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Quartz as indicator mineral in the Central Swiss Alps: the quartz recrystallization isograd in the rock series of the northern Aar massif

In Memoriam GERHARD VOLL

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ABSTRACT

Earlier observations on the deformation of rock-forming quartz during Alpine metamorphism that were made by Voll (1976) along a traverse following the Reuss valley (Aar massif, Central Swiss Alps) are still relevant but can be explained in more modern term. Voll found that a few kilometres south of the contact between the Aar massif and its sedimentary cover quartz has partly undergone a combination of dynamic recrystallization and nucleation along grain boundaries and fractures at the expense of the deformed parent grains. Further to the south, increasing grain growth of quartz under nearly static conditions is observed, with polygonal grain shapes typical of annealed microfabrics. Comparable stages of recrystallization could be found in several N–S traverses through the Aar massif so that "points of first occurrence" of newly formed quartz could be connected to define a quartz recrystallization isograd. This isograd extents over 90 km through the northern Aar massif, following a course parallel to the sanidine/microcline isograd but at a distance of 10–15 km further to the north. The evolution of the quartz microfabric is discussed with respect to recent estimates of the T-t path of the Aar massif.

Introduction

In a profound but rather condensed contribution, Voll (1976) described the recrystallization features of quartz in Variscian granites and gneisses of the Central Swiss Alps. Samples had been taken along a N–S traverse through the Aar massif following the Reuss valley between Erstfeld and Göschenen and further south over the Gotthard massif down to Airolo. Although Voll (1976) announced that "details, including diagrams and pictures, are published elsewhere", this publication never appeared.

Since the pioneering work of Voll, numerous studies have been carried out on the subject of 'recrystallization' in metals and minerals in general, and in quartz in particular. When dealing with 'recrystallization' two principally different petrogenetic situations have to be considered:

(i) Under *static conditions,* for which the stress distribution is isotropic and temperatures are sufficiently high to keep grain boundaries mobile, quartz will undergo *normal grain growth*, which is primarily driven by a reduction of the surface energy. Typical microfabrics for static grain growth are equiaxed grains, consisting of straight grain boundaries and 120° triple junctions. Static grain growth can be predicted by classical grain growth laws (e.g., Joesten 1983, 1991; Evans et al. 2001) where the growth rate primarily depends on the temperature evolution of a rock body. However, parameters like the presence of fluids (Tullis & Yund 1982), chemical impurities (e.g., Freund et al. 2001), second phase minerals (e.g., Berger & Herwegh 2004), and crystallographic misorientations (e.g., Stöckhert & Duyster 1999; Kruhl 2001) can additionally influence normal grain growth.

(ii) Under *dynamic or deformational conditions*, which are characterized by the presence of a differential stress (Urai et al. 1986), stress, strain, and strain rate, in addition to temperature, control the 'recrystallization' behavior of a quartz aggregate (e.g., Hirth & Tullis 1992; Dunlap et al. 1997; Stipp et al. 2002b; Stipp & Kunze 2008). The effect of dynamic recrystallization on grain size is two-fold. The size of the original grains may be reduced due to bulging recrystallization or subgrain rotation recrystallization (e.g., Drury & Urai 1990; Mancktelow 1990; Hirth & Tullis 1992; Stipp et al. 2002a), or it may increase due to *grain growth* via grain boundary migration recrystallization (e.g., Urai et al. 1986; Mancktelow 1990; Stipp et al. 2002a). In contrast to the static case, rearrangement and annihilation of

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the dislocation substructure provide the major driving forces for dynamic recrystallization during deformation.

In the following, we will present a case study on quartz 'recrystallization' along several N–S traverses across the Aar massif (Central Switzerland), documenting the spatial distribution of the onset of recrystallization. Based on these data, we will define a recrystallization isograd and discuss the potential processes associated with the evolution of the isograd.

