Journal of Structural Geology 74 (2015) 24–30

Contents lists available at ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

An experimental investigation of the role of microfracture surfaces in controlling quartz precipitation rate: Applications to fault zone diagenesis

Randolph T. Williams*, John R. Farver, Charles M. Onasch, Daniel F. Winslow[1]

Department of Geology, Bowling Green State University, Bowling Green, OH 43403, USA

A R T I C L E I N F O

Article history:
Received 3 November 2014
Received in revised form
18 February 2015
Accepted 24 February 2015
Available online 5 March 2015

Keywords:
Quartz cement
Fault
Diagenesis
Deformation band
Microfracture
Experiment

A B S T R A C T

We present the results of quartz growth experiments, which were designed to assess the role of microfracture surfaces in controlling quartz-precipitation rates during fault-zone diagenesis. Experiments were run in hydrothermal cold-seal vessels at 300–450 °C and 150 MPa confining pressure for up to 1344 h. Microfractures routinely form at grain contacts during these experiments. Microfracture kinematic-aperture distributions indicate that microfractures form within the first 48 h of each experiment. Regardless of experimental temperature or duration, microfracture-sealing cements account for approximately the same amount of new quartz cement in each experiment. With increasing experimental duration, sealed microfractures were progressively overgrown by grain-boundary overgrowth cements. Spatial and temporal trends in the distribution of overgrowth- and microfracture-sealing cements indicate that precipitation rates on newly formed microfractures greatly exceed those on detrital-grain boundaries. This effect persists regardless of natural iron-oxide grain coatings present in a subset of our experiments. While our results agree with previous research that demonstrated increased growth rates on fracture surfaces in faults in fully lithified rock, fundamental differences in the nature of deformation in our experiments provide insight into quartz cementation in cataclastic deformation bands in faults offsetting high-porosity sandstones.

1. Introduction

Accurate prediction of fault-zone permeability structure is fundamental to our understanding of subsurface fluid migration, a subject of great interest to both petroleum geologists and those assessing potential CO_2 sequestration reservoirs. Structures (e.g., deformation bands, transgranular fractures, dissolution surfaces) formed during fault slip substantially impact fault-zone permeability, and the types and distribution of structures within a fault zone is generally considered to be a primary control on fault-zone fluid-flow potential (Chester and Logan, 1986; Caine et al., 1996; Evans, 1997; Yielding et al., 1997). Research examining fault-zone architecture has typically assumed the fault damage zone to be typified by the presence of transgranular fractures. Damage zones were therefore considered to be zones of high permeability when compared to the fault core or protolith (Chester and Logan, 1986; Caine et al., 1996; Evans, 1997). However, subsequent examination has shown that particulate flow and/or deformation-band formation are the dominant deformation behaviors in faults in poorly lithified sands and high-porosity sandstones (Aydin and Johnson, 1978, 1983; Antonellini et al., 1994; Heynekamp et al., 1999; Rawling and Goodwin, 2003, 2006; Eichhubl et al., 2010; Balsamo et al., 2012). Porosity reduction in these structures not only results in decreased permeability (Antonellini and Aydin, 1994; Fisher and Knipe, 1998; Sigda et al., 1999), but also provides a mechanism for the nucleation of tensile fractures and slip surfaces (Gabrielson and Koestler, 1987; Leveille et al., 1997; Fossen

* Corresponding author. Present address: Department of Geoscience, University of Wisconsin – Madison, 1215 W. Dayton St., Madison, WI 53706, USA. Tel.: +1 937 417 9688.

E-mail addresses: rtwilliams@wisc.edu (R.T. Williams), jfarver@bgsu.edu (J.R. Farver), conasch@bgsu.edu (C.M. Onasch), daniel.winslow@pxd.com (D.F. Winslow).

[1] Present address: Pioneer Natural Resources, 5205 N O'Conner Blvd, Irving, TX 75039, USA.

http://dx.doi.org/10.1016/j.jsg.2015.02.011
0191-8141/

et al., 2007). These structures may ultimately link to form through-going slip surfaces with increased displacement (Shipton and Cowie, 2001; Schultz and Balasko, 2003), and as such an improved understanding of their development during faulting is fundamental to predicting the development of fault-zone and permeability structure.

Diagenesis and cementation also exert a control on the mechanical and fluid flow properties of fault zones (Knipe, 1993; Eichhubl and Boles, 2000; Boles et al., 2004; Rawling et al., 2001; Eichhubl et al., 2009; Laubach et al., 2010). During diagenesis, the development of quartz cements may greatly increase the mechanical strength of sandstones through the formation of intergranular bonds (Dvorkin and Yin, 1995; Hiatt et al., 2007; Cook et al., 2011, 2015) that promote a transition from deformation band to transgranular fracture formation during faulting (Davatzes et al., 2003, 2005; Johansen et al., 2005). Conversely, quartz cementation in dilatant fault zones may also have the opposite effect, preserving porosity in large fractures and weakening the fault damage zone as precipitation rates decrease due to the development of slow-growing euhedral terminations (Lander et al., 2008; Lander and Laubach, 2015). The process of quartz cementation as it pertains to faults in fully lithified rock has received increased attention in recent years (e.g. Becker et al., 2010; Fall et al., 2014; Fisher and Brantley, 2014; Laubach et al., 2014; Lander and Laubach, 2015); still, additional work is required to fully understand the controls on quartz cementation in faults in high-porosity sandstones and how this process contributes to the development of fault-zone architecture.

