CHARACTERIZING FRACTURES AND DEFORMATION BANDS

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Abstract

Multiple approaches are under development to mitigate the release of potentially harmful human-generated CO₂ into the atmosphere. Geologic carbon sequestration is one such process by which CO₂ that would otherwise be vented to the atmosphere is liquefied, injected, and stored in the pore space of a subsurface reservoir. The Cambrian Mount Simon Sandstone (MSs) is a targeted reservoir for CO₂ sequestration in the Illinois Basin. The goals of this research are to analyze a set of subsurface samples related to ongoing CO₂ sequestration demonstrations in the Illinois Basin. These samples contain evidence of small-scale fractures and deformation bands in the MSs. We provide a detailed analysis of their geometry, association with sedimentary facies, potential origin, and any apparent fluid-related diagenesis. Core samples displaying fractures were analyzed visually to characterize the sandstone and fracture geometry, and at higher resolution using thin section transmitted light petrography. Scanning electron microscopy with energy dispersive X-ray analysis (SEM-EDX) was used to analyze even smaller-scale structures along with select geochemical properties. Observed fracture types in the MSs include: 1) deformation bands and 2) open fractures filled with authigenic cements. Observed deformation band types include a) compaction bands, b) shear bands, and c) cemented dilatation bands. Low porosity/permeability deformation bands have the potential to block fluid migration, while open fractures create secondary porosity/permeability. These small-scale deformational structures can impact the routes that migrating fluids will travel along, therefore directly impacting CO₂ sequestration operations.

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Keywords

carbon sequestration, CO₂, compaction bands, deformation bands, diagenesis, dilatational bands, fracture, Mount Simon Sandstone, permeability, porosity

CHARACTERIZING FRACTURES AND DEFORMATION BANDS:

Implications for Long-Term CO₂ Storage within the Cambrian Mount Simon Sandstone

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INTRODUCTION

The lights in your home, your cell phone, and your computer are all things that most people use every day, and they all need electricity to function. That electricity has to come from somewhere. In the Midwestern United States, burning fossil fuels produces most of the electricity we use (US DOE, 2010). Fossil fuels are great sources of energy but one drawback is the generation of carbon dioxide (CO₂). Anthropogenic sources of CO₂ contribute to pollution, climate change, and reduced overall air quality. Limiting the amount of CO₂ released in the atmosphere is a critical concern in the scientific and engineering communities today. Geologic carbon

sequestration is a process by which CO₂ is liquefied, injected, and stored in the pore space (voids between grains) of a subsurface reservoir. This procedure has the potential to significantly reduce the amount of CO₂ released into the atmosphere at point sources such as ethanol production plants, power plants, and so forth. In order to understand and predict how CO₂ will behave once injected, extensive sample-based characterization must be conducted on any proposed reservoir. One factor to be considered is the heterogeneity of a potential reservoir and whether the rock contains fractures or zones of low porosity that could compartmentalize or localize subsurface fluid flow.

Figure 1. Generalized cross section (left) and map (right) of the Illinois Basin illustrating the structural and stratigraphic configuration of the Mount Simon Sandstone (MSs). The basal Cambrian MSs and the overlying conformable Eau Claire Formation are shown as separate units within the Sauk Sequence. The cross section is modeled after Kolata (1991) and map modeled after Bowen et al. (2011). Approximate location of samples analyzed in this study shown by stars (Macon County, Illinois, well = ADM CCS Well 1; Knox County, Indiana, well = Duke Energy IGCC 1). Note that the MSs is extensively faulted in the deepest parts of the basin.

