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The role of dilation and cementation in the formation of cataclasite in low temperature deformation of well cemented quartz-rich rocks

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ABSTRACT

An important textural component of cataclasites in quartz-rich rocks deformed at low temperatures is a fine-grained (<20 μm) matrix composed of anhedral quartz. As cataclasites form during shearing, this component would typically be interpreted to result from extreme grain size reduction through comminution. Tabular bands of fine-grained quartz that texturally resemble cataclasite found in faulted quartz arenites and other quartz-rich, well cemented sandstones have characteristics that are incompatible with a shearing origin. These characteristics include a lack of shear displacement and wall rock fragments, gradational contacts with the wall rock, and a fine-grained quartz fill that has a different cathodoluminescence, water content, oxygen isotope chemistry, and in some cases, mineralogy, than the wall rocks. Rather than being the result of cataclasis, the fine-grained quartz in these tabular bands was precipitated in a dilating fracture. In essence, these structures are veins.

In fault zones, where cataclasite is well developed and shearing is unequivocal, the fine-grained quartz matrix representing up to 50% of the fault rock volume has characteristics similar to those in the tabular bands. We interpret these volumes to be in many cases a result of cement precipitation rather than as a product of comminution. If correct, then the brittle deformation of well cemented, quartz-rich rocks deformed at low temperatures involves much more dilation and cementation than previously recognized.

1. Introduction

Cataclasite is a cohesive fault rock consisting of variable proportions of matrix and rock/mineral clasts with a random fabric that is intermediate in clast/matrix ratio to a breccia and fault gouge (Sibson, 1977). The formation of cataclasite through cataclasis occurs by microfracturing, grain sliding, and rotation associated with faulting or shearing (Engelder, 1974; Blenkinsop, 2000). Grain size reduction through comminution is an integral part of cataclasis (Lloyd and Knipe, 1992; Knipe and Lloyd, 1994) while cementation may or may not be important (Blenkinsop and Rutter, 1986; Power and Tullis, 1989; Knipe, 1991).

The processes involved in the formation of cataclasite have been identified in a number of fault zones (e.g., Blenkinsop and Rutter, 1986; Knipe, 1991; Wu and Groshong, 1991; Lloyd and Knipe, 1992; Knipe and Lloyd, 1994). Typically, the process starts with the formation of extensional microfractures, which grow and link to form through-going shear zones. As deformation accumulates, continued fracturing progressively reduces both grain size and clast/matrix ratio to produce protocataclasite, cataclasite, and ultracataclasite. In these studies, the fine grains in cataclasites are interpreted to be a product of comminution. Once created by shearing, these fine grains may remain in situ or transported elsewhere under high fluid pressures via fluidization (Ujiie et al., 2007).

Although brittle processes are considered to dominate in formation of cataclasite, crystal-plastic deformation may also play an important role. At lower temperatures, strain hardening through cold working can lead to brittle failure and voids created by dislocation motion provide nucleation sites for fractures (Stel, 1981; Lloyd and Knipe, 1992; Knipe and Lloyd, 1994). The low dislocation densities found in the microcrystalline matrix of some cataclasites may be due to recovery of highly strained grain fragments (Knipe and White, 1979; Knipe, 1991; Graves, 1992).

Evidence for diffusive mass transport is common in cataclasites (Knipe, 1991; Lloyd and Knipe, 1992; Knipe and Lloyd, 1994). The very fine grain size (<10 μm) and likely presence of aqueous fluids promotes dissolution and precipitation (Fein, 2000). Precipitation of fine-grained quartz, during or after faulting, may also play a role by cementing cataclastic grain fragments (Power and Tullis, 1989; Blenkinsop and Rutter, 1986; Blenkinsop, 2000) or by filling "vein-like" structures (Stel, 1981).

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In well cemented, quartz-rich sandstones, tabular bands up to a few cm thick, filled with microcrystalline quartz are common and have been interpreted as small faults with cataclasite (Wu and Groshong, 1991; Onasch and Dunne, 1993; O'Kane et al., 2007; Onasch et al., 2009). While these bands contain fine-grained material that resembles the fine-grained matrix in cataclasite, a number of characteristics in some bands are inconsistent with a shear-only origin. We propose that these bands result from dilation and will use several lines of evidence to demonstrate that microcrystalline quartz fill did not originate solely by comminution of the wall rock, but was precipitated from an externally derived fluid. Given this proposition, we will also examine the characteristics of some fault zones with unequivocal evidence for shearing to assess whether this dilation behavior is present in such cases.

2. Nature and occurrence of microcrystalline quartz bands

Samples described in this study come from Paleozoic rocks in the central Appalachian Alleghanian foreland fold and thrust belt and San Juan dome of southwest Colorado (Fig. 1). Samples from the Appalachians include the Middle Ordovician Martinsburg Formation, Upper Ordovician Bald Eagle Sandstone, Lower Silurian Tuscarora Sandstone and Rose Hill Shale, Lower Devonian Oriskany Sandstone, Middle Devonian Mahantango Formation, and Lower Mississippian Pocono Sandstone (Fig. 1a). Samples from the San Juan dome are from the Devonian McCracken Sandstone Member of the Elbert Formation (Fig. 1b).

Samples from the Tuscarora, Oriskany and McCracken Sandstones are quartz arenites composed of >95% quartz detrital framework grains with quartz overgrowth cement. Most are well sorted with grain sizes typically 100–400 μm. Intragranular porosity ranges from <2% in some Tuscarora Sandstone samples to as much as 15% in the Oriskany Sandstone. The Pocono Sandstone samples range from a coarse-grained (~400 μm grain size) quartz arenite to lithic arenite or wacke. Samples from the Martinsburg Formation, Bald Eagle Sandstone, and Mahantango Formation are fine to medium-grained (~50 to 250 μm grain size) lithic wackes. The Rose Hill Shale sample is a hematite-cemented quartz arenite. In all samples, illite is the dominant matrix mineral.

In each of the sandstone samples, microcrystalline quartz bands are visible in outcrop or hand sample as light-colored seams (Fig. 2a) that range in thickness from 30 μm to a few cm, and in length from 100 μm to several meters (Fig. 3). Geometrically, they vary from planar to curviplanar to highly irregular and exist individually or as multiple, subparallel, or anastomosing bands. They are most common in areas of more intense deformation, such as fault zones (Fig. 3a and c), fold hinges, and overturned fold limbs, but they are also found in subhorizontal strata, away from any significant larger structures (Fig. 3d). Their spatial association with faults can be seen by a decrease in number and thickness away from the fault (compare Fig. 3a and b). Preferred orientations or predictable geometric relationships with larger structures, such as parallel to faults (Fig. 3a), may or may not be present.

