Depositional and diagenetic controls on anomalously high porosity within a deeply buried CO₂ storage reservoir—the Cambrian Mt. Simon Sandstone, Illinois Basin, USA

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Abstract

Current diagenetic models predict that sandstone porosity and reservoir quality decrease with burial depth and formation age. However, the opposite trend is true for the Cambrian Mt. Simon Sandstone. The lowermost section of the Mt. Simon is highly porous—it has an average log-derived effective porosity of 17.0%. To understand the possible reason(s) for this anomaly, the amount of porosity reduction due to compaction porosity loss (COPL) and cementation porosity loss (CEPL) was analyzed. The COPL and CEPL were coupled with sedimentary characteristics in order to ascertain which factors controlled porosity and reservoir quality in the Mt. Simon. The underlying Argenta sedimentary unit disconformably underlies the Mt. Simon and is included for diagenetic and depositional comparison.

Similar to expected trends from other deep basin reservoirs, the COPL generally increases with depth in the Mt. Simon. The CEPL is significantly lower in the lower half of the Mt. Simon compared to the upper half of the Mt. Simon, indicating that higher porosity is attributed to having a lower volume of intergranular cement. Early episodes of diagenesis within the arkosic lower half of the Mt. Simon, such as clay infiltration and feldspar alteration, produced diagenetic grain-coating clays, which inhibited the development of quartz cements.

Thus, these grain coatings assisted in porosity preservation within the Lower Mt. Simon by reducing CEPL. The upper half of the Mt. Simon is more heavily cemented as a result of changes in the depositional setting and thus changes in the lithology. Later, largely post-compaction feldspar dissolution further increased porosity in the Lower Mt. Simon Sandstone.

Introduction

Understanding the contributing factors behind highly porous reservoir rocks at depth remains a crucial aspect for the broader viability and implementation of geologic carbon storage projects. Identifying the properties that lead to heterogeneity in porosity within reservoirs has multiple applications, including improving conceptual models that aid in predicting carbon dioxide (CO₂) migration. Additionally, these properties can be used to characterize similar formations that may be suitable for storing CO₂. Properties from improved conceptual models are also important for maximizing petroleum production and improving enhanced oil recovery and liquid waste storage techniques.

The most important criteria of a CO₂ reservoir is injectivity. Most carbon capture and storage (CCS) projects require natural subsurface reservoirs with high values of porosity and permeability to achieve acceptable rates of injectivity. However, formations with high porosity and permeability at depths necessary to achieve high enough pressures for the injected CO₂ to maintain a supercritical state are relatively uncommon. Typically, intergranular volume and porosity decrease with increasing burial depth (Paxton et al., 2002). During burial, three primary diagenetic mechanisms act to reduce porosity: mechanical compaction, chemical compaction, and cementation (Houseknecht, 1984). Mechanical compaction reorients framework grains, resulting in a reduction of intergranular volume. Chemical compaction occurs as a result of lithostatic or tectonic stresses that act to dissolve framework grains, promoting consolidation

(Houseknecht, 1987). The extent to which these mechanisms can reduce porosity relies heavily on the sedimentary properties (i.e., mineralogy and grain size) partly controlled by depositional processes in evolving basins and the subsequent diagenetic history of the target formation. Thus, understanding depositional processes is critical in deciphering diagenetic controls on reservoir properties.

This paper presents research analysis of porosity loss data due to compaction and cementation for the Cambrian Mt. Simon Sandstone. This formation includes the CO₂ storage reservoir for the Illinois Basin–Decatur Project (IBDP), a 1-million metric ton CCS demonstration project on the property of the Archer Daniels Midland Company corn processing facility in Decatur, Illinois. A large dataset acquired by the IBDP was used to determine the role that changing sedimentology plays in controlling the diagenetic processes that affect reservoir quality.

Geological Background

The Mt. Simon Sandstone is a laterally extensive deposit throughout the Midwest (Figure 1) and has been the focus of industrial development, specifically natural gas storage, as well as the focus of scientific research, for multiple decades. The majority of the research on the Mt. Simon has sought to characterize the formation sedimentology and stratigraphy and describe its diagenetic history, primarily utilizing small datasets from multiple wells located throughout the region. Freiburg et al. (2014) used a large dataset developed from newer IBDP wells and described all of the major depositional facies within the Mt. Simon from the Decatur site. This previous work is summarized here.