Geological setting of the Aar massif

The Aar massif was already tectonically affected during Paleozoic times, when intrusion of the major granitic-granodioritic bodies into the pre-existing gneiss series took place (Labhart 1977; Abrecht 1994; Schaltegger 1994). The main foliation and major deformation structures developed, however, during NW–SE compression associated with the Alpine Orogeny (Steck 1968; Labhart 1977; Choukroune & Gapais 1983). In the late Oligocene to Miocene, the Aar massif was overridden first by the sedimentary sequences of the Helvetic nappes during the Kiental Phase (e.g., Burkhard 1988; Pfiffner et al. 1997; Herwegh & Pfiffner 2005), and then became itself thrusted onto the foreland of the Alpine belt (Pfiffner et al. 1997). In a late stage of the Alpine orogeny, referred to as the Grindelwald phase (Burkhard 1988), ongoing compression induced a shortening and up-doming of the Aar massif. In terms of nappe-internal deformation, it is well known that Alpine deformation in the Aar massif increases from the north to the south (Labhart 1977; Keller 1999; Burkhard 1999; and literature given therein). This deformation can be quite heterogeneous at different scales, as manifest by different generations of steeply oriented shear zones, which surround lenses of foliated but less deformed host rock (Choukroune & Gapais 1983; Marquer et al. 1985; Marquer 1990). The shear zones were active during different deformation episodes ranging from ductile down to brittle deformation conditions (Marquer et al. 1985; Hofmann et al. 2004; Baumberger 2008).

The Alpine metamorphic conditions range from approx. 230–300 °C/2–3 kbar in the north to approx. 450 °C/4.4 kbar in the south of the Aar massif, as summarized in the discussion of the late Alpine metamorphism by Frey & Ferreiro Mählmann (1999).

Sampling and analysis strategy

The samples analyzed were originally used to determine the variation of the structural state of K-feldspar along several N–S trending traverses through the Aar massif, starting at its northern rim, i.e. at the lowest metamorphic grade (Bambauer & Bernotat 1982; Bambauer et al. 2005). If possible, the samples were taken at approximately regular spacings. All samples derive from various granites (e.g., the Central Aare Granite) and gneisses (belonging to the northern gneiss zone). Keeping the above mentioned strain heterogeneity in mind, only massive, homogeneously deformed samples were chosen, avoiding highly strained fault rocks from shear zones. To check for the quartz recrystallization behavior, only quartz aggregates embedded in the matrix of the host rock were considered for inspection by polarization microscopy, and quartz veins or alpine fissures were neglected. The quartz content in the analyzed samples apparently corresponds to the original host rock composition, so that quartz segregated from an external source is of no concern.

Development of the quartz microfabric in the Aar massif

The Reuss valley traverse as an example

The Reuss valley represents the northern part of the N–S traverse that was originally investigated by Voll (1976). Motivated by his observations, we studied the sample series along the various N–S traverses in more detail in order to check whether Voll's discovery of 'newly formed' quartz is of general character and can be used as a tool for the correlation of the evolution of the quartz microfabric on a regional scale.

Since more than 30 years have passed since Voll's original studies, we have updated and extended the interpretation of the evolution of the quartz microfabrics, applying recent concepts and models of quartz deformation and recrystallization. In the following, we briefly describe this evolution from north to south as observed in the Reuss valley.

The northernmost samples (distances <5 km from the northern rim of the massif) are characterized by typical gneiss fabrics consisting of large-sized and elongated "primary" quartz and feldspar grains embedded in a well-foliated sheet silicate-rich matrix. The quartz grains are several millimeters in size and typically show undulatory extinction but no evidence for 'newly formed' quartz.

Voll (1976) found first indications of quartz recrystallization in the northern gneiss zone immediately south of Amsteg – we call this location "Voll's point" (closely corresponding to Swiss coordinates 693925/181025). Here, the "primary" quartz grains show the same inhomogeneous undulatory extinction as do the northernmost samples, but in addition their size can dramatically be reduced down to 10–30 µm. Recrystallization preferentially takes place in the rim regions of the original quartz grains, resulting in aggregates of newly formed, finely distributed, tiny grains (Fig. 1).

As well as along quartz rims, tiny quartz grains also occur along well-defined planar structures (kink bands?) in the parent grains (Fig. 2). Here, for example, the widths of the zones consisting of recrystallized quartz are between 50–100 µm. These newly formed grains are, as Voll (1976) already pointed out, more or less equidimensional and typically show polygonal shapes, mostly straight grain boundaries and approximately 120° triple junction geometries. In a few cases, lobate grain boundaries can also be found.

