there has been fault-like slip on the central suture during opening, or distributed vein-parallel shearing (Means and Li, 1997). Indeed the sample of Fig. 3 displayed an additional kind of behavior that can potentially interfere with tracking, even though it had little effect on tracking as seen in Fig. 3. For a time early in the opening, when opening increments in this sample were vein-normal, the fiber growth rate at the surface photographed did not keep up with the opening rate (driven by faster growth rates in adjacent parts of the sample). This resulted in an air gap that eventually did fill with vein-normal fibers, when the opening direction was

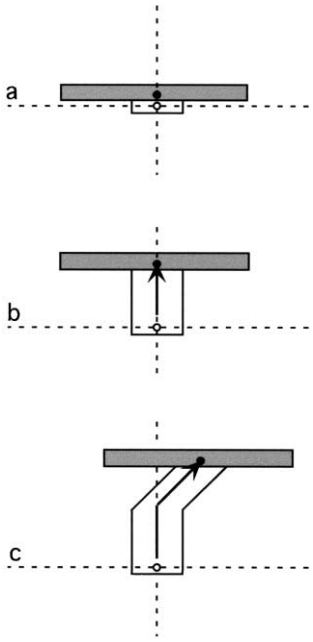

Fig. 4. Diagrams showing why tracking of displacements (arrows) by fiber boundaries (boundaries of white area) is expected in Taber growth. As a particle (filled circle) in the hangingwall (shaded) moves with respect to a particle (open circle) in the oldest part of an antitaxial fiber, the fiber boundaries necessarily parallel the hangingwall displacements (arrows), so long as the fiber continues to grow out of the same part of the hangingwall. This basic process, if repeated at the footwall growth site, leads to fibers that track the relative motion of the vein walls, as explained in the text.

still mainly vein-normal; however, a little of this gap-closing, vein-normal growth occurred when the opening direction had begun to pick up a vein-parallel component. This interfered locally with good tracking, just as suture-slip does.

Fig. 4 shows why tracking is a necessary consequence of ideal Taber growth in antitaxial veins, where there has been no slip at the vein walls or central suture, no rotation of fibers by later deformation, and complete filling of the vein at each instant. Fig. 4(a) shows incipient antitaxial growth of a fiber from the hangingwall of a vein. A pair of reference axes (dashed) is set parallel and perpendicular to the vein wall (shaded), with an origin fixed to a particle (open circle) in the first-crystallized part of the fiber (white). Fig. 4(b) and (c) shows the motion of a hangingwall particle at the growth site (black circle) in the reference frame of the fiber tip described above. This seemingly peculiar choice of reference frame is actually the most convenient one for showing why antitaxial fibers track displacements in ideal Taber growth. Fig. 4(b) shows the situation after an initial series of normal opening increments. Assuming the fiber enclosing the open circle continues to grow out of the region in the wall centered on the black circle, the fiber boundaries must parallel the displacement vector of the black circle (arrow). Fig. 4(c) shows the situation after a later series of oblique opening increments. Once again the fiber boundaries must parallel the oblique displacement vector. The key factor that makes tracking necessary is the continued growth of a given fiber at a single position on the wallrock.

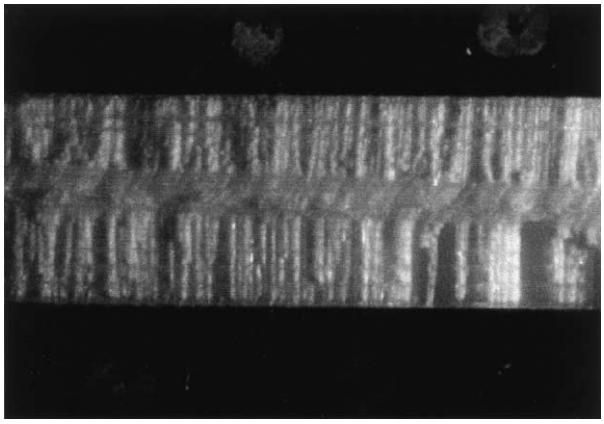

Fig. 5. Videomicrograph of sample TF-53 showing ammonium thiocyanate fibers grown under the constraints of Fig. 2(b), at about 45°C over a period of 46 h. Vein width is 2.7 mm. Fine fibers in the central part of the vein are not well imaged but trend NE–SW. No medial plane is evident. The fibers change direction abruptly at horizons corresponding to the time when the black plate in Fig. 2(b) was removed.