Mt. Simon Units

The Cambrian Mt. Simon Sandstone is a transgressive terrestrial to shallow marine sequence deposited in the proto-Illinois and Illinois basins, as well as the Michigan and Appalachian basins (Kolata and Nelson, 1990). At the IBDP site it can be divided into five distinct units—A, B, C, D, and E (Figure 2)—as determined by the changes in the depositional environment and sedimentology (Freiburg et al., 2014). Depositional environments in the Mt. Simon are highly variable; the numerous interpretations include shallow-marine, deltaic, fluvial, eolian, sabkha, and coastal (Driese et al., 1981; Hagadorn et al., 2002; Fischietto, 2009; Bowen et al., 2011; Freiburg et al., 2014). The Mt. Simon is unconformably underlain by the basal Cambrian Argenta Formation (formerly called the pre-Mt. Simon), a sedimentary unit that is composed of shallow marine (Freiburg et al., 2015) and fluvial clastic deposits and unconformably overlies Precambrian felsic rocks of the Granite-Rhyolite Province. The Upper Cambrian Eau Claire Formation, a tidally influenced marine deposit marked by a prominent shale unit, conformably overlies the Mt. Simon. In Illinois, the Mt. Simon varies in thickness from about 2,600 ft (792.5 m) at its depocenter in east-central Illinois to less than 400 ft (122 m) thick in southern Illinois (Figure 1). A postulated unconformity separates the Lower Mt. Simon (Units A and B) from the Middle Mt. Simon (Units C and D; Freiburg et al., 2014). The Middle Mt. Simon units and the Upper Mt. Simon (Unit E) appear to be transitional and represent the major Sauk transgression (Collinson et al., 1988). The Mt. Simon is predominantly a fine- to medium-grained quartz or subarkosic arenite with rare shales, wackes, and sublithic arenites. It is highly variable in sedimentary and diagenetic characteristics.

Unit Depositional Environments, Bedding, Texture, and Classification

Mt. Simon Unit A includes mixed fluvial, eolian, and possible beach deposits and is dominantly composed of medium- to fine-grained cross-bedded to ripple-laminated subarkose arenite. To a lesser extent, it contains varying amounts of planar-bedded, ripple-laminated sandstone and conglomerate composed of subarkosic arenite, arkosic arenite, sublithic arenite, arkosic wacke, and mudstone (Freiburg et al., 2014).

Unit B contains mixed eolian and fluvial deposits, which are dominantly composed of fine- to medium-grained planar-bedded to fine-grained low-angle cross-bedded subarkosic and quartz arenites.

Unit C fluvial deposits are dominantly composed of medium- to coarse-grained cross-bedded subarkosic and quartz arenites with rare mudstones.

Unit D is composed of eolian deposits that are fine- to medium-grained planar-laminated and cross-bedded quartz arenites and quartz wackes.

Unit E of the Mt. Simon contains marine deposits of medium- to fine-grained bioturbated cross-bedded quartz to subarkosic arenites with thin interbedded black shales and red siltstones to mudstones.

In comparison to the Mt. Simon, the underlying Argenta contains mixed marine and fluvial deposits composed of fine- to medium-grained bioturbated cross-bedded to ripple-laminated sublithic and quartz arenites with common interbedded coarse-grained sandstones to conglomerates.

Porosity

Regionally, the Mt. Simon shows a trend of decreasing porosity with increasing depth (Hoholick et al., 1984; Medina et al., 2011), although there are few wells that penetrate the entire

Mt. Simon with quality well data in the proto-Illinois or Illinois basins. For wells that only penetrate the Upper and Middle Mt. Simon Units C, D, and E, the observation of decreasing porosity with depth may stand true but is likely an oversimplification for the entirety of the Mt. Simon. There exists a range of porosities for any given depth within the Mt. Simon (Bowen et al., 2011); however, wells that penetrate the Lower Mt. Simon Units A and B, such as all the wells at the IBDP, generally show porosity increasing with depth from the Middle Units C and D to the Lower Units A and B (Bowen et al., 2011; Freiburg et al., 2014; Figure 2). Out of the three Mt. Simon sections, the Lower Mt. Simon (Units A and B) contains the highest porosity, with an average whole core analysis porosity of 16.6% but may range as high as 27% (Freiburg et al., 2014). Porosity within the Mt. Simon is dominantly primary with the dissolution of feldspars contributing to moderate amounts of secondary porosity (Heald and Baker, 1977; Fishman, 1997; Bowen et al., 2011; Freiburg et al., 2014). Partial dissolution of framework grains commonly occurs in the Lower Mt. Simon (Units A and B).

Diagenesis

On average, the most dominant diagenetic cement in the Mt. Simon is quartz. The abundance of authigenic quartz is significantly lower in the Lower Mt. Simon Units A and B than the Middle and Upper Mt. Simon Units C, D, and E (Freiburg et al., 2014) and in the eastern extents of the formation (Heald and Baker, 1977). It forms thin or partial syntaxial overgrowths and pore-filling cements. Authigenic quartz formed during burial, where potential sources of silica may have originated from pressure solution, shale diagenesis, feldspar dissolution, or migrating paleofluids (Mississippi Valley-type; Pollington et al., 2011; Freiburg et al., 2014). Recent isotopic analysis of authigenic quartz cements suggests quartz precipitation occurred with

increasing temperatures during burial and basin evolution rather than migrating warm paleofluids (Pollington et al., 2011).