As seen in thin section (Fig. 2b and c), the bands are filled with anhedral quartz with a grain size of 5–20 μm (Fig. 2c) regardless of the composition or grain size of the wall rock. X-Ray diffraction analysis of the band fill shows that it is α-quartz and not a less ordered polymorph, such as opal CT. As seen in TEM, individual quartz grains in the fill have low dislocation densities (Fig. 2d), which is in contrast to the high dislocation densities of wall rock grains. The contacts between the bands and wall rock as seen in polarized light are generally irregular and gradational. The similar optic orientation of grains at the margins of the band with adjacent wall rock grains indicates that they are syntaxial overgrowths (Fig. 2e). Many bands are zoned with finer-grained margins grading to a coarse-grained, sometimes vuggy core with euhedrally terminated quartz crystals up to 1 mm long (Figs. 2f and 4a). In addition to the grain size variation related to the vuggy cores, the fill can have a distinct banding defined by color and texture variations (Fig. 4b).

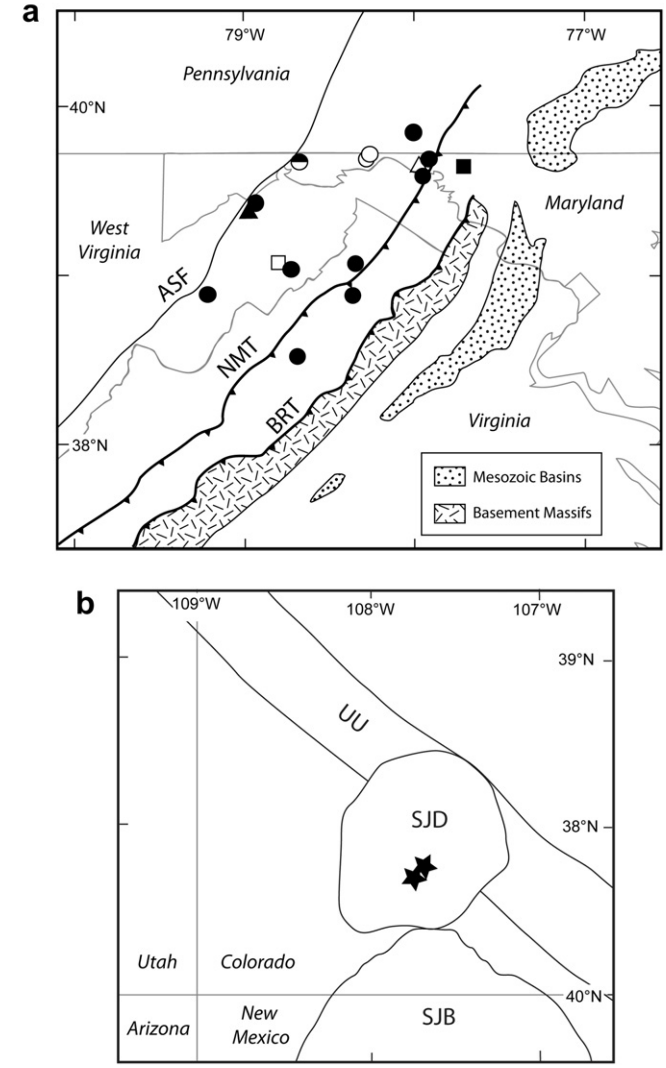

Fig. 1. Regional tectonic maps showing location of samples described in this study. (a) Central Appalachians. BRT – Blue Ridge thrust; NMT – North Mountain thrust; ASF – Alleghany structural front. Sample symbols: filled circle – Tuscarora Sandstone; open circle – Pocono Sandstone; half-filled circle – Bald Eagle Sandstone; filled triangle – Rose Hill Shale; open triangle – Mahantango Formation; open square – Oriskany Sandstone; filled square – Martinsburg Formation. (b) Southwest USA. UU – Uncompahgre uplift; SJD – San Juan dome; SJB – San Juan basin. Filled star – McCracken Sandstone.

In cathodoluminescence (CL), the band fill is uniformly dark in comparison to the brighter blue or reddish-brown luminescing wall rock grains (Fig. 4e). Some bands contain recognizable wall rock grains, but many do not. In some bands, what appear in polarized light to be wall rock fragments are grains with the same dark luminescence as the rest of the band fill (Fig. 4c and d). When viewed in CL, the bands are wider and have sharper contacts than when viewed in polarized light (Fig. 4e and f).

Kinematically, the bands can be classified as shear plus dilation or dilation alone by matching features on opposing walls. About 40% of the bands examined display shear across the band with wall-parallel displacements ranging from a few to several hundred microns (Fig. 5a). Dilation occurred in these cases also, as displacement vectors for the change in position of one wall with respect to the