The Cambrian (542 to 488 million years ago) Mount Simon Sandstone (MSs) is commonly the basal siliciclastic (composed of predominately silica-bearing rock fragments and minerals) unit within the Illinois Basin (Figure 1). The MSs unconformably overlies Precambrian crystalline basement rocks and is overlain conformably by the Upper Cambrian Eau Claire Formation. The MSs is interpreted to have been deposited as a broad sheet across a shallow marine embayment that was open to the south. The unit is the target reservoir for CO₂ sequestration throughout the Illinois Basin and Midwest region. Its petrophysical qualities, structure, and stratigraphic setting makes it an ideal reservoir for sequestration. Reservoirs need to be porous, permeable, in a tectonically stable environment, capable of storing large volumes of CO₂, and have an adequate seal in order to keep fluids from escaping. The Eau Claire Formation is identified as the primary seal for CO₂ sequestration programs targeting the MSs. The MSs meets all of the requirements for a long-term storage reservoir, and it is estimated that the unit is capable of storing up to 370 gigatons of CO₂ (Bowen et al., 2011).

CO₂ sequestration begins when CO₂ is injected into the reservoir as a liquid in supercritical conditions. The fluid then migrates through the pore space of the reservoir where it is stored. Migrating fluids will interact with the minerals within the MSs, and active research is underway to determine these effects. The MSs contains various deposition and diagenetic (alterations to a sedimentary rock after burial) variances, which affect the ability to predict how CO₂ will behave in the subsurface (Bowen et al., 2011). Fluids moving through a reservoir will also interact and respond to any structural deformation present in the reservoir. Understanding how porosity and permeability change throughout the reservoir is critical to understanding the dynamics of CO₂ flow and changes in the system through time both during and after the sequestration process.

In this paper we work to document and characterize fractures and deformation bands in the MSs along with associated diagenesis. Fractures and deformation bands have been known in the petroleum industry to both inhibit and promote fluid flow through reservoirs. Open fractures can greatly increase a reservoir's production if the proper drilling methods are employed. Conversely, reservoirs that have high porosity and permeability, and thus should have high transmissibility, sometimes produce well below expectations due to cemented fractures and deformation bands (Antonellini & Aydin, 1994). In oil fields where production is the primary concern, understanding fracture and deformation band formation, geometries, and diagenetic histories can be

crucial to accessing stored reserves of petroleum (Fossen, Schultz, Shipton, & Mair, 2007). The abundance of these structures in Earth's crust is poorly understood. Research has shown that deformation band permeability can be orders of magnitude lower than the surrounding host rock (Torabi & Fossen, 2009). Previous studies emphasize that these calculations are highly dependent on the deformation mechanism, in particular the degree of cataclasis (grain fracturing) and phyllosilicate (sheet silicates) content within the band. As a result of this reduced permeability, deformation bands can act to reduce the overall permeability and in extreme cases can compartmentalize reservoirs. Compartmentalization of a reservoir occurs when sections of a reservoir are disconnected from the system as a whole. The effect that these small-scale structures will have on injection programs such as carbon sequestration is not yet fully understood. However, we assume that open fractures will act as conduits to fluid flow and zones of low porosity and permeability as inhibitors to subsurface flow. With regards to open uncemented fractures, there are active examples of oil and gas fields where the presence of open fractures has made it economical to access stored reserves. Hydraulic fracturing is a technique by which open fractures are generated in a subsurface reservoir to enhance oil recovery. Open fractures, whether natural or artificial, can be a controlling factor on whether a reservoir can be produced economically. Understanding fractures and deformation bands in the MSs may be critical to understanding the dynamics of the reservoir system to increase injection efficiency.

MATERIALS AND METHODS

Samples of the MSs from Knox County, Indiana, were derived from 3.5-inch whole cores, and samples from Macon County, Illinois, were derived from 0.9-inch diameter sidewall cores. The MSs at these locations are similar in stratigraphic thickness: 1,500–2,000 feet. However, the structural depth the MSs reaches differs by almost 2,000 feet. Cores from both wells that had visual evidence of deformation and diagenesis were selected for use in this study. No preference was given to the style of deformation and the samples collected, as the main purpose of this study was to document their presence and any diagenetic features related to them. Cores from Knox County were described and traced to document the orientation of fractures with respect to horizontal (Figure 2). This could be accomplished because stratigraphic up in the core was known; however, no azimuthal orientation could be obtained. Eight Macon County sidewall cores were selected, and 14 intervals of the Knox County cores were chosen for detailed analysis. All 22 samples were analyzed using transmitted light petrography.

