DEFORMATION IN VEIN GENESIS

By

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Abstract. It is shown that the formation of veins in metamorphic psammitic rocks is closely related to creep, involving fracturing, subgrain development, stress-induced diffusion, syntectonic-recrystallization, and chemical replacement. The veins are easily subjected to annealing recrystallization and grain growth resulting in equilibrium disposition of grain boundaries and a general coarsening of the vein fabric.

Introduction

One of the most interesting problems connected with the origin of metamorphic rocks concerns the processes involved in the formation of associated veins. In the past few years, some attention has been directed towards an understanding of vein genesis (RAMBERG 1960, BOYLE 1963). A point not often referred to is the commonness of the vein structure; hardly a single metamorphic rock in the Caledonides does not contain veins of one kind or another, the composition being strongly dependent upon the parent rock (RAMBERG, op. cit.). It is the main object of the present note to discuss the incipient stages of vein formation which are often blurred by later metamorphic events. In an attempt to simplify the problem, only veins which are associated with extension fractures in low-metamorphic feldspathic sandstones and are less than about 2 mm in thickness have been considered. The advantage of this approach is that a detailed knowledge of the pre-vein rock fabric allows conclusions to be drawn regarding the mode of emplacement; and because detrital grains and vein thicknesses are in the same size range, the behaviour of the individual rock fragments subjected to vein-forming processes may be elucidated. The rock

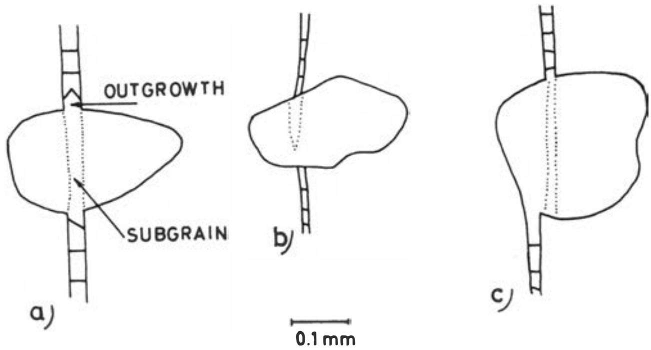

Fig. 1. Subgrain veinlet in quartz and outgrowth of quartz from detrital grain. Usually, the subgrain extends across the entire grain (a), but incomplete veinlets have often been noticed (b). Occassionally, outgrowth forms in the vicinity of the subgrain (c).

specimens used in this study were partly arkosic pebbles sampled from the shores along the Trondheim Fjord, partly arkoses (sparagmites) sampled in road-cuttings near Lillehammer.

Vein-rock relationships

The smallest structure which may be recognized as a vein is about 10μ in thickness. Even though the course of the veins is slightly sinuous, they cut right through the various sand grains and show no preference for grain boundaries. The veins may be continuous for at least 2–3 cm (the width of the thin section). There appears to be a consistent relationship between the composition of a vein and the minerals which it penetrates. Thus, the vein consists of quartz, feldspar, or calcite depending upon whether it cuts a quartz, feldspar, or limestone fragment. This state of dependence is especially marked in the smallest veins and is usually somewhat diminished or erased in the thicker ones, the amount of quartz and calcite constantly increasing at the cost of feldspar. Those parts of the veins which transect cementous material usually consist of quartz or calcite, the composition of the cement being decisive. The behaviour of the individual rock components — mineral grains, rock fragments, and matrix — during the development of the veins is discussed below.

Quartz. The first vestiges of a vein structure in a detrital quartz grain are marked by the formation of a substructure. This may simply be a long, narrow grain (as seen under the microscope) having low-angle boundaries towards the original quartz. Various types of subgrains are shown in Fig. 1. Tiny, brownish inclusions, less than 1μ in size, are always present along the sub-boundaries or distributed more haphazardly in the interior of the subgrains or its vicinity. The embryonic stage is thus characterized by veins of quartz in quartz, a type of phantom veinlets, the veinlets being only slightly disoriented with respect to the parent grain. The misfit across the sub-boundaries measured as extinction differences seldom amounts to more than 2–3 degrees. The continuation of the vein on leaving the detrital quartz is commonly, for a short distance, quartz in crystallographic continuity with the subgrain. These outgrowths may also extend into adjacent detrital feldspar. In the subgrains, we sometimes find smaller grains having high angle boundaries towards them and usually elongated parallel to the sub-boundaries. They are also generally rather similarly oriented. These grains are believed to be due to syntectonic recrystallization and are discussed below. While it appears that the matrix has been offset by an amount corresponding to the width of the vein, there is neither any trace of a fracture through the quartz grains nor any signs of displacements. It is therefore obvious that the detrital quartz grains lying in the path of a propagating fracture did not rupture by the loss of coherence, but yielded by a complex mechanism of subgrain formation and recrystallization. Because sub-boundaries, which are common in metamorphic quartz, usually appear to be crystallographically controlled, VOLL (1959) asserted that subgrains in quartz originated by polygonization during post-tectonic anneal. The non-crystallographic nature of the sub-boundaries in vein-quartz — determined by the casual orientation of the grains relative to the veins — suggests, on the other hand, that the sub-boundaries are directly related to the migration of vacancies during plastic flow (GARAFALO 1965). Böhm lamellae, if present in the detrital quartz grain, do not continue into the subgrains. This may give some support to the dislocation model of the sub-boundaries because the lamellae probably represent arrays of edge dislocations due to slip on a near basal plane (CARTER *et al.* 1957). We may conclude that the earliest stages of vein formation in quartz consist essentially of slight rearrangements of matter within the volume of the pre-vein quartz.