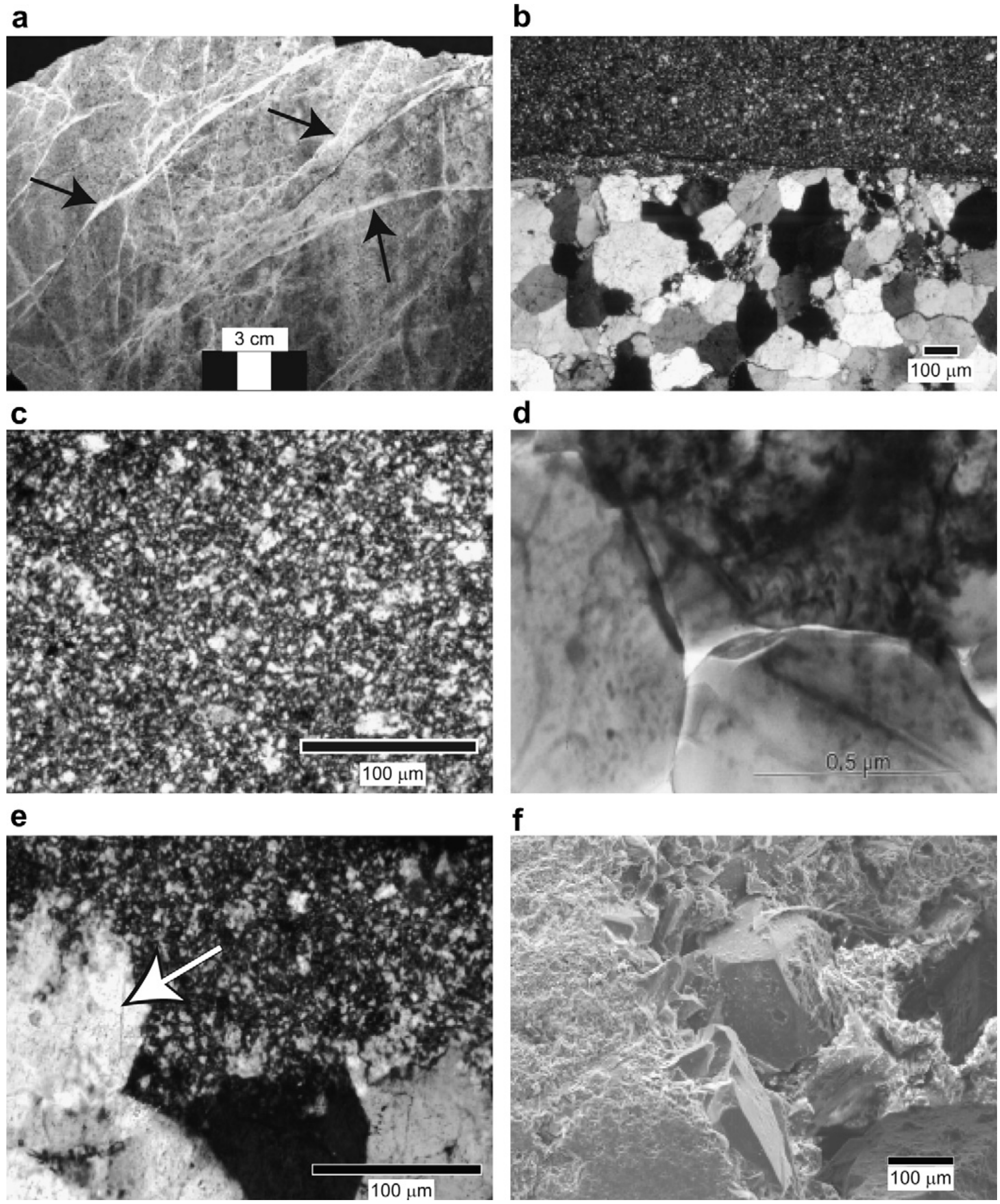

Fig. 2. Characteristics of microcrystalline quartz bands in Tuscarora Sandstone. (a) Handsample with several bands (arrows). (b) Sharp contact of microcrystalline quartz band with wall rock below. (c) Typical texture of band fill. (d) Brightfield, high resolution TEM micrograph of quartz grains in band fill. "Orange peel" texture is a result of beam damage. Note lack of dislocations. (e) Details of contact between band above and wall rock below. Note the gradational nature of contact and syntaxial overgrowth on wall rock grain that extends into band (arrow). (f) SEM micrograph of vuggy zone in center of band with euhedrally terminated quartz crystals. Note uniform fine grain size and texture of quartz surrounding the vug. (b, c, e) Cross-polarized light.

other are wall-oblique and not wall-parallel (Fig. 5a). About 20% of the bands show only dilation (Fig. 5b). The remaining 40% of the bands lack matching features from the two walls so displacement is not known (e.g., Fig. 5e and f). While all kinematic types occur in each structural location, those with shear and dilation are more common in the vicinity of faults.

On a thin section scale, most bands are somewhat planar in profile, but some are highly irregular (Fig. 5c). Individual bands may start and end abruptly, sometimes in a single grain (Fig. 5d). In many samples, the bands are parallel to microveins and fluid inclusion planes (Fig. 5e) in adjacent wall rock grains. No relationship was seen between the grain size of the quartz fill and the thickness of the band or amount of displacement for those where wall-parallel displacement could be documented.

2.1. Water concentration in microcrystalline quartz bands

Fourier Transform Infrared (FTIR) spectroscopy was used to measure the intracrystalline water concentration in the wall rock quartz grains and the microcrystalline quartz fill within the bands from the Tuscarora Sandstone. Spectral data were collected from individual spots along step-scan traverses across cataclastic bands in 100–200 μm thick, doubly polished plates using a 50 μm × 50 μm aperture. In the wall rock, the aperture was placed in the center of detrital grains to avoid grain boundaries, which may contain adsorbed water (Kronenberg and Wolf, 1990). Using the 3400 nm peak (Kronenberg and Wolf, 1990; Nakashima et al., 1995), the water concentration was calculated by:

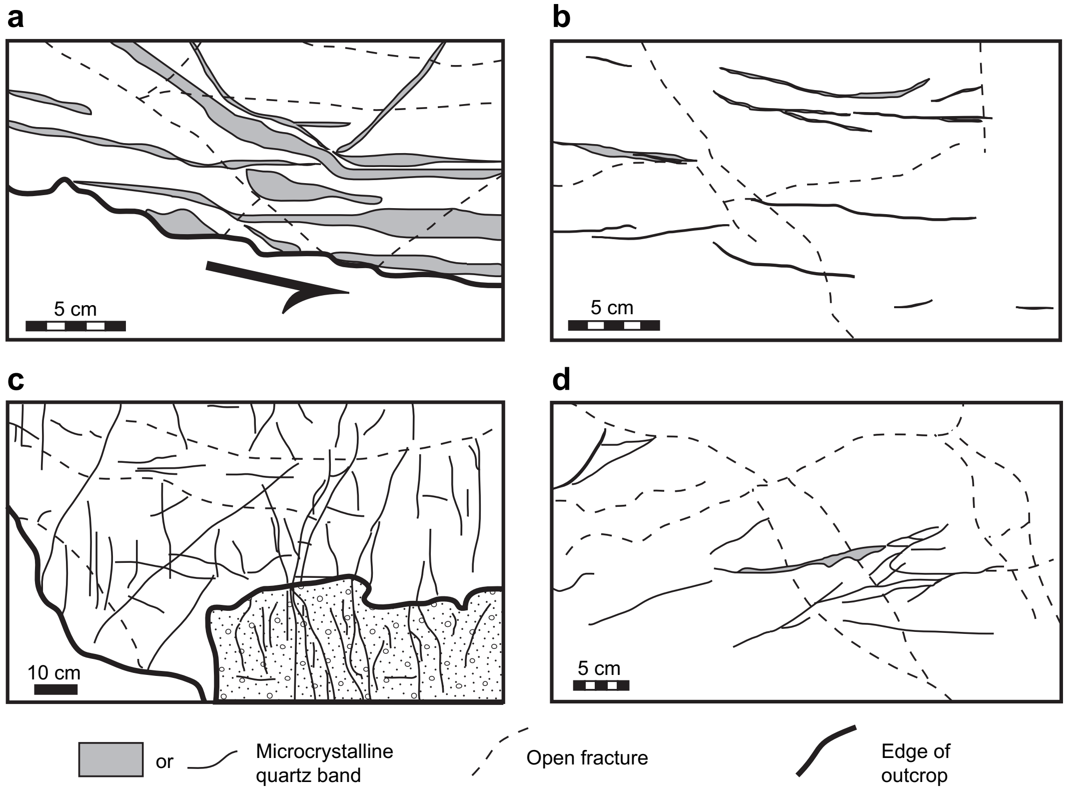

Fig. 3. Sketches from outcrop photos showing characteristics of microcrystalline quartz bands. (a) Concentration of thick bands near bedding-parallel slip surface (bottom edge of outcrop in sketch) in Oriskany Sandstone. Amount of slip is unknown, but probably <10 cm. (b) Same outcrop as (a), but 3 m from slip surface (measured normal to surface). Note decrease in thickness and density of bands. (c) Bedding surface within horse of Tuscarora Sandstone in regional fault zone showing abundance of microcrystalline quartz bands. A large number of bands subparallel to the bedding surface are also present, but not shown in sketch. Stippled area is different bedding surface than rest of sketch. (d) Microcrystalline quartz bands in Tuscarora Sandstone on northwest limb of regional anticline. Bedding dips 20° to left.

$$\text{Water concentration} = (1.05 \times A_{\text{cor}})/t \times 10^4 \quad (1)$$

where, A_{cor} is the area under the absorption curve determined through integration of the 3400 nm peak after removal of background, and t is the thickness of the sample, determined by micrometer (Nakashima et al., 1995). The coefficient (1.05) is based on calibration in synthetic quartz by Aines et al. (1984). Recent work by Stipp et al. (2006) indicates that this value may underestimate the water concentration. Water concentrations are reported in $H^+/10^6Si$ (i.e., ppm H^+/Si).