Authigenic feldspar is abundant in the Upper Mt. Simon Unit E and Middle Mt. Simon Unit C with trace amounts in all other units, including the Argenta. In the Upper Mt. Simon Unit E, authigenic feldspar is most commonly found in arkosic sandstone beds beneath black shale beds, giving them a distinct pink color (Freiburg et al., 2014). The close spatial relationship between shale beds and abundant feldspar cements in the Upper Mt. Simon Unit E may support the idea that ions for authigenic feldspar cements originated in the shale beds and were expelled during compaction or pore-water-rock interaction (Freiburg et al., 2014). Petrographic evidence of authigenic feldspar forming both before and after quartz overgrowths (Duffin et al., 1989; Freiburg et al., 2014) implies that multiple episodes of cementation occurred during continued burial and compaction. It is also possible that different generations of feldspar cement originated from different sources.

Clay Mineralogy and Associations

Besides depositional facies rich in clay (i.e., mudstones and wackes), clays found in the Mt. Simon are thought to be of largely diagenetic origin (Freiburg et al., 2014). They form as grain coatings on detrital quartz and feldspar and as pore-filling cements. However, thin laminae of depositional clays associated with intertidal mud flats, eolian-playa adhesion ripples, and hiatal surfaces are common throughout the Mt. Simon. Authigenic clays appear most commonly near weathered feldspar grains and casts of dissolved feldspar grains, indicating that the feldspars may be one possible source of the authigenic clays (Bowen et al., 2011). The most common clays within the Mt. Simon are illite and mixed layered illite-smectite with small fractions of

chlorite and kaolinite (Freiburg et al., 2014). The Lower Mt. Simon contains common friable sandstone intervals as a result of dominant clay cementation.

Iron oxides, primarily hematite and goethite, occur as grain coats, Liesegang bands, and as residues in stylolites within the Mt. Simon (Bowen et al., 2011; Freiburg et al., 2014), giving the Mt. Simon its red-maroon color. Most iron-oxide cements precipitated before other diagenetic alterations occurred (Fishman, 1997; Freiburg et al., 2014). In the Mt. Simon, high porosity values and small amounts of quartz cement were observed where illite (Freiburg et al., 2014) and low fractions of iron-oxide minerals (Bowen et al., 2011) form grain coatings.

To fully understand the intricate mechanisms that contribute to compaction and cementation porosity loss, quantification of these mechanisms is necessary in order to fully understand how reservoir quality develops. Houseknecht (1984) was the first paper to quantify the amount of porosity loss due to compaction and cementation, and subsequent research (Paxton et al., 2002) supports the conclusion that high porosity in reservoir rocks is achieved because of low volumes of cement and small to negligible amounts of pressure solution. As for the main cause of porosity loss, there is general agreement that compaction is the dominant mechanism (Lundegard, 1992; Makowitz and Milliken, 2003). Though there exists a large body of research on the chemical and physical conditions that occur during diagenesis and the resulting effect on reservoir quality, the role that changes in depositional facies play in determining reservoir quality is less studied.

Methods

Samples used in this research consist of whole core (4 in. [10 cm]) and rotary sidewall core (1 in. [2.5 cm]) samples from Verification Well #1 at the IBDP site (Figure 2). Samples were collected from all five units of the Mt. Simon as well as the underlying Argentina.

Following Houseknecht (1987), variations in compaction and cementation have been quantified from modal analysis of thin sections in terms of intergranular volume while observing point-counting recommendations from Ehrenberg (1995). Cements (diagenetic and depositional matrix) were quantified by point-counting both plane polarizing light (PL) and cathodoluminescence (CL) thin section photomicrographs. Because of the difficulty in differentiating clay and hematite and the minute amounts of hematite identified in X-ray diffraction (XRD; Freiburg et al., 2014), hematite was included as a clay modal count. Each count consisted of 450 points per image, and CL was used in order to differentiate between detrital and authigenic quartz and feldspar. Plane polarizing light and CL photomicrographs were taken at 5× magnification. Using the Wentworth (1922) scale classification, median grain size was determined using measurements made on grains using point-counting methodologies. To deal with the complexities and problems associated with thin section grain-size measurements, the median grain size determined from the thin section measurements was compared to grain-size descriptions of the core sample in which each thin sections was made from. Macroporosity was quantified through thin section point-counting of PL photomicrographs and checked against whole core and rotary sidewall core helium (He) porosity analysis. Point-count-generated porosity values were always less than He-generated values because of errors associated with point-counting (Ehrenberg, 1995), inability to count microporosity tied up in the abundant intergranular clay, and the inherent differences between two-dimensional (2D) point-count analysis and three-dimensional (3D) He-porosity analysis. Ratios of monocrystalline to polycrystalline quartz were determined by point-counts of cross polarizing light (XP) photomicrographs for each sample.