Figure 4. Photographs of sidewall cores from Macon County, Illinois, which show evidence of deformation and complex diagenesis. (A) Bleached zone of compaction, this sample was analyzed using the Purdue University SEM, 6,788 ft. (B) Quartz cemented fracture with evidence of different diagenetic histories on either side of the fracture, 6,763 ft. (C) Fractured zone, petrographic analysis revealed quartz cements along fracture, 6,899 ft. (D) Zone of bleached compaction, petrographic analysis revealed ~1mm of offset of compaction bands, 6,803 ft.

Figure 5. Photomicrographs of thin sections of the MSs cut from the Macon County well. Thin sections were embedded in blue epoxy (blue = porosity). All photos were taken with transmitted plane light. Annotations on micrographs: Q = quartz grains; F=feldspar; P = porosity. (A) Upper: Band of iron oxides and clays in a fine- to medium-grained quartz sandstone; Lower: 400x magnification of clays in band, 6,200 ft. (B) Upper: Quartz cemented fracture (zero permeability band). Lower: 400x magnification of quartz cemented band, encapsulated quartz grains indicates band is secondary feature, 6,763 ft. (C) Upper: quartz cemented zone in a coarse-grained to fine-grained, poorly sorted quartz sandstone. Lower: 100x magnification of quartz cement, grains are coated in iron oxide, 6,899 ft. (D) Upper: Compaction band (dashed green lines). Lower: 100x view of compaction band, grain size within the band range from clay-sized to medium sands, many grains are crushed within the band, 6,788 ft. (E) Upper: Compaction band. Lower: Clay within compaction band, 7,048 ft. (F) Upper: Heavily fractured quartz and feldspar grains. Lower: 10x magnification.

Figure 6. Photo mosaic of a thin section from the ADM CCS Well 1 in Macon County, Illinois, which shows offset of two compaction bands. Offset of the compactions bands is ~ 1.5 mm and a small shear zone is indicated by aligned grains within a narrow zone. If abundant in a reservoir, structures like this can reroute or in extreme cases block fluid flow through a reservoir.

Transmitted light petrography takes advantage of the interactions of light with individual minerals in a sample. A combination of plane-polarized and cross-polarized light was used to facilitate mineral identification. This tool allows us to determine the mineralogical composition of the sample as well as the effects fracturing and deformation has on increasing or decreasing pore space. Diagenetic alterations of the host rock can also be determined, which allows for a more detailed history of the rock to be developed. Thin sections of the 22 samples were taken and embedded with blue epoxy under vacuum and stained for potassium feldspar (K-feldspar). Blue epoxy, when viewed through the microscope, illustrates pore space. Stained K-feldspar appears brown when viewed with plane-polarized light. Two of the samples from Macon County, which display macroscopic and microscopic evidence of small-scale deformation and diagenesis, were examined using Scanning Electron Microscopy with Energy Dispersive X-ray analysis (SEM-EDX).

SEM-EDX analysis was used to analyze two samples, one compaction band and one quartz-filled fracture. Samples were imaged with an FEI Quanta 3D FEG scanning electron microscope using a low vacuum secondary electron detector. X-ray analysis (EDX) was also run on these samples. We will discuss some general conclusions and omit a detailed discussion of the data itself.

RESULTS

Knox County, Indiana

Two main styles of fracturing were observed in the MSs in Knox County, Indiana: open, tensional fractures and highly compacted zones we describe as having a stylolitic texture (Figures 2 and 3). Tensional fractures are most commonly open along the length of the fracture; however, we observed mineralization along some sections of the aperture. Iron oxides, clays, and other fine-grained material represent what was contained within cemented zones. Macroscopic examinations of cores found that fractures cross cut stratigraphic boundaries and sedimentary structures, as well as other deformational features (Figure 2). Microscopic analysis confirms these observations.