In the Tuscarora Sandstone, the water content in the bands is an average 6000 $H^+/10^6Si$ less than the adjacent wall rock grains (Fig. 6). Large variations in water content of the detrital grains from less than 4000 to over 20,000 $H^+/10^6Si$ appear to be characteristic of the Tuscarora Sandstone and are believed to be proportional to the degree of crystal-plastic deformation (O'Kane et al., 2007).

2.2. Oxygen isotope geochemistry

The oxygen isotopic composition in the microcrystalline quartz fill of the bands and the wall rock was determined on a gas source mass spectrometer at the University of Michigan using conventional BrF_5 extraction techniques. Wall rock samples were prepared by homogenizing at least 25 randomly picked grains collected from at least 2 mm away from the contact with the band. Samples from the microcrystalline quartz bands were prepared by hand-picking fragments from a 100–200 μm thick, polished plate that was fractured after being adhered to double-sided tape. Care was taken to avoid wall rock grains that might adhere to the microcrystalline quartz of the band. All samples were acid washed to remove any iron oxide stain. The data are reported in ‰ VSMOW (corrected to NBS-28) and have a precision of ±0.2 ‰ (1σ). Duplicates were run for most samples.

Wall rock $\delta^{18}O$ values range from 10.2 to 15.2‰ VSMOW, whereas $\delta^{18}O$ for quartz in the bands ranges from 12 to 26‰ (Fig. 7). In every sample analyzed, the quartz in the band is isotopically heavier than the wall rock grains (Fig. 7). The difference is greatest (up to 9.6‰) in the CF Tuscarora Sandstone samples, which are from a major fault zone. RF Tuscarora Sandstone samples, which are from a moderately dipping fold limb, average 2.3‰ higher whereas those in the McCracken Sandstone, which are from gently dipping beds, average 1.6‰ higher than wall rock grains.

3. Discussion

A number of lines of evidence indicate that these microcrystalline quartz bands did not all originate during wall-parallel displacement across the bands and that the microcrystalline quartz filling the bands is not always comminuted wall rock. Observations relevant to this assessment include the following.

(1) A number of bands only show only wall rock geometries consistent with positive dilation. A prerequisite for cataclasis is shearing (Engelder, 1974; Blenkinsop, 2000). Some bands show evidence for wall-parallel displacement (Figs. 4e–f, 5a), and others may have had out-of-plane motion where no form of geometric fit exists between the two sides of wall rock visible in the thin section (Fig. 5e). Still, many bands only show

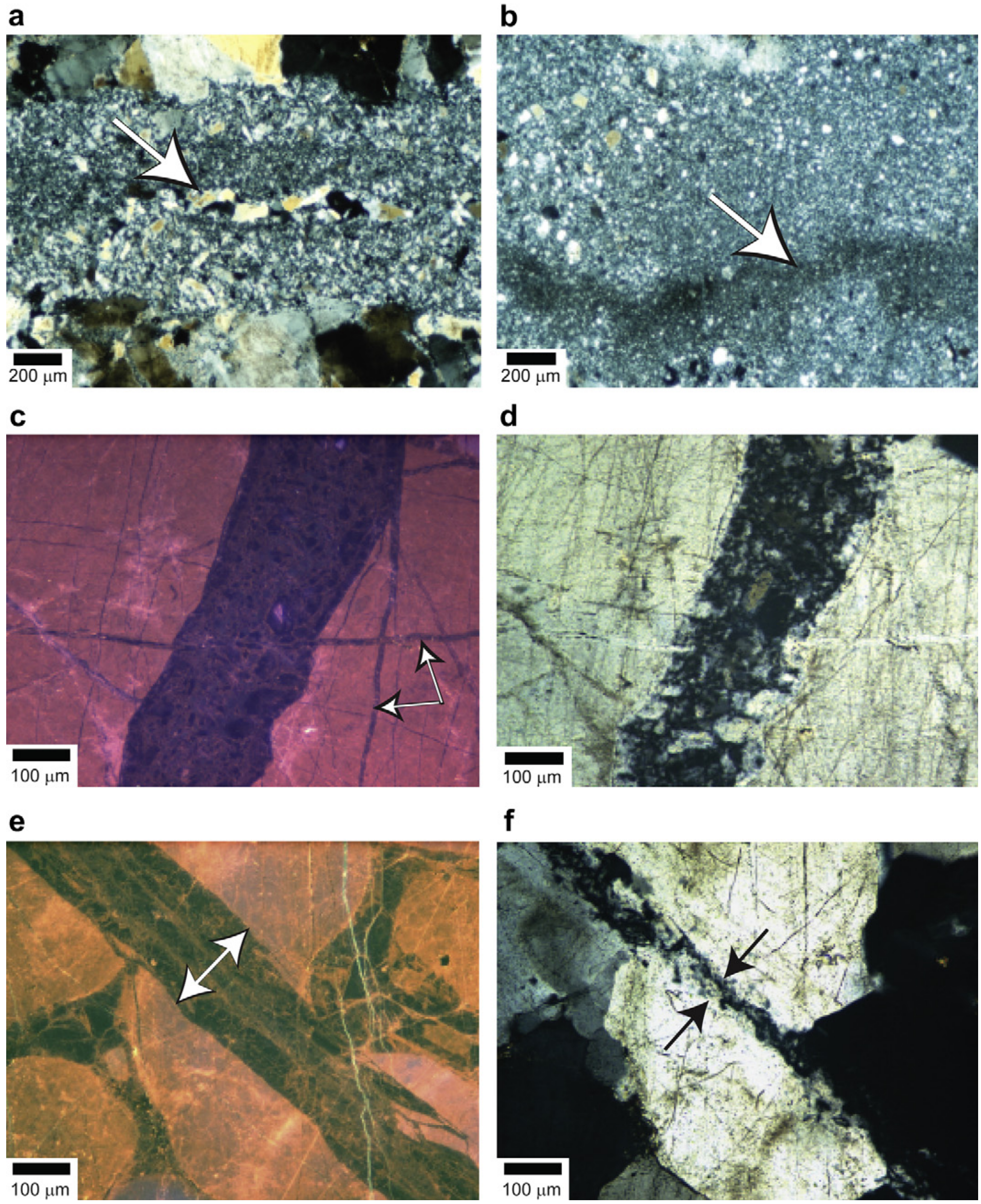

Fig. 4. Thin section features of microcrystalline quartz bands. (a) Band with coarse-grained, vuggy center (arrow). (b) Wavy banding (arrow) within microcrystalline quartz band. (c–d and e–f) Matched cathodoluminescence (CL) and polarized light (PL) photomicrographs of microcrystalline quartz bands in Tuscarora Sandstone. (c–d) Band with wall-normal displacement and no shear. Note what appear in PL (d) to be wall rock fragments in the band have same luminescence (c) as rest of fill, not the luminescence of wall rock grains. Note also that band has same luminescence as cement in cross-cutting microveins (arrows in c). (e–f) Band with both wall-normal and shear displacements. Note disparity between CL (e) and PL (f) in band width (arrows). Band is much wider in CL.

a geometric fit consistent with wall-normal displacement related to positive dilation (Fig. 5b and c).