Perhaps the reader can see why, if the footwall is moving in a similar way relative to the earliest fiber segment grown at the footwall, and there has been continuous contact between fibers grown from the two walls and no slip between them, the incremental hangingwall and footwall displacements for a given time interval can be combined vectorially to yield the displacement of the hangingwall relative to the footwall for that time interval. Taber growth as explained above seems to provide a simpler explanation for tracking than models that explain tracking or partial tracking in the context of the crack-seal process (Cox and Etheridge, 1983; Urai et al., 1991; Bons, 2001; Hilgers et al., 2001).

5. Criteria for growth-sense

Our veins are all antitaxial yet some of them bear two features generally associated with syntaxial veins by Durney and Ramsay (1973) and Ramsay and Huber (1983), and current textbooks. Fig. 5 shows a vein produced under the constraints of Fig. 2(b). Antitaxial Taber growth occurred, so the fibers in the vein center are oblique to the vein walls, and the fibers at the vein margin are normal to the walls. This is the pattern of fiber orientations customarily illustrated in books for *syntaxial* veins (see for example, fig. 7.27(b) in Van der Pluijm and Marshak, 1997). The syntaxial interpretation is clearly reasonable for rocks, since initial opening increments of extensional veins in nature will generally be vein-normal (Durney and Ramsay, 1973, p. 82). This pattern of fiber orientations, however, is not a reliable indicator of syntaxial growth-sense in our

experimental vein, in which the growth-sense is known to have been antitaxial, with early opening oblique to the vein walls. Early vein-oblique opening may also be expected in some natural situations, for example where rock is mechanically anisotropic and loaded asymmetrically with respect to the plane of anisotropy. Van der Pluijm and Marshak (1997) anticipate this possibility in their text (p. 142) where they caution that a given fiber orientation pattern should *not* be used by itself to identify growth-sense. For confirming evidence of syntaxial growth in a vein like their fig. 7.27 or our Fig. 5, Van der Pluijm and Marshak direct the reader to look for a medial line in the vein. We wonder whether even this feature is always a reliable indicator of syntaxial growth-sense, because many of our veins, all known to be antitaxial, display a medial plane, a plane across which fibers that nucleated separately at the two walls abut (e.g. Fig. 3). Some of our veins do not contain a readily visible suture, however (e.g. Fig. 5) and may not contain one, at least over parts of the vein. In these cases one fiber nucleus must have been shared by both walls, which fed its growth from both sides, to produce the classic lattice continuity across antitaxial veins recognized by Durney and Ramsay (1973). We have not been able to produce thin sections of these ammonium thiocyanate veins, because the material deforms plastically and recrystallizes readily when machined.