Towards the south, i.e. with increasing metamorphic grade, the volume of newly formed quartz increases at the expense

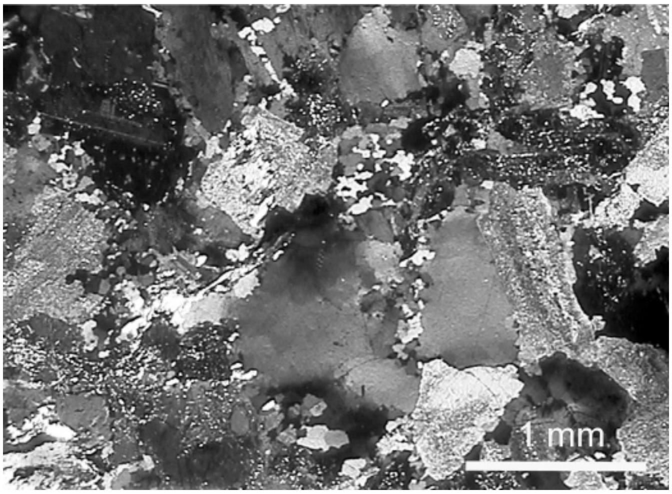

Fig. 1. Granitoid gneiss, northern Aar massif, about 2.5 km south of Amsteg. Newly formed, finely distributed, tiny grains of recrystallized quartz occur at grain boundaries of primary larger parent grains that show undulatory extinction. Sample SZA 1920, west of Meitschligen, Reuss valley; coordinates 692025/178400.

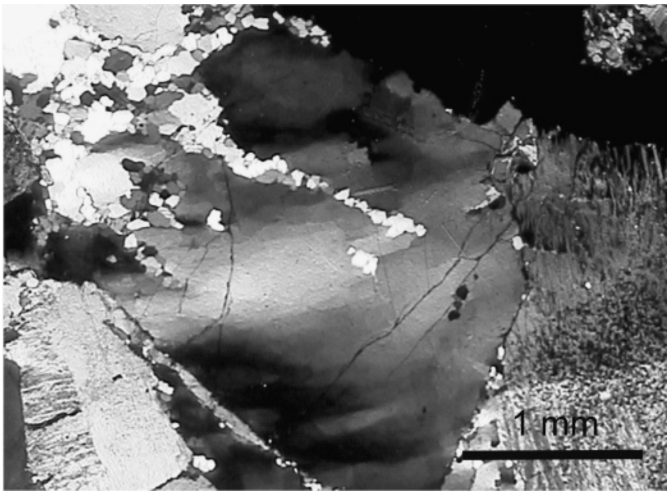

Fig. 2. Central Aare granite, about 4 km south of Amsteg. Newly formed, finely distributed, tiny grains of recrystallized quartz occur at the boundary and along planar structures (kink bands?) of a large parent grain that shows undulatory extinction. Sample GPS 53, Ob Felliberg, east of Gurtnellen, Reuss valley; coordinates 691750/176925.

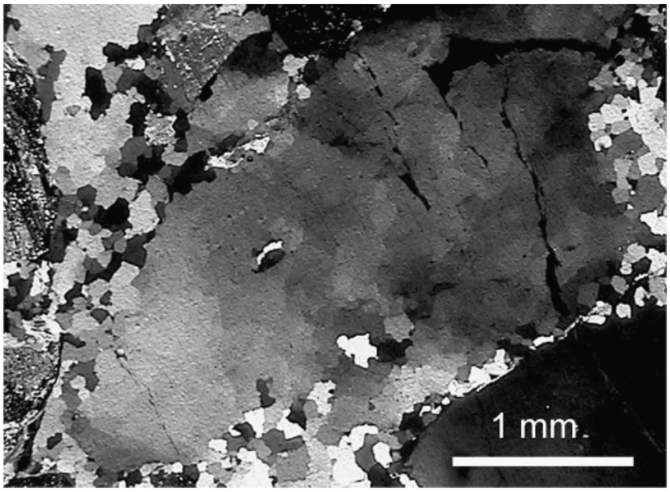

Fig. 3. Central Aare granite, about 8 km south of Amsteg. Noticeable coarsening due to annealing ("collective crystallization") of newly formed quartz grains around a primary quartz grain, which shows subgrains and undulatory extinction. Sample SZA 1928, south of Hörni, Reuss valley; coordinates 689300/174050.