The nature of the brownish inclusions studded along the sub-boundaries is unknown. It has been proposed that similar but smaller inclusions associated with Böhm lamellae are voids formed by the aggregation of lattice vacancies received from nearby dislocations (CHRISTIE *et al.*, 1964). The fact that the inclusions occur primarily along the sub-boundaries supports the void hypothesis as grain boundaries, especially if transverse to the tensile stress, are preferred sites

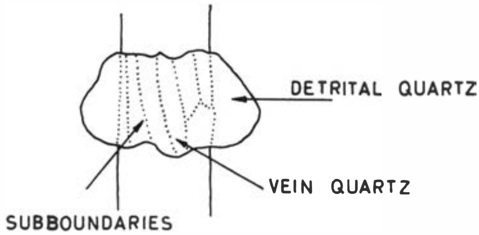

Fig. 2. Vein quartz between offset detrital grains. Sub-boundaries are generally sub-parallel to the boundaries of the vein.

for the nucleation and growth of holes (BALUFFI and SEIGLE 1957). If the void hypothesis is correct, the sub-boundaries may be potential surfaces along which fractures may nucleate because of the possibility of the growth of voids into cavities which may initiate rupture.

The dilational nature of the ensuing stages of vein development in quartz, however, is unquestionable. This is shown by an offsetting of the detrital half-grains which are separated by sub-boundaries (Fig. 2). During no stage in the dilation do vein quartz and detritla quartz lose coherence. The growth of vein quartz occurs in crystallographic continuity with the old quartz, except for the simultaneous development of a complex substructure consisting of a number of subgrains loaded with small, brownish inclusions. The infilling of vein quartz is not related to an open fracture; the growth is synchronous with the dilation. During these processes, quartz has been altered from a rounded, detrital grain to a drawn-out ellipsoidal grain. By a comparison with the veins in the alkali feldspar (see below), it may be inferred that the elongation is due to self-diffusion of Si- and O-ions induced by stress. It is well known that polycrystalline metals during creep deform principally by slip, climb, and grain boundary shearing. Nabarro and Herring (HERRING 1950), however, have described a method whereby metals deform by a stress-motivated diffusion seeking to relieve the inequality of pressure. According to these authors, a vacancy current directed away from boundaries normal to the tensional stress corresponds to a migration of atoms in the opposite direction. By a diffusional flux of this kind, quartz may grow perpendicular to the vein boundaries in crystallographic continuity with the original grain. The pre-condition for this process to work is that the sub-boundaries function as normal high-angle boundaries. The formation of wall-to-wall crystals may continue as long as the supply of material keeps up with the dilation. If the diffusion current slows down relative to the extension, only crystals oriented with the fastest direction of growth (c-axis) normal to the vein walls continue to grow across the vein, and local openings (vugs) may come into existence. Eventually a comb structure may form.

Because crystal growth occurs under stress, sub-boundaries may form continuously. The vein quartz is therefore highly strained and inclined to recrystallize. Recrystallization probably first occurred during the vein formation. It seems to be closely related to the origin of subgrains, and only the most severe crystals were affected (syntectonic recrystallization). The whole rock, including the veins, was commonly exposed to post-tectonic or annealing recrystallization. The driving force, in both cases, is the stored strain energy. In a rock undergoing annealing recrystallization, the degree of recrystallization of individual quartz grains varies considerably. While some grains show trivial signs of recrystallization, others are completely replaced by an assemblage of clear strain-free grains. Grain corners and grain boundaries are always preferentially recrystallized, probably because grain boundaries interrupt the slip processes and are therefore more distorted than the central parts. This also explains why small grains with large boundary areas seem to recrystallize more easily than the larger ones. Grain boundary recrystallization in quartzites may result in a continuous, vein-like pattern sometimes interpreted in terms of cataclastic deformation (see, e.g., OJAKANGAS 1965). The fact that the small quartz grains along the boundaries are strain-free or less strained than the large, primary grains shows that this structure is due to recrystallization rather than crushing. Low-angle boundaries are also favourable nucleation sites. The growing grains usually have high-angle convex boundaries towards the crystal being consumed. Sutured growth fronts have been observed where the new grains are only slightly differently oriented from the parent one. In this case, the mobility of the grain boundaries is reduced, and the growth may depend upon local fluctuations of the strain energy along the border. Brownish inclusions and sub-boundaries are effectively eliminated by the re-crystallization growth.