The thin section modal point-count data was compared to elemental analysis (ELAN) log data (Figure 2). The ELAN log reports quantitative formation evaluation based on log measurements of tools such as neutron porosity, gamma ray, and bulk density. The ELAN is processed every 0.5 ft (15 cm). Lithics are reported in point-count results. However, because of their compositions, they are reported among clay and feldspar values in the ELAN.

The thin section modal point-count data were used to establish amounts of porosity loss during diagenesis, using the formulas from Ehrenberg (1989), which are revisions of original equations from Houseknecht (1987). Because CL images of samples showed minimal intragranular fractures, and previous research had shown that individual grain crushing was not a factor in altering porosity in the Mt. Simon (Makowitz and Milliken, 2003), use of the modified porosity loss formulas from Makowitz and Milliken (2003) were deemed unnecessary. Porosity loss was calculated for each sample depth.

Compactional porosity loss (COPL) was calculated using the formula

$$COPL = P_i - \frac{(100 - P_i) \times IGV}{100 - IGV} \quad \text{Eq. 1}$$

where P_i is an estimate of the initial, unconsolidated porosity, and IGV is the sum of the intergranular pore space of the rock sample, intergranular diagenetic cement (including quartz, feldspar, clay, and iron oxide), and matrix material (depositional clay), per total volume (Ehrenberg, 1989), and where $0 \leq COPL \leq P_i$. Averages of input values can be found in Table 1.

Cementation porosity loss (CEPL) was calculated using the formula

$$CEPL = (P_i - COPL) \cdot \frac{C}{IGV} \quad \text{Eq. 2}$$

where C equals the volume of cement per total volume, with $0 \leq C \leq IGV$ and $0 \leq CEPL \leq P_i$.

The Index of Compaction (I_{comp}) is defined by Lundegard (1992) as

$$I_{comp} = COPL / (COPL + CEPL) \quad \text{Eq. 3}$$

where $0 \leq I_{comp} \leq 1$. Compaction is the dominant mechanism behind porosity loss if I_{comp} is greater than 0.5, and cementation is the dominant mechanism if it is less than 0.5. Thus, this metric quantifies the relative amount of compaction vs. cementation that has occurred to the samples from the Mt. Simon, and it was used to compare the relative amount of cementation vs. compaction among samples and subunits of the Mt. Simon.

Because of the enormous variation of porosity in freshly deposited sands (Lundegard, 1992; Ehrenberg, 1995), P_i of the Mt. Simon and Argenta was determined using the Beard and Weyl (1973) thin section comparator of artificially mixed sand. Beard and Weyl (1973) have determined that grain size and sorting are the major controls on P_i of freshly deposited sands. They measured porosity using combinations of artificially mixed sand ranging from very fine to coarse grains with sorting from very poorly sorted to extremely well sorted. Mudstones and samples with detrital clay greater than 30% were excluded from the study presented here. The P_i values of wet-packed sand calculated by Beard and Weyl (1973) were used for the research presented here. It is important to note that if the estimated P_i is too high, COPL is overestimated, and if too low, COPL is underestimated. The CEPL will be affected the same way. Mold collapse of dissolved feldspars and intergranular pressure solution may also result in underestimation of COPL because of the reduction of total grain volume (Ehrenberg, 1995). Thus, the COPL may be a minimum value in well-sorted samples with an IGV value below 26% (Houseknecht, 1987; Ehrenberg, 1995). This situation is present in the vast majority of the Mt. Simon and Argenta intervals.

The grain size, initial porosity, cement, IGV, He porosity, and modal porosity were plotted (Figure 3) as context to understand controls on porosity and input parameters in the calculation of COPL and CEPL. Therefore, they are reported as methods.

The mean grain size in Units B and C are lowest, and not significantly different (at the 0.05) level. The mean grain size is highest in Units C, A, and the Argenta, and the means in these units are not significantly different (Figure 3A). The calculated P_i in the Argenta is distinctly lower than the units overlying it because of sorting (Figure 3B). The mean P_i among Units A–E is not significantly different. The profiles of cement (Figure 3C) and IGV (Figure 3D) are quite similar. Both IGV and cement abundance are higher in Units C and above, and the means in these units are not significantly different (at the 0.05 level). Both IGV and cement abundance are lower in Unit B and below. The difference in the cementation index among Units B, A, and the Argenta is not statistically significant. The He-porosity measurements (Figure 3E) and the modal porosity measurements (Figure 3F) follow the same pattern with depth. The He-measured porosity is lowest in Unit D and the Argenta, and their means are not significantly different. The same is true for modal porosity in Units C, D, and the Argenta. Porosity by either measure generally decreases with depth from Unit E down to Unit D, then rises with depth and is highest in Units B and A (which are not statistically different), and lowers again in the Argenta.