Fractures observed in Knox County are present in various textures of the MSs such as poorly-sorted, quartz cemented, quartz pebble conglomerates; well-sorted, well-rounded, cross-bedded, quartz cemented sandstone; and well-sorted, fine-grained, quartz sandstone with mud drapes. Stylolitic-textured fractures were observed within two samples: 8,081 feet (Figure 3A) and 8,646 feet. Thickness of these structures was between 0.1 mm and 0.4 mm. The MSs where we observed these structures is characterized by having a very high percentage of

quartz and quartz cements. Microscopy shows evidence of fluid-related diagenesis and mineralization along some zones of fracturing. Authigenic (crystal grew in place) K-feldspar was observed in one sample (Figure 3G) along a zone of open fracturing, aperture 0.1 mm to 0.2 mm. The K-feldspar in this sample is very angular while surrounding quartz grains are well rounded and have quartz overgrowths. Alteration of muscovite to clay minerals was also observed (Figure 3H). Muscovite is a sheet silicate and is cut by a fracture, and the section of the muscovite within the fracture is seen breaking down to clay. Fractures penetrate grains as well as cements and connect pore space (Figure 3C).

The most common cement in our samples was quartz; however, some small amounts of clay and calcite are present as cements (Figure 3D and 3J) and are fractured. Not all fractures are highly continuous; some fractures, like those seen in Figure 3L, only have an aperture of < 0.1 mm. These very small-scale fractures are observed in multiple samples used in our study and penetrate grains, cements, and pores.

Macon County, Illinois

Two dominant forms of deformation were observed in samples collected from Macon County, Illinois: compaction bands and quartz cemented dilatation bands. One sample (Figure 5F) was extremely deformed by grain crushing/cataclasis. Of the eight samples studied from Macon County, four showed signs of compaction band formation, two were dilatational, one contained highly fractured grain material, and one contained bands of iron oxides.

Of the four samples containing deformation bands, one sample, illustrated in Figure 6, has visible offset of deformation bands and small shear zone. The small shear zone was interpreted by what appears to be a preferred orientation of grains within a narrow zone, which is outlined in red in the figure. Total offset in this sample was ~ 1 mm and was measured using the compaction bands as markers. Other compaction bands are present but do not show signs of offset.

All compaction bands documented in this study contain a number of fractured grains within them. SEM images of a compaction band (Figure 7) show in detail some of the fractured grain structures within these bands. The SEM images are of a compaction band with no offset; however, the band does contain numerous fractured grains along with high amounts of phyllosilicates. Even though these structures are small in comparison to the entire MSs reservoir, on a local scale they could have an impact on CO₂ injection programs.

Figure 7. Back scattered electron images acquired from the Purdue University scanning electron microscope (SEM) of a Macon County well sample from 6,788 ft (see Figure 4A). (A) Comparison between the host rock below the dashed white line and the compaction band above. (B) The behavior of individual grains in response to compaction. The white grain labeled “Z” is a highly resistant Zircon grain. (C) Heavily fractured K-spar. Pore space surrounding the grain is filled with clays and cements. Zones like this contain a high abundance of reactive minerals and have low porosity and permeability.

DISCUSSION

It is important to recognize the possibility of open tensional fractures observed in this study having occurred during the coring process. Drilling processes commonly induce fractures, and such fractures are always open, containing no mineralization along them. The MSs in Knox County was recovered from depths over 8,000 feet in the subsurface. Removing the core from this depth could create tensional fracturing due to the rapid change in pressure. We have documented several lines of evidence that lead us to believe that many of the fractures studied from these cores are natural and not only a result of sampling. For example, the observed core samples were still intact; fractures did not result in the core completely severing into multiple pieces. A major line of evidence for supporting the natural formation of these fractures was the observation of mineralization both in hand specimens and under the petrographic microscope within zones of fracturing. Only with exposure to subsurface fluids would mineralization occur, indicating that fractures with cements along them were naturally formed before the cores were cut. We accept the possibility that some of the open fractures studied may have been formed as a result of the drilling process, but argue that open fractures do exist in the MSs in the subsurface in the Knox County region. Working off this conclusion, studied fractures can add to the already fascinating story of the Mount Simon Sandstones geologic history.