(2) Some bands have non-planar band walls in profile (Fig. 5c) precluding wall-parallel motion either in the plane or oblique to the plane of observation.

(3) The bands are often parallel to microveins and fluid inclusion planes (Fig. 5e), which are positive dilational structures. These structures could differ in age, and hence, be unrelated in terms of causative stresses, but mutual cross-cutting relationships indicate that they are coeval. Parallelism with coeval extensional structures would also preclude any significant shear stress parallel to the band.

(4) Band width and grain size of the quartz fill do not correlate. Many shear zones show a relationship between shear displacement magnitude and grain size for the fault rock (Scholz, 1987; Hull, 1988; Evans, 1990; Power and Tullis, 1989). In our samples, the grain size of the quartz fill is similar regardless of whether geometric evidence for wall-parallel displacement exists or not. Where evidence for shear displacement exists, the amount of displacement does not correlate to grain size. Lack of correlation between grain size and displacement was also noted by Lloyd and Knipe (1992) who found “low displacement” (<100 μm) shear zones with well-developed cataclasite.

(5) Most bands do not contain recognizable wall rock fragments. What appear in polarized light to be fragments in the band have the same dark luminescence as the microcrystalline fill, not that of the wall rock grains (Fig. 4c and d). The lack of wall fragments is particularly problematic for a shear origin because

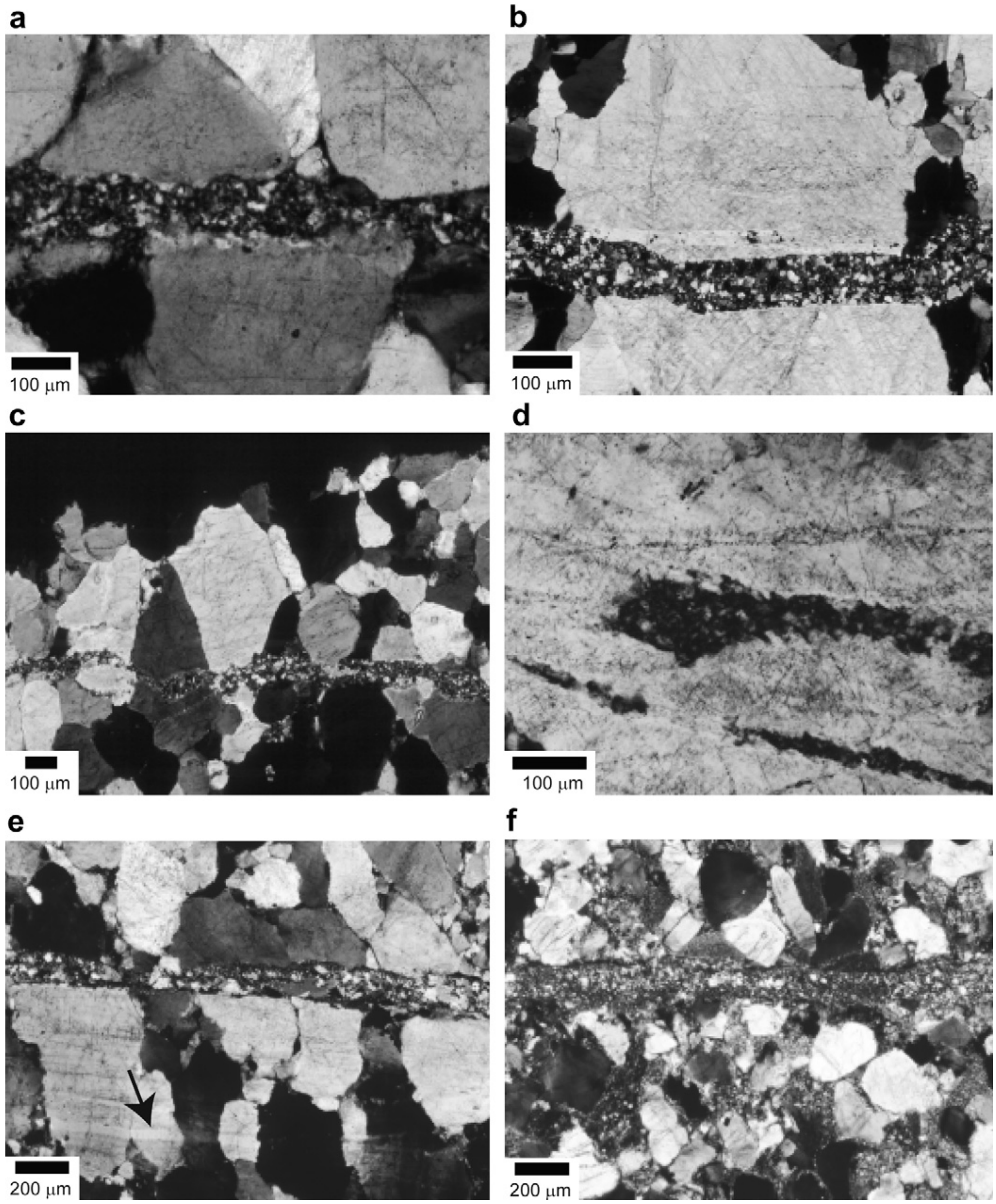

Fig. 5. (a–e) Movements associated with formation of microcrystalline quartz bands in Tuscarora Sandstone. (a) Wall-parallel shear displacement across band. (b) Band with only wall-normal displacement. (c) Wavy geometry of band. Note that there is little or no shear parallel to band. (d) Microcrystalline quartz band terminating in a single detrital grain. Note that texture of band does not change as aperture changes. (e) Microcrystalline quartz band parallel to fluid inclusion planes (horizontal dark lines) and microveins (arrow). (f) Microcrystalline quartz band in Bald Eagle Sandstone. Sandstone is a lithic wacke with abundant argillite rock fragments and clay matrix; yet, band is composed entirely of quartz with same texture as bands in quartz arenites. Cross-polarized light.

cataclasis involves the progressive grain size reduction through microfracturing of wall rock grains. It could be argued that shearing progressed to the point that all recognizable fragments were destroyed, except shear displacement cannot always be demonstrated, and where it has occurred, tends to be minimal. Convincing evidence against comminution is that bands consisting entirely of microcrystalline quartz were found in clay-rich rocks of the Martinsburg Formation, Bald Eagle Sandstone (Fig. 5f), and Mahantango Formation, and a hematite-cemented sandstone in the Rose Hill Shale. No wall rock fragments were found in bands in these rocks.