Results

The profile of COPL with depth is somewhat complex (Figure 4A). It is least in Units C, D, and E. The means for those units are not statistically different at the 0.05 level. The COPL is greatest in Units A, B, and the Argenta, and these means are not statistically different at the 0.05 level.

The CEPL with depth is less complicated (Figure 4B). The mean CEPL is greatest in Units C, D, and E, and the means in these units are not significantly different. The CEPL is least in Units A, B, and the Argenta, and the means are not statistically different from the Argenta. Thus, there is a marked change in CEPL between Units C, D, and E and Units B, A, and the Argenta, with the decrease in CEPL appearing to start within the base of unit C, occurring rather abruptly right at the boundary.

The profile of I_{comp} is reversed from that of CEPL (Figure 4C). It is lowest and less than 0.5 in Units C, D, and E, and the means in these units are not statistically different. This indicates that porosity loss due to cementation is a larger factor than porosity loss due to compaction in Units C, D, and E. The I_{comp} is highest and greater than 0.5 in Units A, B, and the Argenta, and the means in the units are not statistically different. As with CEPL, there is a marked change in I_{comp} between Units C, D, and E, in which cementation loss dominates, and Units B, A, and the Argenta, in which compaction loss dominates. The increase in I_{comp} appears to start within the base of Unit C, occurring rather abruptly right at the boundary.

Because the mean I_{comp} for Units A, B, and the Argenta is not statistically different (Figure 4C), they are reported together below and are further analyzed with respect to COPL and CEPL (Figure 5A–C). The Argenta's average I_{comp} is 0.66 (Table 1), indicating that compaction is the dominant mechanism in destruction of reservoir porosity. Figure 3A shows that only 3 samples had an I_{comp} below 0.5, indicating that compaction was the dominant mechanism is porosity loss in all but three samples. Two of those samples are located near the top of the Argenta unconformity within a residual facies dominated by clay buildup and thus slightly skewing the results for the Argenta. Without these two samples, the I_{comp} increases. For individual samples, Figure 5A indicates that compaction has caused between 7%–33% porosity

reduction while cementation has only resulted in a loss of porosity between 3%–19%. Thus, COPL values indicate that compaction is responsible for most of the porosity loss among the samples.

For samples from Unit A, the average $I_{\text{comp}} = 0.69$, indicating that compaction is the dominant mechanism contributing to porosity loss in the interval (Table 1). All but seven samples have an I_{comp} above 0.5, providing further evidence that compaction is the dominant mechanism for porosity loss (Figure 5B). For individual samples, compaction has induced a loss of porosity within the interval, which ranges between 7%–33%, while cementation has produced a loss of porosity between 2%–24%. Thus, COPL is responsible for the most porosity loss among the samples, with cementation having a significant effect on porosity loss on a much smaller subset of the samples.

Samples from Unit B have the highest average I_{comp} at 0.76, indicating that compaction is the dominant mechanism behind porosity loss in the interval (Table 1). All samples have an I_{comp} above 0.5, which indicates that compaction is the dominant mechanism for porosity loss (Figure 5C). For individual samples, porosity loss due to compaction ranges between 17%–34% while porosity loss due to cementation in the samples has a much narrower range, between 4%–12%. Thus, compaction is responsible for the most of the reduction in porosity in this interval. The average $P_i = 37.13\%$. The grain size averages between fine upper (177–250 μm) to fine lower (125–177 μm) and sorting averages between well to moderately sorted. The higher P_i value compared to Unit A is attributed to the finer grain size and better sorting of Unit B. The average $\text{IGV} = 15.72\%$. The average thin section porosity is 5.48%.

Because the mean I_{comp} for Units C, D, and E is not statistically different (Figure 4C), they are reported together below and are separately analyzed (Figure 5D–F). For samples from

Unit C, the average $I_{\text{comp}} = 0.43$, indicating that porosity loss due to cementation is the dominant mechanism (Table 1). All but five samples have an I_{comp} below 0.5, identifying cementation as the dominant mechanism for porosity loss (Figure 5D). Compaction induced porosity loss is between 6%–25%. The bulk of the samples indicate that cementation reduced porosity between 12%–23%. This is another indication that CEPL is responsible for the most porosity loss among the samples.