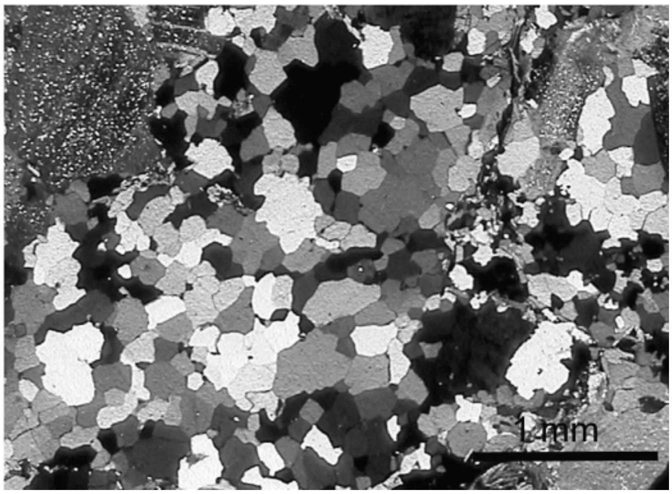

Fig. 4. Central Aare granite, about 14 km south of Amsteg. Distinct coarsening due to annealing ("collective crystallization") of newly formed quartz grains and development of polygonal grain shapes. The primary quartz has largely disappeared. Sample SZA 4576, Göschenen, Reuss valley; coordinates 688200/169050.

of parent quartz up to complete recrystallization. In addition, there is an increase in the size of the recrystallized grains from north to south, (e.g., Figs. 1–4) but the polygonal appearance of the resulting microfabrics clearly persists.

As described by Voll (1976), the microfabrics becomes more complex a few kilometres south of the sample point described in Fig. 4. In the present study, however, we mainly focus on the northern part and refer to Voll's earlier work for a short description.

Spatial distribution of quartz microfabrics in the Aar massif

With few exceptions, the samples collected along the other traverses through the northern part of the Aar massif compare well with the trends in quartz microfabrics along the Reuss valley (Figs. 1–4). It is thus possible to collect the observations into a coherent view of the regional distribution of recrystallized and non-recrystallized rock-forming quartz over the whole of the Aar massif (Fig. 5). A tentative line has been drawn connecting the points of onset of quartz recrystallization. The