The Illinois Basin is a long-lived intracratonic (situated in North American craton) basin in which the MSs is commonly the oldest sedimentary unit. The basin has experienced various stages of uplift and subsidence throughout geologic time. As a result, the MSs has undergone a complex burial, deformational, and diagenetic history. These secondary alterations are not homogeneous across the basin, and as a result, the diagenetic and structural features represented in the MSs vary within the unit. Faulting is known to occur within the MSs (see Figure 1), but the existences of small-scale deformation features in the MSs are poorly understood. Our study has documented the presence of two distinct styles of small-scale deformation within the MSs.

The lithology and degree of cementation varies within the MSs and appears to have a control on the style of deformation we observed. Samples from Knox County tended to be quartz cemented, well-indurated, mature sandstones. Stylolitic textured fractures are interpreted to have formed from high pressures resulting in deformation by way of pressure solution. This interpretation requires

the presence of subsurface fluids in which material would be able to enter solution. If these fluids were present, they would have to be connected to the plumbing system within the unit to carry material away. This further constrains the timing of cementation to be during or after this process. The connectivity of pore space in Knox County is low due to the high degree of quartz cement that has developed. For these stylolitic textured fractures to have formed, they must have appeared before pore space was filled with quartz cement. Open fractures cut grains, quartz cements, and stylolitic fractures. These fractures are likely to have formed during a period of time when tension was the dominant stress in this section of the Illinois basin.

Grain rolling, compaction, crushing, and dilatation characterize the more poorly cemented MSs of Macon County. This style of deformation is well documented within sandstones that are unconsolidated and have a high porosity. In our samples we observed mineralization within and geochemical variances across dilatation bands. Samples showed color variances across these bands, and we interpret this to be the result of fluid interaction with minerals on one side of the band and not the other. This suggests that these cemented dilatation bands acted to localize subsurface fluid flow.

Compaction bands are generally zones of lower porosity than that of the surrounding host rock. Grain crushing is common within observed bands in the Macon County section of the MSs. SEM analysis of one compaction band has provided detailed images of crushed grains and the presence of the clay minerals within the bands (Figure 7). These two factors are known to control the permeability of deformation bands. The higher the degree of cataclasis and clay content within a deformation band, the lower the permeability will be across it.

The effects that small-scale deformational structures will have on CO₂ sequestration programs are not well understood. It is known that small-scale structural features such as those discussed in this study can have measurable influence migrating fluids. The extent they will impact injection programs depends on a number of factors: their abundance, continuity, connectivity, diagenetic alteration, mineral content, and orientation. This study has demonstrated that fluids have interacted with and responded to the presence of deformation bands in the MSs. To develop a fully comprehensive reservoir model it is important to take into account all factors that could influence migrating fluids.

CONCLUSIONS

Small-scale deformation occurs in the Mount Simon Sandstone in the form of open tensional fractures, fractures with zones filled with authigenic cements, compaction bands, and dilatational bands filled with authigenic cements. Open fractures act to increase porosity and permeability. Fractures could act as fluid flow pathways, moving injected fluids into the reservoir quickly and efficiently. Zones of low porosity and permeability such as compaction bands, cemented fractures, and dilatational bands, if abundant, could act to reduce the overall porosity and permeability within sections of the reservoir. Macro- and microscopic analysis of samples from Macon County indicates diagenetic heterogeneity across compaction bands and cement-filled dilatational bands. These differences are interpreted to be the result of fluids interacting with one side of the host rock and not the other due to the presence of the low porosity and permeability zones. If compaction bands, open fractures, and bands of authigenic cements are present in abundance and have a preferred orientation, it could prove useful to include them in reservoir models to accurately predict the routes that migrating fluids will take once injected in the subsurface.

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