For samples from Unit D, the average $I_{\text{comp}} = 0.51$, indicating a nearly equal impact of compaction and cementation on porosity loss (Table 1). For individual samples, compaction has generated porosity loss between 5%–33% while cementation porosity loss ranges between 3%–30% (Figure 5E).

For samples from Unit E, the average $I_{\text{comp}} = 0.43$, indicating that cementation is the dominant mechanism behind porosity loss (Table 1). For individual samples, compaction has generated porosity loss between 3%–30% while cementation porosity loss ranges between 4%–31% (Figure 5F).

Discussion

When considering the diagenetic losses of porosity resulting from compaction and cementation through the stratigraphic section that includes the Upper, Middle, and Lower Mt. Simon and the Argenta Formation, there is a clear discontinuity across the contact between the Middle and the Lower Mt. Simon. The greatest porosity loss due to compaction occurs below this contact, in the deepest units, including the Lower Mt. Simon and the Argenta, as expected. The greatest porosity loss due to cementation occurs above this contact, in the Middle and the Upper Mt. Simon. Though the Lower Mt. Simon has more compaction loss of porosity relative to the overlying Middle and Upper sections of the Mt. Simon, it has a higher porosity. It has a

higher porosity primarily because it has less porosity loss due to cementation relative to the overlying units. Furthermore, the Lower Mt. Simon appears to contain abundant secondary porosity that doesn't occur in the other sections of the Mt. Simon. The units overlying the Lower Mt. Simon contain abundant authigenic quartz and feldspar cement within their intergranular volume. There is relatively little of this authigenic quartz and feldspar cement in the Lower Mt. Simon, because diagenetic clay coatings on grains prevented nucleation of the cement, as discussed further below.

The porosity losses due to both compaction and cementation within the Lower Mt. Simon are similar to those of the underlying Argenta. The Lower Mt. Simon has a higher porosity than the Argenta because original porosity was higher in the Lower Mt. Simon, largely due to a better sorted grain fabric. Furthermore, the Argenta contains more pore-filling clays and lacks secondary porosity due to overall low feldspar content.

Thus, porosity loss by cementation is dominant above the contact between the Middle and Lower Mt. Simon, and porosity loss by compaction is dominant below the contact. The sections that follow elaborate more on the observed porosity loss by compaction and by cementation, and discuss how those observations support interpretations of the diagenesis and depositional history of the Mt. Simon and Argenta sections.

Compaction

Compaction occurred to some extent within all units of the Mt. Simon and Argenta. Lower units, having larger overburdens, undergo more compaction than units higher up. This is common within many sandstone formations (Paxton et al., 2002). However, the wide range of porosities (log, laboratory, and thin sections) found throughout the Mt. Simon, and even within individual units (Figure 2), indicates that nonuniform compaction occurred throughout the Mt.

Simon. The presence of sutured grain contacts (Figure 6) and deformation bands (Chentnik, 2012) throughout the Mt. Simon indicate that both chemical and mechanical compaction occurred. The extent of porosity loss due to mechanical compaction is dependent not only upon a formation's burial history (Lander and Walderhaug, 1999; Paxton et al., 2002), but also upon the size and shape of the grains (Pittman and Larese, 1991) and mineralogy. In the Argenta and Unit A, abundant lithic clasts (Table 1), which are prone to plastic deformation (Figure 6A, B), contribute to the high degree of compaction. Mechanical compaction mechanisms, such as grain rotation and reorientation, are common throughout the Mt. Simon, especially in fine grained sandstones (Figure 6C).

Grain size and pressure solution have been shown to have an inverse relationship; as grain size decreases, the amount of pressure solution increases (Heald, 1956; Houseknecht, 1984; Lander and Walderhaug, 1999). Additionally, previous research has observed that quartz-rich Mt. Simon sandstones are most likely to show evidence of pressure solution (Heald and Baker, 1977). This matches our observations that intervals with finer-grained sands, such as Units D and E, which are also the most quartz rich, have the highest volumes of cements (Figure 7A, B) and show abundant suturing at grain contacts (Figure 6D). The exception is Unit B that is comprised of fine-grained sediments but lacks cement.

Cementation

The greatest porosity loss due to cementation occurs in the Middle and Upper Mt. Simon. The cement responsible for this reduction in porosity is primarily authigenic quartz with minor authigenic feldspar. These cements are relatively lacking in the Lower Mt. Simon units and Argenta relative to the Middle and Upper Mt. Simon units. As suggested in the previous section, the high degree of chemical compaction may be a major contributor to the large volume of

authigenic quartz observed in the Middle and Upper Mt. Simon units. However, to a lesser degree, sutured grain contacts throughout the Lower Mt. Simon Units A and B and Argenta indicate that pressure solution has occurred and may account for the minor authigenic quartz overgrowths observed.