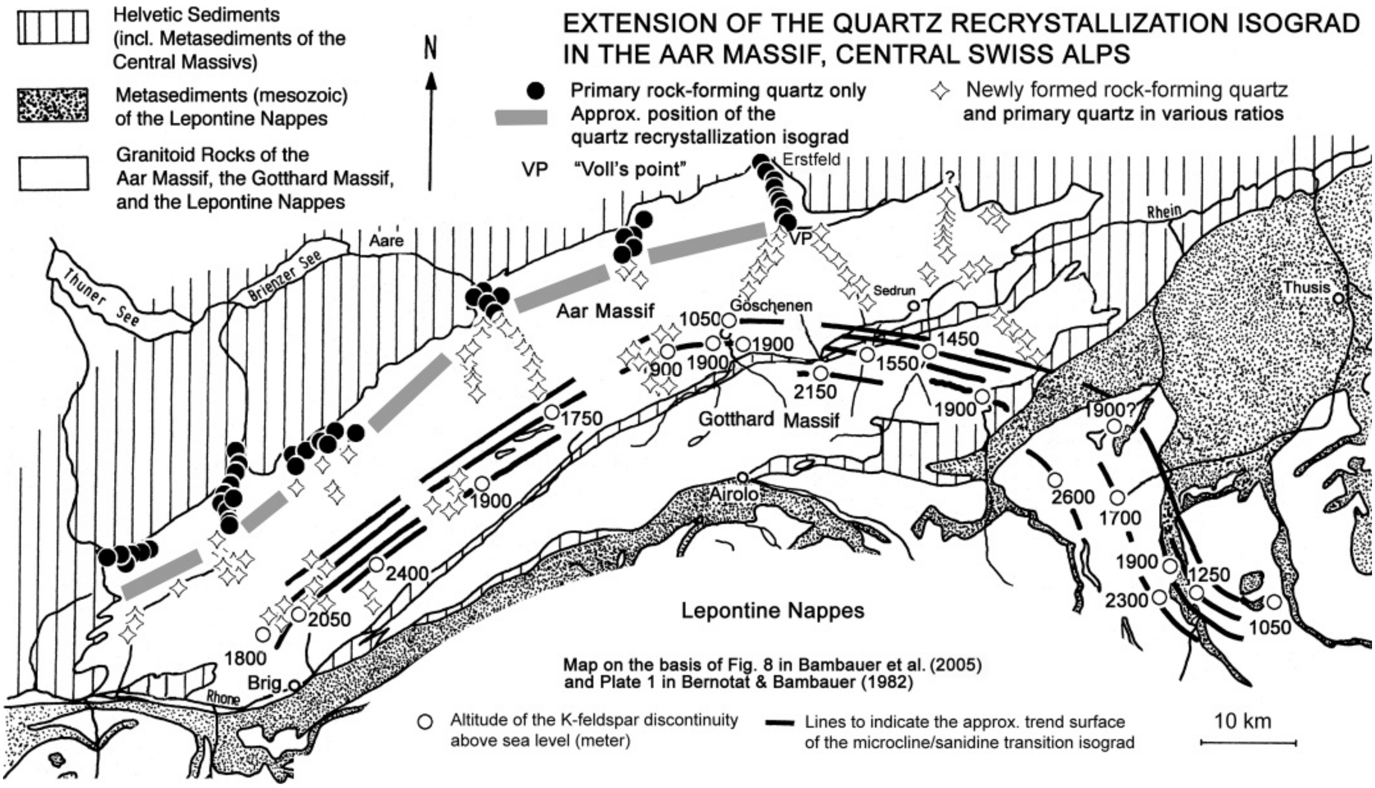

Fig. 5. Regional distribution of recrystallized (newly formed) and non-recrystallized (primary) rock-forming quartz in granites and massive gneisses of the Aar massif, Central Swiss Alps. The true number of samples is too large to be shown without considerable overlap. A tentative line has been drawn which connects the position of the first occurrence of newly formed quartz to give a quartz recrystallization isograd. The three-dimensional extension of the microcline/sanidine transition isograd (Bambauer et al. 2005) has been added for comparison.

quartz recrystallization isograd so defined extends over nearly 90 km from the Gastern granite in the west to "Voll's point" in the east, running subparallel to both the northern rim of the Aar massif and the microcline/sanidine transition isograd (Bambauer et al. 2005). Further to the east the recrytallization isograd is apparently hidden under the Helvetic sediments.

Generally, coarse-grained granites show relics of "primary quartz" further south of the point where newly formed quartz is first observed, whereas finer grained gneisses (probably from shear zones) may already show full recrystallization in a similar position. As a result, some local uncertainty in the interpretation of the very first appearance of newly formed quartz is unavoidable. Therefore, for some of the samples a more detailed inspection of the variation in the local fabric is desirable; these samples were not considered in the present large-scale study.

Discussion of the mechanisms of quartz recrystallization

In terms of deformation and recrystallization behavior, quartz microfabrics can reflect the geological history of a region (e.g., Mancktelow 1987; Dunlap et al. 1997; Stipp et al. 2002b; Toy et al. 2008) and serve as an important tool for the detection of former deformation and temperature conditions (e.g., Hirth & Tullis 1992; Herwegh & Handy 1996; Stipp et al. 2002a; Trepmann & Stöckhert 2003). Overprinting of older deformation microfabrics may pose a problem, and annealing, i.e. the static overprint of former deformation microfabrics, can also severely change original microfabrics (e.g., Heilbronner & Tullis 2002; Park et al. 2001; Barnhoorn et al. 2005; Herwegh et al. 2008). Concerning our sample suite, we have to address the questions how, when and under which conditions the quartz microfabrics evolved, and what their significance is in terms of the geodynamic evolution of the Aar massif.