(6) The contact between wall rock and band is gradational with fine-grained quartz syntaxially overgrowing wall rock grains. The gradational contact between band and wall rock (Fig. 2e) is also inconsistent with a shear origin, but can be explained if the fill is cement precipitated in a dilated fracture. This origin would also explain what appear to be syntaxial overgrowths on wall rock grains.

(7) The microcrystalline quartz fill has a low dislocation density (Fig. 2d). If the fill is comminuted wall rock, then the grains should have a high dislocation density as a consequence of the shearing. A low dislocation density was also found in some cataclasites by Knipe (1991), who attributed it to recovery.

(8) The bands are filled with quartz, regardless of the composition of the host rock (Fig. 5f).

(9) The microcrystalline quartz fill has a different luminescence, water concentration, and oxygen isotopic composition than the wall rock grains. The luminescence difference indicates that trace element chemistry is not the same between fill and wall rock (Marshall, 1988; Muller et al., 2003; Gotze et al., 2005)

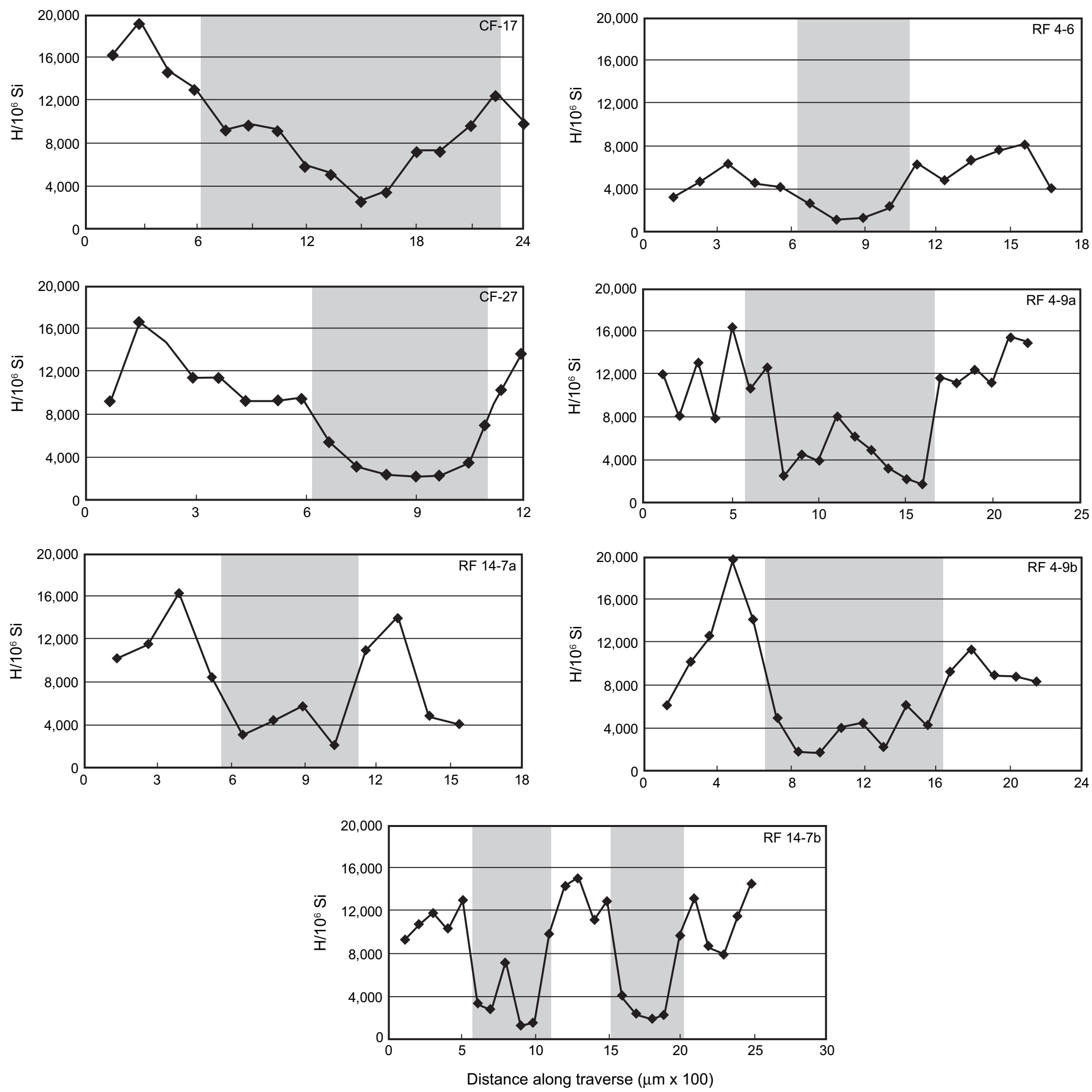

Fig. 6. Water concentrations ($H^+/10^6$ Si) in microcrystalline quartz bands and adjacent wall rock in the Tuscarora Sandstone as determined from FTIR step-scan traverses. Horizontal axis is the distance along sample traverse ($\mu m \times 100$) with shaded portion along each traverse being microcrystalline quartz band and unshaded part, wall rock. Aperture window was $50\ \mu m \times 50\ \mu m$.

(Fig. 4c and d). The water concentration data show that the microcrystalline quartz in most samples has less intracrystalline water than the wall rock grains (Fig. 6). Wall rock grains do have recognizable fluid inclusions, which might account for the greater water concentration; however, water in optical-scale fluid inclusions is generally not detected by FTIR (Kronenberg et al., 1990; Kronenberg and Wolf, 1990). Rather, the greater water concentrations in the wall rock grains are believed to reflect the greater crystal-plastic deformation (O'Kane et al., 2007; Onasch et al., 2009). The oxygen isotope data (Fig. 7) indicate that the composition of the microcrystalline quartz fill cannot be explained by being sourced from the wall rock through comminution, but must have been precipitated from a fluid. The variation of the $\delta^{18}O$ composition of the bands between samples (Fig. 7) is thought to reflect differences in the parent fluid isotopic composition (Clayton et al., 1972) arising from their different structural settings. The band fill in the DEM and RF samples, which are from fold limbs, was precipitated from isotopically light fluid in a regional, meteoric-dominated system, whereas bands in the CF samples precipitated from isotopically heavy formation fluids channelized in regional fault zone (O'Kane et al., 2007).

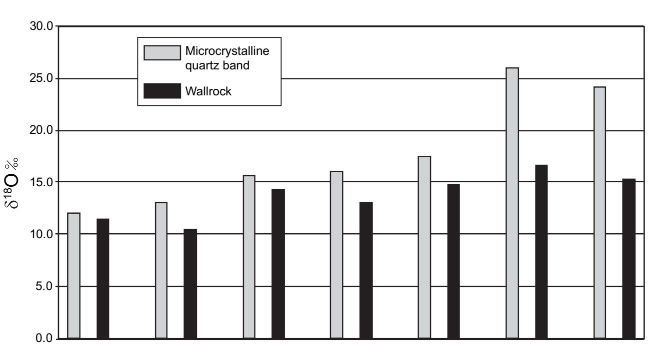

Fig. 7. Comparison of oxygen isotopic composition (per mil relative to VSMOW) of microcrystalline quartz bands with adjacent wall rock for McCracken Sandstone Member (DEM sample numbers) and Tuscarora Sandstone (RF and CF sample numbers).