It is also observed that areas of high clay volume cause higher CEPL in units, including the Argenta, A, and C (Figure 7C). Although, the most common presence of clay in the Mt. Simon is in the form of clay coatings (Figure 8A, B). The common presence of authigenic clay coatings and the lack of authigenic quartz cement in the Lower Mt. Simon suggests that cementation is most likely inhibited by clay coatings around quartz grains (Figure 8A, B). Clay coatings have been shown to inhibit quartz overgrowths during burial (Heald and Larese, 1974; Surdam et al., 1989; Pittman et al., 1992; Bloch et al., 2002; Wordan and Morad, 2003). The clays appear to have largely originated early, likely by means of infiltration; however, early alteration of feldspar to clay also appears likely (Figure 8B). In addition, it is observed that clay coatings appear to pre-date feldspar dissolution as evidenced by common feldspar casts composed of illite (Figure 8A, C). Early illite coatings are generally more laminar or sheet-like, suggesting an allogenic origin (Pittman et al., 1992) succeeded by a fibrous or hairy illite of likely authigenic origin (Figure 8B). Samples missing the clay coatings (appear bleached in core) have lower porosity as shown in a detailed study of the Lower Mt. Simon by Ritzi et al. (2016).

Inferences on Diagenetic History

Diagenetic differences between all the units of the Mt. Simon Sandstone and the Argenta Formation suggest complex paragenetic histories partly controlled by events of subaerial exposure and sediment burial. In the Lower Mt. Simon Units A and B, the majority of feldspar

grains are partially to completely dissolved and altered to albite and clays, primarily illite, and mixed-layer illite/smectite (Figure 8A, C; Freiburg et al., 2014). The sheer abundance of feldspar in the Lower Mt. Simon units, as well as the paragenetic relationship of early clay coatings followed by compaction, feldspar dissolution and alteration to clay, and later authigenic quartz cementation (Freiburg et al., 2014), suggests that the presence of early clay coatings is the most important reason for the preservation of primary porosity and secondly the later dissolution of feldspar generating abundant secondary porosity. The preservation of moldic porosity in clay casts of dissolved feldspars suggests feldspar dissolution largely occurred later in burial history when consolidation and compaction was largely complete (Figure 8C). However, it should be mentioned that mold collapse may contribute to an underestimation of COPL, but this was not observed in the Lower Mt. Simon units. Hoholick et al. (1984) and Fishman (1997) reported that cement dissolution among detrital grain dissolution is a major contributor to secondary porosity. Dissolution of early cements such as gypsum, anhydrite (Mozley et al., 2016), and ferroan dolomite (Fishman, 1997) have been proposed. However, in the Lower Mt. Simon at the IBDP site, evidence for secondary porosity in the form of late-stage cement dissolution was not observed. The controls on later feldspar dissolution is poorly constrained. Labotka et al. (2015) found that the Mt. Simon brine geochemical and isotopic signature is distinct from other Illinois Basin brines and can't be explained by water-rock interaction suggesting that it has been influenced by an outside source. Narrowing the origins of the Mt. Simon brine may be key to constringing late feldspar dissolution.

It is unclear why early infiltration of clays in the form of grain coatings and late dissolution of feldspar occurred in the Lower Mt. Simon Units A and B and not the Middle Mt. Simon Units C and D, but there may be a relationship to an inferred unconformity separating the

Lower and Middle Mt. Simon (Freiburg et al., 2014). An unconformity at the top of the Lower Mt. Simon Unit B may have allowed for increased infiltration of clay in the form of clay coatings. Minor clay coatings occur in the Middle Mt. Simon Units C and D but are commonly enclosed in with authigenic quartz and feldspar (Figure 7B). It is possible that minor clay coatings in Unit C didn't coat the entire grains. Furthermore, feldspar dissolution is rare in Unit C compared to Units A and B. Unit E in the Upper Mt. Simon contains high authigenic cements like the Middle Mt. Simon Units C and D. These diagenetic differences indicate different paragenetic sequences between the Mt. Simon units.

The ELAN logs (Table 2; Figure 2) suggest an increase of kaolinite in the Lower Mt. Simon Units A and B, which supports an unconformity on top of the Lower Mt. Simon. However, kaolinite above detection limits has not been identified in the Mt. Simon, but rather illite and mixed layered illite-smectite dominate (Freiburg et al., 2014). ELAN log values for quartz, feldspar, and bulk clay totals are relatively consistent with point count analysis and may be used as a reliable tool for mineral heterogeneity. However, ELAN results for clay mineralogy should be interpreted with caution.