The appearance of the newly formed quartz grains with a size much smaller than that of the parent grains suggests that deformation is responsible for the reduction of the original grain size. Thus, either crystal plastic processes via dynamic recrystallization or brittle processes involving fracturing have to be considered. Voll (1976) interpreted the microfabrics in question as "formation of new seeds, which grow undeformed at the expense of the deformed parent grains". The occurrence of recrystallized rims around quartz parent grains, as well as the similar size of the recrystallized grains compared to those of subgrains in the hosts, suggest *dynamic recrystallization* via subgrain rotation (e.g., Fig. 3) to be responsible for the grain size reduction (see also Poirier & Guillopé 1979). Evidence for the occurrence of bulging nucleation recrystallization has not yet been found in our samples, although this process would be typical for low temperature and/or high strain rate deformation in quartz (Drury & Urai 1990; Hirth & Tullis 1992; Stipp et al. 2002a). Potential reasons for this lack of evidence for bulging nucleation are discussed below. The recrystallized quartz grains along the planar structures mentioned above, which dissect the parent grains (e.g., Fig. 2), may be indicative for a brittle fracturing of the parents along preferential crystallographic planes accompanied either by the nucleation of new grains or by growth of tiny fragments of the fractured host grains (see also Vernooij et al. 2006). In the case of quartz fibres deformed under similar temperature conditions as those of our study, van Daalen et al. (1999) and Stipp & Kunze (2008) demonstrated very similar fabrics, where fracturing and shearing along specific crystal planes (e.g., rhomb planes, Dauphiné twin boundaries) of quartz result in the formation of recrystallized quartz bands. Various lines of evidence for ductile and brittle deformation processes being simultaneously active were recently found in different geodynamic contexts and mineral systems (e.g., Herwegh et al. 2005; Mancktelow 2006) and seem to be very common.

The more or less equigranular newly formed grains with straight grain boundaries and ±120° triple junction geometries are typical for annealing of former deformation fabrics (Heilbronner & Tullis 2002; Park et al. 2001; Barnhoorn et al. 2005). Voll (1976) called the formation process of these microfabrics by the German standard term 'Sammelkristallisation' (= "collective crystallization", which corresponds to "secondary recrystallization", as used in metallography), where larger concave quartz grains grow at the expense of the smaller convex ones, producing polygonal grain shapes (see also "Quartz Grain Coarsening by collective Crystallization in Contact Quartzite" in Buntebarth & Voll 1991).

The dominance of such annealed microfabrics in our sample suite (e.g. Figs. 2–4) suggests a thermal overprint under *nearly static conditions*: the observed increase in size of the newly formed grains must clearly be attributed to the N–S gradient in regional metamorphism. The relation between grain size and temperature can be interpreted in two different ways: (i) The N–S temperature gradient (as shown in Fig. 2 of Frey et al. 1980), and possibly the longer residence time of the southern samples under the given conditions, kinetically favor grain growth toward the south. (ii) Alternatively, the existence of a temperature gradient already during the period of deformation would result in larger sizes of the dynamically recrystallized grains, due to lower differential stresses and/or lower strain rate conditions (e.g., Twiss 1977; Austin & Evans 2007). The increase in the amount of newly formed grains and the southward-directed general increase in the subgrain size of the parent crystals (Fig. 3) would favor such an interpretation. In reality, as already mentioned by Voll (1976), a combination of both processes was probably responsible for the presently observed sequence of quartz microfabrics.

One has also to keep in mind that the Aar massif as a whole is dissected by a large number of shear zones, among which at least some underwent a long lasting deformation history (Baumberger 2008, Challandes et al. 2008). Therefore, we cannot fully exclude that some of our samples might have been affected by weak to moderate deformation related to such a heterogeneous strain distribution. This uncertainty would explain the local deviations in the grain sizes of newly formed quartz that where mentioned above. To be conclusive with regard to deformation history, strain distribution and degree of annealing, the quartz microfabrics should be analyzed in more detail in future studies. Nonetheless, we can make two statements at this stage: (i) Voll's point represents the onset of dynamic recrystallization in quartz. (ii) The deformation microfabrics, at least formed in part by dynamic recrystallization, have been overprinted by subsequent annealing at a later stage. Hence, Voll's point represents the location where the grain boundary mobility was high enough to allow the migration of dislocation substructures and grain boundaries during both processes, i.e. dynamic recrystallization and annealing.

