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Astrid Makowitz



I attended Michigan State University (1992-1999) where I received both B.S. and M.S. degrees. My Master's thesis, conducted under the supervision of Duncan Sibley, was entitled "Crystal growth mechanisms in a quartz arenite, Galesville Sandstone, South Central Wisconsin." My continuing curiosity in diagenesis led me to pursue a Ph.D. at the University of Texas at Austin, where I am currently a Ph.D. candidate, working with famous diagenesis gurus Drs. Kitty Milliken and Earle McBride. My dissertation is entitled "The genetic association between brittle deformation and quartz cementation elucidated by cathodoluminescence imaging." My interest is in clastic diagenesis and its interrelationship with other geology disciplines, namely structural geology. I also enjoy both carbonate and sandstone petrography.

**The Genetic Association Between Brittle Deformation and Quartz Cementation
Elucidated by Scanned Cathodoluminescence Imaging**

Astrid Makowitz, The University of Texas at Austin, Department of Geological Sciences, 1
University Station, Austin, TX 78712-0254, makowitz@mail.utexas.edu

This study examines the mechanical and chemical processes of brittle deformation and quartz cementation in the context of burial compaction and fault gouge formation. Results from this work contribute to our fundamental understanding about porosity evolution in sandstones having undergone different deformation styles, with implications for reservoir quality prediction in the subsurface. Sandstones used in the studies are from geographic locations in which each deformation style is prominent and where samples are accessible. Samples used in the compaction study are from the lithic-rich Oligocene Frio Formation from the Gulf of Mexico Basin and quartz-rich Cambrian Mount Simon Formation from the Illinois Basin. Samples for the fault gouge study are from the Pennsylvanian Breathitt Group and Lee Formation located within and in the vicinity of the Pine Mountain Overthrust in the southern Appalachian Basin.

Brittle deformation in these rocks is manifested as breakage of individual grains resulting in the formation of microfractures. Such intragranular fractures are open Mode I (extensional), associated with sites of highly concentrated stresses at grain contacts. Intra- and intergranular microfracture classification is still juvenile because fracture recognition using CL images is a relatively new tool. Laubach (1997) has distinguished three types of fractures based on CL imaging. Category I are fractures that cut numerous grains and associated cement, Category II includes intragranular fractures contained in single grains and Category III are inherited fractures. For the most part, fractures observed in the quartz grains of the Frio, Mount Simon, Lee Group and Breathitt sandstones belong to category II. Many microfractures are wedge-shaped with the widest fracture aperture at contacts. Expansion, or inflation, of individual grains along numerous fractures may create an “exploded” appearance. Extreme crushing may also occur along grain/grain contacts, where smaller comminuted particles are at the contact and less comminution occurs away from the contact (e.g., Land and Milliken 2000, their Fig. 7). In some instances, particles are spalled and rotated. These fracture characteristics are detectable in samples in quartz grains from both the fault gouge and compaction studies. Fractures in quartz grains are subsequently filled with quartz cement. Broken grain surfaces provide fresh nucleation sites for quartz cementation, which may be inhibited on the detrital grain surface due to the presence of clays and microcrystalline oxide impurities (Laubach and Milliken, 1996, Milliken and Laubach, 2000).

The primary technique used in this study is scanned cathodoluminescence (CL). CL has been widely used as a tool in diagenetic studies (Sipple, 1968; Sibley and Blatt, 1976; Stone and Siever, 1994). CL imaging performed on a scanning electron microscope (SEM) has greater utility than conventional light microscope-mounted CL because images are more readily captured, higher magnifications are available, and the automated SEM system facilitates other functions such as sample rotation and acquisition of other image types (e.g. backscatter and secondary electron images). Scanned (CL) imaging combined with backscattered electron imaging (BEI) provides an unambiguous method for distinguishing detrital quartz, authigenic quartz, and voids. A fracture in a grain without filling observed by backscattered electron imaging (BEI) shows an epoxy filled void within the grain whereas in the case of a closed fracture, BEI illustrates a continuous quartz surface. With these imaging techniques, quartz filled fractures in quartz grains can be observed which are otherwise undetectable using conventional light microscopy. In contrast to panchromatic CL images, scanned CL color images provide even greater detail and information of the internal structure of the inherently less luminescent authigenic quartz, crosscutting relationships between fracturing events and relative timing of grain fracturing with respect to quartz overgrowth formation.

The quantitative measurements proposed here are not ones conventionally collected in deformation studies. Specifically, observation and quantification of microfractures are often underestimated or ignored because these features are often healed with quartz cement and therefore undetectable during routine petrographic analyses (Wilson and Stanton 1994). Grain size, fracture frequency, aperture width (filled and partially filled) and the number of pieces and sizes of cemented broken grains are data types that will be collected as well as conventional point counts to quantify framework components, authigenic phases, porosity types and matrix. Quantifying the amount of quartz cement within a brittle deformed grain allows for determining the

amount of intergranular volume (IGV) lost due to brittle deformation. To do this, individually fractured grains will be individually point counted (400 point counts each) to determine the percentage of intragranular cement and detrital quartz components. The average percentage of intragranular quartz cement combined with information on the degree of fracturing allows for the calculation of a numerical value for the amount of intergranular volume (IGV) lost by either compaction or gouge development. Quantifying the amount of quartz cement localized in fractured grains is important because this volume of material is conventionally counted in the grain volume, leading to incorrect assessment of IGV, which is important in quantifying cementational porosity loss (CEPL) and compactional porosity loss (COPL). It follows similarly; this volume of cement is not accounted for in calculations relating to silica mass balance.