3.1. Model for formation of microcrystalline quartz bands

The two processes that yield microcrystalline quartz bands during deformation of well cemented, quartz-rich rocks are dilation and precipitation of quartz cement. Shearing may occur, but is not required. Releasing bends along faults, or propagation or reactivation of Mode I fractures with high fluid pressures are conditions for having dilational deformation with or without shearing (Laubach, 1988; Sibson et al., 1988; Sibson, 1990; Bangs et al., 1996; Cook et al., 2006; Woodcock et al., 2007). Concurrent precipitation during dilation is needed to create the bands.

Quartz cement in intergranular porosity or dilated fractures is precipitated from a fluid (e.g., McBride, 1989; Worden and Morad, 2000) the nature of which may vary depending on the physicochemical conditions. While silica can be precipitated at depths of <1 km in an amorphous form (Fournier, 1985), most models for the formation of quartz cement at greater depths assume precipitation from an aqueous fluid supersaturated with respect to the higher order polymorphs of silica (i.e., quartz). Some studies, however, have found evidence for an amorphous silica precursor to vein quartz (Stel, 1981; Herrington and Wilkinson, 1993; Stel and Lankreyer, 1994) or detrital grain overgrowths (Goldstein and Rossi, 2002). Because the texture of the fill in the microcrystalline quartz bands is atypical of that filling most veins, precipitation from both an aqueous fluid and from a silica gel will be considered.

3.1.1. Precipitation from an aqueous fluid

The grain size of minerals precipitated from a solution is controlled by the competition between the nucleation rate and the crystal growth rate (Vernon, 2004; Sunagawa, 2005), along with the nature of the substrate (Lander et al., 2008). For the microcrystalline quartz in the bands, the nucleation rate exceeded the growth rate. At a low degree of supersaturation of the fluid with respect to the mineral being precipitated, this condition can be brought about by a large number of nucleation sites (Vernon, 2004). At a high degree of supersaturation, rapid nucleation will take place regardless of the number of sites (Fournier, 1985). The presence of discontinuities (e.g., inclusions) on a growth surface can also lead to a fine grain size of minerals growing on that surface because they break the surface into separate smaller crystal domains (Lander et al., 2008). The surface of a Mode I fracture transecting well cemented, coarse-grained sandstone, would be relatively free of inclusions or other discontinuities (Lander et al., 2008) so one would predict large grain sizes growing there. Therefore, the uniform fine grain size of the microcrystalline quartz band fill appears to be the product of rapid precipitation from a supersaturated fluid.

Supersaturation of an aqueous fluid with respect to quartz can be brought about by a number of physical or chemical changes that lower the silica solubility, including a drop in pressure and/or temperature, decrease in pH, or decrease in electrolyte concentration (at low fluid densities). Assuming the rock is saturated, a rapid fluid pressure drop can be accomplished by Mode I fracturing (Engelder, 1992) or motion along a non-planar fault (Sibson et al., 1988), both of which create new space for an existing volume of incompressible fluid. This process would be most effective if the change is so rapid so that reequilibration by slow crystal growth cannot occur. Seismogenic stress drops where fluid pressure decreases from lithostatic to hydrostatic have been described or inferred in a number of active fault zones (Sibson et al., 1975; Sibson et al., 1988).

For the Appalachian sandstone samples examined, which deformed at ~6 km (Epstein et al., 1977; Harris et al., 1978; Onasch and Dunne, 1993; O'Kane et al., 2007), an adiabatic fluid pressure drop from lithostatic (156 MPa) to hydrostatic (60 MPa) pressure at 250 °C would lower the solubility of quartz in pure water by 0.084 g of SiO_2/kg H_2O (Fournier and Potter, 1982). At 60 MPa pressure and 250 °C, 1 kg of water has a density of 0.85 g/cm^3 (Burnham et al., 1969) and would occupy 1176.5 cm^3. The 0.084 g of quartz precipitated from the pressure drop occupies only 0.032 cm^3, so it is clear that insufficient quartz is produced to fill a fracture from a single volume of fluid under these conditions. Repeating the process with multiple volumes of fluid could cement the fracture (Eichhubl and Boles, 2000). Episodic fluid flow and cementation can result in alternations of cement mineralogy or texture, banding consisting of inclusions or wall rock fragments, and/or concentric zoning in cement minerals The homogeneous, fine-grained fill of the microcrystalline quartz bands shows none of these features, so evidence for multiple fluid flow-precipitation events is lacking.

A temperature drop also lowers the solubility of quartz (Fournier, 1985) and might be expected if warm fluids encounter a cooler wall rock during fracturing. A 50 °C temperature drop (250–200 °C) would yield 0.288 g (or 0.109 cm^3) of SiO_2/kg H_2O from an initially saturated fluid (Fournier and Potter, 1982). One kilogram of water at 200 °C and 160 MPa occupies 1055.2 cm^3 (Burnham et al., 1969) so again, the potential volume of quartz precipitated is insufficient to fill the fracture. A combined temperature and pressure drop does yield more quartz, but it still falls short by more than two orders of magnitude of filling the fracture with quartz from a single volume of fluid.

Changing the pH enough to supersaturate the fluid with respect to quartz is unlikely because quartz solubility is only significantly affected by a pH of greater than 9 (Fyfe et al., 1978), a condition found only in near-surface weathering environments (Drever, 1997). Changes in electrolyte concentrations are also unlikely to bring about supersaturation because they do not greatly affect quartz solubility at the pressures and temperatures at which these rocks were deformed (Fournier and Marshall, 1983; Fournier, 1985; Evans, 2007).

Another way of supersaturating a fluid with respect to quartz is to bring it into contact with very fine-grained quartz. Stel and Lankreyer (1994) proposed that quenching a hot fluid against cool wall rock in a fault zone, enhanced by admixture of fine silica particles produced by grinding of quartz, resulted in a state of supersaturation. Grinding not only reduces the grain size thereby increasing surface area, but it also disorders the quartz, which greatly increases its solubility (Wintsch and Dunning, 1985; Blum et al., 1990). This model appears not to apply to the microcrystalline quartz bands because of the lack of evidence for shearing and comminution of wall rock.