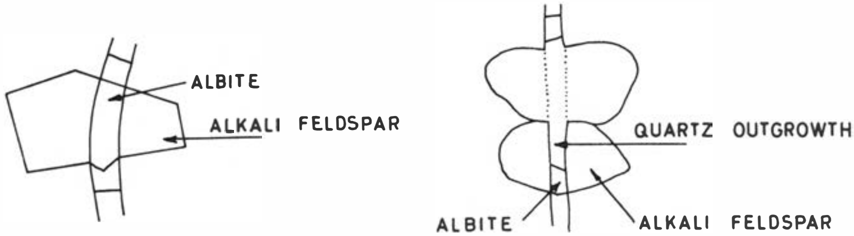

Fig. 3. Albite vein in alkali feldspar. Outgrowth from quartz makes its way into adjacent feldspar.

The impingement structure of the recrystallized quartz may be altered by subsequent grain growth. Thus, the quartz veins are sometimes more coarse-grained than the rock in which they occur because of the scarcity of grain-growth-inhibiting inclusions.

Feldspar. Most of the feldspar in the sandstone is microcline (usually non-perthitic) and perthite (usually untwinned). Acid plagioclase occurs in varying amounts. The embryonic veins in alkali feldspar with few exceptions consist of albite (Fig. 3), the origin of which appears to be intimately related to the perthite problem. In contrast to the vein formation in quartz, the development of albite veins in feldspar from the beginning seems to be connected with fracturing. The importance of deformation in the genesis of perthites was recognized by GATES (1953), who showed that mobilized sodic feldspar material has been drawn to fractures and precipitated there. Furthermore, he was able to demonstrate that the feldspar around the albite veins was impoverished in albite, definitely pointing to the source of the sodic feldspar in the fractures. Perthites subjected to vein formation in the sandstone thus contain two generations of unmixed albite, the first of which may pre-date the last sedimentary cycle. In the larger veins ($>50\mu$), albite is usually replaced by quartz in the central parts, probably indicating that the source of the albite component has been exhausted. It is also interesting to note that vein-growth in feldspar adjacent to quartz commonly proceeds by the growth of quartz from the latter grain, suggesting greater mobility of quartz than albite (Fig. 3).

The short distances over which the sodic feldspar and quartz material migrated offers no obstacle to transport by a vacancy or interstitial diffusion mechanism (JENSEN 1965). The fractures are healed

Fig. 4. Albite and quartz between fractured and displaced detrital plagioclase.

because ions are expelled from the alkali feldspar lattice and constrained towards the fracture driven by a gradient in the chemical potential brought about by pressure differences (RAMBERG 1960).

Acid plagioclase similarly yields by fracturing and healing of the fracture by expulsion of albite. Albite so formed usually occurs in crystallographic continuity with the parent plagioclase and may also be twinned according to the same pattern (Fig. 4).

Limestone fragments. Although fragments of various kinds occur, only particles of clastic limestone (marble) is of interest in this connection. Vein formation takes place by fracturing and precipitation of calcite concurrently with the opening of a fracture. In contrast to the polycrystalline, fine-grained fragments, the veins consist of rather few, large calcite crystals (Fig. 5). Sometimes vein calcite is mixed with considerable amounts of quartz.

Matrix. Where the veins border on cementing minerals — quartz, ferruginous matter, sericite, etc. — they usually consist of quartz crystals extending from walls to walls. If the matrix contains abundant carbonate, calcite may, however, entirely predominate in the veins. Closely akin to these veins are so-called 'pressure shadows' around brittle porphyroblasts, e.g. pyrite, believed to be due to growth of available rock material mobilized by tensional stress acting parallel

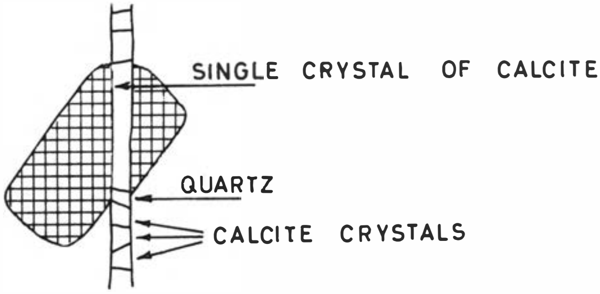

Fig. 5. Vein of calcite through limestone fragment.

to the schistosity (PABST 1931). Pabst found that there is a definite lack of orientation of the 'feathered' quartz extending across this structure. This is consistent with the present observations of vein quartz, the orientation being determined by the chance orientation of the first nuclei which formed, irrespective of their orientation in relation to the direction of fastest growth. The obvious interpretation of the fact that quartz and calcite extend across the vein structure as single crystals is that these minerals grew in step with the dilation. This has already been suggested by RAMBERG (1960).

Conclusion

Vein formation is usually considered as a two-stage process of fracturing and fracture-filling separated in time and of different origin. Contrary to this belief, it is held that the development of veins under discussion is synchronous with deformation, proceeding by fracturing, subgrain development, diffusion, and syntectonic recrystallization.

The material filling the embryonic veins originates by reconstruction of matter *in situ*, or by transport from the immediate neighbourhood. Full-grown veins, on the other hand, may have sucked mobile atoms from considerable distances, that is up to several centimetres.

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