In the case of the fault gouge, quantifying and comparing degree of fracturing, timing of *intragranular* versus *intergranular* quartz cement and total quartz cement volumes in the quartz-rich gouge versus the adjacent undeformed sandstones of identical composition will provide information on the preferential localization of quartz cement and perhaps possible sources of silica cement such as mineral transformation and/or dissolution nearby shales, alteration of feldspars within the Pennsylvanian sandstones, and/or pressure solution within the formation. CL enables the detection of individually broken pieces of a once whole grain that was subjected to comminution. Using CL imaging, the true particle size distribution can be determined within a quartz-rich fault gouge, conventionally done by loose particle sieving. Deformational influence has profound implications on fluid flow within faulted systems because of the decrease in particle size, allowing fluids to migrate through at a lower flow rate. This will provide information on the permeability evolution within the fault gouge.

Documenting the distribution of quartz cement within deformed and undeformed sandstones of identical mineral composition will provide new insight into porosity and permeability distribution and ultimately, their prediction in sandstones that have undergone deformation. Microfractures provide avenues for fluid flow and are preferential sites for quartz nucleation, possibly providing evidence for localized fluid flow along fault planes rather than uniform regional fluid flow in an orogenic system. Comparing porosity and quartz cement percentages in the deformed and undeformed sandstones can determine whether these parameters increase, decrease or remain constant within the fault compared to the undeformed sandstone. A greater amount of intergranular quartz cement within the fault gouge compared to the undeformed sandstones suggests that fluids may have been concentrated along the fault or perhaps there is evidence of internally derived quartz such pressure solution or extensive comminution of particles such that they are highly reactive and dissolve. Similar porosity values in both sample sets suggest that fluid-flux may not have been as important as diffusion controlled internally derived silica, because the low permeability fault gouge has equal quantities of quartz cement as the higher permeability undeformed sandstone. Or it may signify regional scale fluid movement. However, if regional scale fluid flow existed, less intergranular quartz cement is predicted in the deformed sandstone suit. Comminuted (smaller) particles within the deformed zone decreases the flow rate of fluids. If quartz cement is externally derived, (fluid flux dependent), less fluid per volume flowed through a less permeable rock, resulting in less cementation in the deformed rocks compared to undeformed rocks. Overall, quantification and distribution of porosity, permeability and quartz cement will help us understand the origin of fluids in the PMO region and other systems like it.

Initial results from the compaction study have demonstrated our ability to quantify the amount that brittle deformation influences porosity loss. Compaction is the major cause of porosity loss in the subsurface (Lundegard, 1992), but mechanisms of porosity decline are poorly understood. The Frio Formation is a lithic-rich unit with an average feldspathic litharenite composition and only represents one end member range of sandstone compositions in the Gulf of Mexico region that are of interest in compaction studies, therefore a second comparison study was conducted for the Mount Simon Formation of the Illinois Basin, classified predominantly as a quartz arenite, to determine the quartz-rich end member trend. Such a study has a direct implication for the Gulf of Mexico basin, where a regional trend in Cenozoic sandstone composition, generally quartz-rich in the northern areas and lithic-rich in the southern areas, exists (Loucks *et al.*, 1984).

During compaction, the number of fractured quartz grains increases exponentially with depth for both the Frio and Mount Simon Formation, with the difference being that the more quartz rich grains of the Mount Simon Formation are fractured at shallow depths (< 2000 m) compared to the Frio Formation (Makowitz and Milliken, 2002). At depths greater than 2000 m, quartz grains in the Frio Formation are more fractured than quartz grains in the Mount Simon Formation. Comparing fracture intensity trends for the mature Mount Simon Formation to the lithic-rich Frio Formation enable extrapolation of results to more quartz-rich units in the Gulf of Mexico basin such as the Wilcox Formation and allow prediction of compaction trends in different regions of the Gulf of Mexico Basin, where samples are not available. Such a study has great implication for sandstones having undergone extensive compaction such as the Gulf of Mexico Basin and where exploration targets are moving deeper into the subsurface.

The results from these two studies will document the role of mechanical influences in diagenesis and have implications for a variety of diagenetic problems. (1) Quartz filled microfractures sequester significant amounts of quartz cement within grains, representing a volume of authigenic quartz previously unaccounted for in silica mass balance calculations. (2) Microfractures provide avenues for fluid flow and preferential sites for quartz nucleation. (3) Mechanical compaction may directly cause silica mobilization due to increasing surface area in conjunction with decreasing grain size, contrary to current notions of chemical compaction. Quantitative data collected from each deformation scenario will increase our understanding of the evolution of IGW, quartz cement, and particle size distribution during deformation that will, in turn, have ramifications for porosity and permeability prediction.

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