6. Discussion

Returning to the four questions about fibrous veins mentioned in the Introduction, and assuming for the moment that some natural fibrous veins *are* products of Taber growth, we note the following. (1) Since Taber growth of fibers can occur into empty (or fluid-filled? space) as in our Fig. 1, some natural fibrous veins could be post-tectonic. That is, a fissure of finite width might open and then be filled with fibrous crystals growing from the two fissure walls after opening ceased, a possibility recognized previously by Passchier and Trouw, 1996, p. 134) and by J.G. Ramsay (pers. comm., 1999). We believe, however, that fibers grown into an open or fluid-filled space should always grow *normal* to the vein walls, to satisfy a least-work law (Li, 1998). So, veins with curved fibers and non-curved lattice directions within the fibers could still be reliably interpreted as syntectonic, as Durney and Ramsay (1973) and others have indicated. (2) Since our Taber veins are not crack-seal veins, and some veins in nature may be similar, we discourage use of the term 'crack-seal vein' as a general descriptive term for any fibrous vein. The same sentiment is expressed in notes for a 1998 Geological Society of America short course on veins by D. Wiltschko and others (Wiltschko, 1999). We even discourage use of this genetic term for veins bearing the classic signature of crack-seal veins, inclusion bands, until more is known of the mechanism(s) that produce inclusion bands. (3) Although tracking is thought to be a necessary consequence of simple Taber growth, some natural Taber veins may have experienced internal slip or deformation during opening. So, it remains important to try to confirm tracking or lack of it in all fibrous veins, as Cox and Etheridge (1983), Cox (1987), Van der Pluijm (1984), Williams and Urai (1989) and Urai et al. (1991) have done. (4) Since some of our antitaxial veins bear features thought characteristic of syntaxial growth-sense, the remote possibility exists that *all* good fibrous veins in nature are antitaxial, that is, all veins bearing very long, parallel-sided fibers (with aspect ratios of 10 or more). A more moderate and probably more likely hypothesis is that only *some* apparently syntaxial veins are antitaxial. Clearly other growth-sense criteria need to be employed whenever possible to confirm that a vein is syntaxial, for example, fibers widening toward the vein center, fibers overgrowing host rock grains at the vein wall (Durney and Ramsay, 1973, p. 82), and new growth-sense indicators need to be discovered.

7. Relevance to nature

Given that the discussion above, based mainly on our experience with evaporative Taber veins, presumes to question mainstream interpretation of natural fibrous veins, the following challenge needs a reply. Do evaporative Taber veins produced in the laboratory have any bearing at all on the development of natural veins? We offer the following incomplete reply.

Our Taber veins clearly involve advection of pore fluid to the vein walls, where water evaporates and the fibers crystallize. Although a few kinds of natural veins may also result from evaporation-driven crystallization (e.g. fibrous gypsum veins forming in the groundwater phreatic zone, El Tabakh et al., 1998; fibrous veins of ulexite in evaporite settings), advection of pore fluid to the vein wall and its *loss* there, seems unlikely for the ordinary quartz and calcite veins in pelites of low metamorphic grade. In these settings there may be advection of nutrient-bearing fluid *past* a site of vein formation (e.g. upward advection driven by a greater-than-hydrostatic pressure gradient), but no water should be lost at the crystallization site, unless hydrous minerals are also forming in the vein or wall-rock (as Gustavson et al., 1994 have proposed for some fibrous gypsum veins).

If loss of solvent is not the main precipitating mechanism in common natural veins, then rock and fluid cooling during uplift and erosion, or cooling of fluid only as it rises through rock of more or less constant temperature, are possible causes of supersaturation of pore fluid in vein constituents, as are pressure decreases caused by fluid rise or tectonic dilation of host rock. Supersaturation may also arise from dissolution of vein components in nearby pressure solution seams. Whatever the cause of supersaturation at the vein

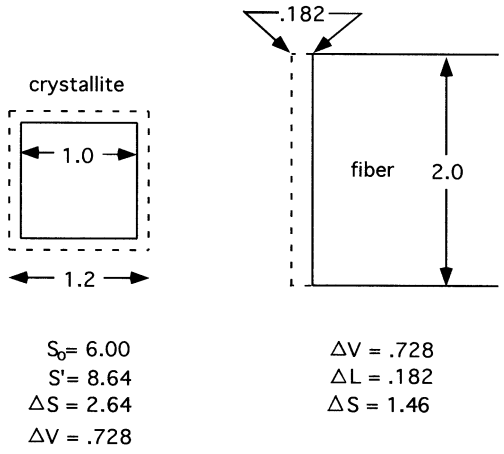

Fig. 6. A numerical example showing how new surface area (hence energy) is minimized if an increment of growth of the vein-filling substance occurs at a fiber root in the vein wall rather than onto a hypothetical crystallite of the same substance in a wall-rock passageway delivering material to the vein. The argument relies on the wall-rock diffusion passageways being sufficiently smaller than the cross-sectional area of the fiber, as explained in the text.

wall, we see no reason why Taber growth should not proceed there, although we can imagine that intimate details of the growth process may be different depending on the saturation mechanism.