3.1.2. Precipitation from a silica gel

Given the difficulty of identifying a probable cause for supersaturation of an aqueous fluid and that crystallizing 5–20 μm anhedral even from a supersaturated aqueous fluid is problematic, another possible explanation is to crystallize from a silica gel rather than an aqueous fluid. A supporting observation for this hypothesis is that textures similar to those in the microcrystalline quartz bands were described in low temperature basement fault zones by Stel (1981) and Stel and Lankreyer (1994). Additionally, the existence of gels in fault zones has been argued from field observations (Power and Tullis, 1989) and rock mechanics experiments (Di Toro et al., 2004). Occurrence of vein quartz with a microcrystalline texture is not restricted to fault zones. Microcrystalline quartz in veins in the Miocene Monterey Formation is believed to have precipitated from amorphous silica derived from opal-CT dissolution in the host rock during diagenesis (Eichhubl and Boles, 1998). Evidence consists of radially sweeping, feathery extinction in some larger quartz grains suggesting a chalcedony precursor. The presence of geopetal structure indicates that mineral growth occurred into a fluid-filled cavity during diagenesis and is not related to faulting.

Crystallization from a silica gel is consistent with many observations in the microcrystalline quartz bands. The uniform grain size would be a product of homogeneous nucleation within the fluid (Iler, 1979). If crystallization were from less saturated (i.e., aqueous) fluids, crystal growth would initiate on the walls and proceed inward with a progressive increase in grain size toward the center of the void resulting in a cock's comb texture (Vearncombe, 1993). The vuggy center observed in a number of bands can be explained by the shrinkage that accompanies crystallization of a gel as a true aqueous solution is expelled from the polymer (Oehler, 1976; Sweetman and Tromp, 1991). The expelled fluid, now trapped in shrinkage voids, would crystallize in a normal fashion to euhedral crystals. As these crystals grow, they lower the concentration of silica in fluid in the vug, which can readily dissolve the more soluble amorphous silica around the vug margins, thereby allowing more euhedral crystal growth in the vug (Sweetman and Tromp, 1991).

Crystallization from a gel of amorphous silica is also attractive because amorphous silica is up to an order of magnitude more soluble than quartz (Fournier and Rowe, 1977). For example, the pressure drop from lithostatic to hydrostatic yields 0.550 g SiO_2/kg H_2O compared to 0.084 g for precipitation of quartz from an aqueous fluid. Despite the increased solubility, a fracture still cannot be filled by the silica precipitating from a single volume of solution. However, the required fluid-rock ratio is greatly reduced.

What is missing in the microcrystalline quartz bands is direct evidence for a gel precursor, such as sphereulites or chalcedony (Stel, 1981; Stel and Lankreyer, 1994; Eichhubl and Boles, 1998). Banding, such as might have resulted from flow of a viscous gel was observed in some bands (Fig. 4b), but its origin is equivocal. Yet, this type of textural evidence could be absent from the sandstones because the primary textures from precipitation from a gel would not be preserved. At the temperatures of deformation (200–250 °C), amorphous silica is thermodynamically unstable and would be rapidly replaced by anhedral quartz (Fournier, 1985; Herrington and Wilkinson, 1993); hence, preservation of sphereulites or chalcedony would not be expected. The isotopic data might be used to evaluate the existence of a gel precursor; however, there is insufficient difference between quartz–water and amorphous silica–water fractionation to be useful (Kita et al., 1985).

3.2. Comparison to deformation bands in porous sandstones

These bands of microcrystalline quartz have some similarities to deformation bands in porous sandstones, which are tabular zones of shear with or without a component of dilation (Fossen et al., 2007). Kinematically, they can be classified as shear bands, dilation bands, or compaction bands (Aydin et al., 2006). Deformation occurs by grain reorganization, fracturing, sliding, and or rotation (Aydin, 1978; Fossen et al., 2007). Texturally, the microcrystalline quartz bands bear some resemblance to compaction bands (Mollema and Antonellini, 1996); however, evidence for shortening across the bands is lacking. Thus, while cataclastic faults and microcrystalline quartz bands are kinematically equivalent to shear and dilation bands, respectively, the difference in host rock and deformation conditions causes microtextural differences. The well cemented sandstones that host the cataclastic faults and microcrystalline quartz bands do not show the variation in porosity between host rock and fault/band because porosity was essentially absent at the onset of deformation. Secondly, while shear bands and cataclastic faults will involve fractured grains, the microcrystalline quartz bands differ from dilation bands because the former are the result of the precipitation of new mineral grains from a fluid most likely derived from outside the bands.

3.3. Implications for the formation of cataclasite in fault zones

Formation of the microcrystalline quartz by precipitation from a fluid, rather than by wall rock comminution, has important implications for the importance of dilation and cementation in fault zones of all scales. Quartz-rich sandstones in the footwall of the North Mountain thrust (Fig. 1a), a major thrust in the central Appalachians with up to 60 km of displacement (Evans, 1989) contain abundant cataclasite along much of its strike length. Stratal disruption, brecciation, and measurable shear displacement of clasts attest to the origin of this rock by shearing. The same features occur with smaller faults in quartz-rich sandstones across the Appalachian foreland (e.g., Wu and Groshong, 1991; Harrison and Onasch, 2000; Cook et al., 2006). Common to all these cataclasites is a fine-grained quartz matrix that is up to 50% of the rock volume. This fine-grained quartz shares a number of characteristics with that in the microcrystalline quartz bands, including grain size, texture, vugs with euhedral crystals, and different CL from the wall rock clasts (Fig. 8). In addition, this microcrystalline quartz fills in voids between clasts that separated without shearing. Our conclusion is that fine-grained quartz in the cataclasites, like that in the microcrystalline quartz bands, is a cement that precipitated from a silica gel. If so, then the importance of dilation and cementation in the formation of cataclasite is more important than previously thought.

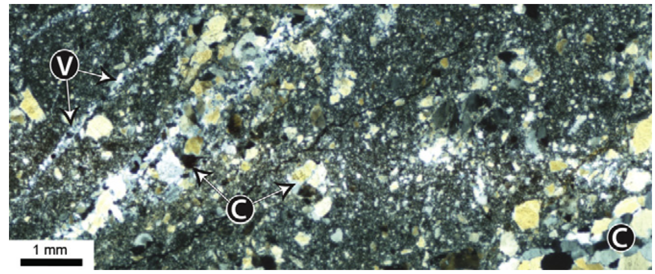

Fig. 8. Photomicrograph mosaic of Tuscarora Sandstone showing texture of cataclasite along a minor fault (displacement ~1 m) in a fold hinge located in the westernmost anticline of the Appalachian fold-thrust belt. Fine-grained matrix has many characteristics of microcrystalline quartz bands. V – vugs; C – wall rock clast.

4. Conclusions

Field, textural, and geochemical data argue that tabular microcrystalline quartz bands in well cemented sandstones originate by the rapid precipitation of fine-grained quartz in dilating fractures: in essence, they are veins. Wall-parallel shear and grain comminution are not necessary for their formation. Certain characteristics of the bands, such as the uniform grain size, flow-like banding, and vugs lined with euhedral quartz crystals, suggest that the parent fluid was a silica gel. If this model for the formation of fine-grained quartz can be extended to the texturally similar matrix in volumetrically significant cataclasites in fault zones, then the amount of dilation and cementation in these zones may have been underestimated.

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