In faults in high-porosity sandstones, damage zone strain is generally accommodated via deformation-band formation (e.g., Aydin and Johnson, 1978, 1983; Antonellini et al., 1994; Rawling and Goodwin, 2003, 2006; Eichhubl et al., 2010). When cataclasis is a significant component of deformation-band formation (see review by Fossen et al., 2007), microfracturing of detrital grains may lead to the localization of quartz cements in these structures (Fisher and Knipe, 1998; Milliken et al., 2005; Eichhubl et al., 2010). The preferential development of quartz cements inside cataclastic deformation bands may result from the disruption of iron-oxide or clay coatings, increased microfracture surface reactivity, or the generation of fast-growing non-euhedral growth substrates following microfracturing of detrital grains (Berner, 1980; Pittman, 1981; Fisher and Knipe, 1998; Milliken et al., 2005; Lander et al., 2008; Eichhubl et al., 2010). Quartz cementation in these structures contrasts sharply with that in opening-mode fractures, as the former involves a significant component of compaction rather than dilation (e.g., Antonellini and Aydin, 1994; Main et al., 2000; Mair et al., 2000; Eichhubl et al., 2010).

We present the results of hydrothermal cold-seal experiments designed to assess the role of microfracture surfaces in controlling the rate of quartz precipitation in deformation-band fault zones. Cementation followed a common pattern in all samples. Microfractures, which formed at grain contacts during initial pressurization of each experiment, were rapidly sealed by quartz cement. Sealed microfractures were later overgrown by grain-boundary overgrowth cements. Our results indicate that the rate of quartz cementation on microfracture surfaces exceeds that on detrital-grain boundaries regardless of whether those grains have iron-oxide coatings. This result is consistent with previous numerical modeling and outcrop examinations of quartz-cement accumulations in faults and fractures in fully lithified rock (Laubach, 2003; Laubach et al., 2014; Lander and Laubach, 2015) and provides a basis for understanding large accumulations of quartz cement inside deformation bands in faults offsetting high-porosity sandstones.

2. Methods

2.1. Experimental methods

This research utilized hydrothermal cold-seal experiments to assess the role of microfracture surfaces in determining the precipitation rate of quartz cements (Fig. 1). Au tubes (5 mm OD) were loaded with NaCl brine (25 wt. % NaCl), amorphous SiO_2, $AlCl_3$ (a luminescent tracer), and finally either fine-grained (90–125 μm) or mixed-grained (90–500 μm) disaggregated St. Peter sandstone. St. Peter sand grains are typically well-rounded, although a volumetrically minor subset of grains contain angular, euhedral quartz overgrowths (Mazzullo and Ehrlich, 1983). A subset of mixed-grain size experiments contained minor amounts of natural iron-oxide grain coatings, whereas the remainder of experiments used sand grains that were treated with a sodium hydrosulfite and sodium bisulfate solution to remove those coatings (Table 1). Charges were weighed following each material addition and weld-sealing of the Au tube. After welding, charges were placed into a 60 °C oven for 1 h and reweighed to test weld integrity. Charges were then loaded vertically into the cold seal vessel and experiments were considered to have begun once temperatures reached ±5 °C of the target temperature at a confining pressure of 150 MPa. Temperatures utilized for these experiments were either 300 or 450 °C at durations of 48, 168, 336, 672, and 1344 h (Table 1). Microfractures commonly form at grain contacts during the pressurization of each experiment.

Following removal from the cold seal vessel, charges were placed into a 60 °C drying oven for 1 h and weighed to ensure that no fluid had escaped during the experiment. Charges were then opened and dried in a 60 °C oven to a constant weight. Once dry, each sample was vacuum impregnated with a low viscosity epoxy (Epotek 301) and allowed to cure for 24 h prior to polishing and analysis. A Renishaw inVia Micro-Raman system equipped with a 785 nm laser was used to assess potential reactant recrystallization and ensure that infinite-reservoir conditions were satisfied with regards to the amorphous SiO_2 reactant. Reference spectra were collected from amorphous SiO_2 and St. Peter sand starting materials

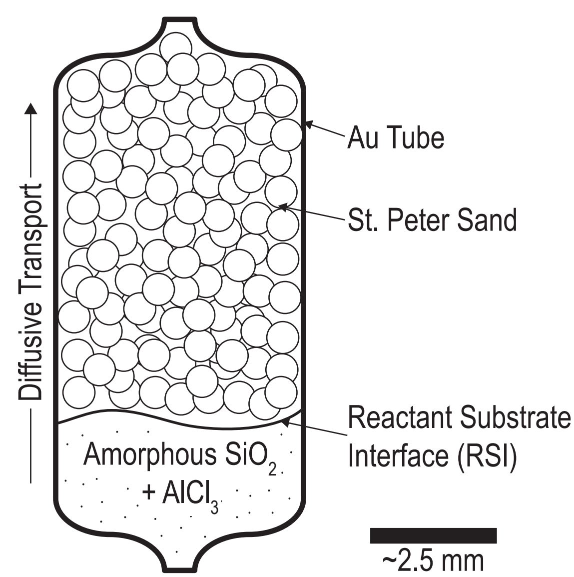

Fig. 1. Schematic diagram showing hydrothermal cold-seal experimental charge geometry. Au tube is approximately 1.5 cm in length and 0.5 cm in diameter. Diffusive transport proceeds away from the reactant substrate interface (RSI) into undersaturated portions of the charge.