In the case of the low temperature microfabrics of the Tonale line discussed by Stipp et al. (2002), the onset of dynamic recrystallization occurred at about 280–300 °C (see their Fig. 2). In their samples, however, bulging nucleation was the dominant dynamic recrystallization mechanism at these low temperatures. In comparison to our study, we cannot detect recrystallization via bulging nucleation, either because overprinting by annealing was too severe or simply because the microfabric was never formed by this mechanism. In contrast to the situation at the Tonale line, which is a high strain structure, both strain and strain rates must have been orders of magnitude lower in the weakly to moderately deformed parts of the Aar massif. As a result, the formation of dislocations was reduced and the ability to glide and creep was probably increased, possibly allowing the activation of subgrain rotation recrystallization even under such low temperature conditions.

The suggested quartz recrystallization isograd as shown in Fig. 5 fits well with the general metamorphic zoning in the Central Alps (Frey et al. 1999). The "recrystallization temperature" of 290 °C estimated – but not justified – by Voll (1976) is somewhat lower when compared to the range of temperatures given by Frey et al. (1980) for the Swiss Geotraverse across the Aar massif. In general, the isograd line lies north of the Lötschen – Färnigen shear zone (see Table 1 of Labhart 1968). As far as the available maps show, its position is located south of the reaction isograd kaolinite + quartz = pyrophyllite + H_2O of Frey (1987) and coincides more or less with the biotite isograd (Steck & Burri 1971) and the stilpnomelane-out zone boundary (Niggli 1974; Frey & Ferreiro Mählmann 1999, Fig. 2).

Voll (1976, 1978; cf. Frey et al. 1980) recommended the use of quartz recrystallization as a tool for mapping three-dimensional boundary planes. Because recrystallization (neglecting the difficulty of detecting its very first beginning) can be easily observed in thin sections, we suggest application of this method to rock bodies that can be taken to be homogenous with respect to their fabric development.

With regard to the time scale of the onset of recrystallization along the isograd we can only speculate at the present stage. For the Morcles- and Doldenhorn nappes, finite difference modeling of ^{40}Ar concentration in detrital and neocrystallized micas by Kirschner et al. (1996) yields peak metamorphic conditions at about 29–27.5 Ma, followed by a period of slow cooling till 17.5–16 Ma, before major exhumation and cooling took place. For the Aar massif in the Doldenhorn-Gastern area, Huon et al. (1994) suggested the end of active thrusting to occur at about 15 Ma. Recently, Challandes et al. (2008) modeled ^{39}Ar-^{40}Ar deformation ages in the Grimsel area to have occurred under peak metamorphic conditions between 21–17 Ma (late stage of Kiental phase of Burkhard 1988) but also recognized fluid-induced perturbation events between 14 and 5 Ma, which were associated with the doming and exhumation of the Grimsel area during the Grindelwald phase (Burkhard 1988; Challandes et al. 2008). In terms of the quartz recrystallization isograd, we can currently propose the following hypothesis. The deformation-induced grain size reduction of quartz probably is related to the shortening of the footwall, i.e. the Aar massif, during emplacement of the overriding Morcles-Doldenhorn nappes during the Kiental phase (at about 29–16 Ma). Peak metamorphic conditions were reached rapidly (Fig. 4 in Kirchner et al. 1996 and Fig. 9 in Challandes et al. 2008), probably allowing the weak to moderate pervasive deformation of our samples and a simultaneous formation of high strain shear zones (Marquer et al. 1985; Marquer 1990; Baumberger 2008). During slow retrograde cooling, further strain localization occurred (Baumberger 2008). As a consequence, the former deformation microfabrics, which became inactive at that time, were then overprinted by annealing. A potential influence of the fluid perturbation events between 14 and 5 Ma on the annealing of quartz cannot be completely ruled out yet. To be conclusive in this respect, more detailed investigations on the quartz crystallization and annealing behavior are required in future studies. Therefore, we expect that valuable additional information can be gained from the study of fluid inclusions and the analysis of trace elements of primary and newly formed quartz by micro-methods, which may be compared with corresponding results obtained by Bambauer et al. (1962) and Mullis et al. (1994, 1996) on fissure quartz.

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