For Taber growth to proceed at vein walls, rather than within (and blocking) the narrow, intergranular, wallrock pathways delivering nutrients to the veins, we need an explanation such as the following. Imagine diffusive connectivity, via intergranular fluid, between the interior of a fine-grained wall rock block and the wall of an existing, partially filled fibrous vein, where the vein mineral is not a major constituent of the wall rock. Imagine that the intergranular fluid becomes slightly supersaturated by one of the mechanisms in the last paragraph. This means that growth will tend to occur, either as: (1) necessarily tiny grains ('crystallites') in the narrow intergranular pathways occupied by the fluid in the fine-grained wall rock, or (2) at the roots of the fibers already occupying the vein, or (3) as overgrowths (pressure shadows) on rigid objects distributed through the wall rock. Disregarding (3) for the moment, it can be shown that there is a surface energy advantage in adding material to the fiber roots rather than to incipient crystallites in the intergranular passageways (Fig. 6).

Fig. 6 (left) shows a cube-shaped crystallite of the vein mineral in a wall rock intergranular passageway. Before an increment of growth (solid outline), the crystallite is 1 length unit on a side, and its surface area (S_0) is 6.00. After an increment of growth it is assumed to be 1.2 length units on each side, and its new surface area (S') has increased to 8.64. Its surface area has increased (ΔS) by 2.64 area units. Its volume has increased (ΔV) by 0.728 volume units. Now the question is, if this same volume of new crystal is added to a fiber in the vein instead of to the crystallite in the wallrock, will this involve more or less new surface area? Fig. 6 (right) represents a fiber with square cross-section and a width of 2 length units. If 0.728 volume units are added to the root (left end) of the fiber, then it can be calculated that the resulting new fiber length (ΔL) will be 0.182 length units and the new fiber area will be 1.46 area units. This is about 45% *less* new surface area than if the same volume of material is added to the crystallite. Assuming that new surface energy is at least roughly proportional to new surface area, there is a distinct surface energy advantage in crystallizing new material onto the fiber rather than onto the crystallite.

The crystallite edges in Fig. 6 are just half of the fiber width. In reality, the intergranular crystallite would be an order of magnitude or more smaller than this relative to the fiber. If the calculation is repeated for a more realistic intergranular crystallite size, the surface energy economy favoring growth of the fiber is even larger than above. Likewise if the volume of 0.728 is distributed over many crystallites, rather than just one as in Fig. 6. If the crystallite is taken to be rod-shaped or platy instead of cube-shaped, or if it grows on only four sides instead of six, a similar result is obtained. So long as the intergranular crystallite size is small relative to the vein fiber diameter, surface energy will favor growth onto the vein fibers over growth onto wall-rock crystallites. Another, equivalent, way to express what draws vein constituents from the wall rock to the vein walls is to say that the intergranular fluid is just saturated with respect to the tiny crystallites in the fluid passageways, but *oversaturated* with respect to the somewhat larger fiber roots (Putnis et al., 1995; Li, 1998). Once crystallization onto the fiber roots begins, a downhill concentration gradient is set up toward the fiber roots, and the process continues, so long as saturation with respect to the crystallites in the wall rock is maintained.

Returning to (3) above, this model predicts equally ready Taber growth at 'pressure shadows' in the wall rocks as in a vein, if the fibers in the pressure shadows are as large in cross-sectional area as the fibers in the veins. Rocks bearing both fibrous veins and fibrous pressure shadows are indeed common.

Surface energy terms are admittedly only part of the energy budget for growth of antitaxial fibrous veins. Other factors that determine where crystals grow in vein environments include the work done by crystal growth against tectonic or lithostatic stress fields and the work done against any cohesion at the growth site. Perhaps it will be possible in the not too distant future to add to what we understand of fibrous veins and overgrowths by simulating non-evaporative Taber veins in laboratory samples, including real rock samples.

Acknowledgements

This work was supported by NSF grants EAR-9404872 and EAR-9705701. Janos Urai generously gave advice

throughout the research. Reviewers Paul Bons, David Durney, Chris Mawer, John Ramsay, and David Wiltschko helped greatly by suggesting improvements to the paper. In the spirit of Paul Williams, we have followed some but not all of their thoughtful advice.

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