Kaolinite was observed in the Argenta (Figure 8D; Freiburg et al., 2014). The discontinuities in clay mineralogy between the Argenta and Lower Mt. Simon units and the Lower and Middle Mt. Simon units may relate to differences in detrital mineralogy, such as the increased lithic content in the Lower compared to the Middle Mt. Simon. Lithics are largely composed of rhyolite and especially abundant in the Argenta (Freiburg et al., 2014). Water-mineral interaction in rocks abundant with iron- or magnesium-rich volcanoclastic fragments would produce different clay products than feldspar-rich rocks (Worden and Morad, 2003). Kaolinite forms under humid climatic conditions by the action of low-pH ground waters on

detrital aluminosilicates (Emery et al., 1990). Plagioclase and albite tend to be more susceptible to kaolinitization than K-feldspar (Worden and Morad, 2003) and plagioclase is a common constituent of the rhyolitic basement directly underlying the Argenta (Freiburg et al., 2014; Labotka et al., 2015). A combination of increased subaerial exposure (unconformity) and humid conditions (increased meteoric recharge) would lead to increased amounts of kaolinite in the lithic-rich Argenta. This is demonstrated in a known unconformity within the Precambrian Basement in which increased kaolinite was observed (Freiburg et al., 2014).

Inferences on Depositional History

The differences in sediment composition between the Lower Units A and B and Middle Units C and D is indicative of a change in sediment source, from a more proximal lithic-, feldspar-, and quartz-rich source to a more distal feldspar- and quartz-rich source. This aligns with the observations of increasing maturity and overall fining upwards throughout the Mt. Simon, indicating that the sediment source for the Middle and Upper Mt. Simon Units C, D, and E was more distal and thus more mature than the source for the Lower Mt. Simon Units A and B (Lovell and Bowen, 2013). Overall compaction and cementation in the Mt. Simon and Argenta appear to be partially controlled by the observed changes in the lithology, which is ultimately caused by the depositional environment and the sediment source in relation to the location of the basin depositional center.

We propose that (1) the Lower Mt. Simon Units A and B and the underlying Argenta were deposited in a smaller catchment, the proto-Illinois Basin (Kolata and Nelson, 2010) or pre-Mt. Simon Basin (Freiburg et al., 2014); (2) the unconformity separating the Middle Units C and D and the Lower Units A and B marks the beginning of Illinois Basin subsidence; and (3) the Middle and Upper Mt. Simon Units C, D, and E were later deposited in a slowly subsiding

Illinois Basin. Considering the lithologies and immaturity of sediments of the Argenta and Lower Mt. Simon Units A and B, the proto-Illinois Basin likely had high relief and is postulated to be of failed-rift origin. The sediment source was likely more proximal, with nearby Precambrian highs as a major source. As the basin filled and relief lessened, the sediment source became more distal and thus more mature (finer grained, less feldspar and lithics, and less polycrystalline quartz). The Middle Mt. Simon Units C and D were deposited in a low-relief intracratonic sag structure (Illinois Basin) resulting in muddy, low-gradient braided river deposits in Unit C. In a perennially arid climate with a slowly subsiding basin, an eolian environment was pervasive, depositing the highly mature quartz arenites in Unit D. Rising sea level and the continued Illinois Basin subsidence resulted in the intertidal deposits of the Upper Mt. Simon Unit E. Similar to the proto-Illinois Basin sediments, Illinois Basin sediments become more mature upward until marine incursion in the Upper Mt. Simon Unit E.

Conclusion

Anomalously high porosity in the Lower Mt. Simon makes it favorable for CO₂ storage. This investigation examined the diagenetic characteristics of the entire Mt. Simon Sandstone (Upper, Middle, and Lower) and the underlying Argenta Formation, to identify the differences in those characteristics that explain the anomalously high porosity in the Lower Mt. Simon. The major conclusions of the investigation are as follows:

- 1.) Differential compaction occurs with depth through the stratigraphic section of the Upper Mt. Simon and Argenta Formation. The greatest porosity loss due to compaction occurs in the deepest units, including the Lower Mt. Simon and the Argenta, as expected.

Though the Lower Mt. Simon units have more porosity loss due to compaction relative to

the overlying Middle and Upper units of the Mt. Simon, they have a higher porosity.

They have a higher porosity primarily because they have less porosity loss due to cementation relative to the overlying units. The porosity loss due to both compaction and cementation within the Lower Mt. Simon units is similar to that of the underlying Argenta. The Lower Mt. Simon has a higher porosity than the Argenta because its original porosity was higher, because of a better sorted grain fabric and abundant secondary porosity created by feldspar dissolution.

- 2.) The Lower Mt. Simon has less porosity loss due to cementation relative to the Middle and Upper Mt. Simon for the following main reason: the Lower Mt. Simon has abundant diagenetic clay coatings over detrital quartz grains, and the clay coatings inhibited authigenic quartz nucleation during later diagenesis. The origin of these early clays in the Lower Mt. Simon is unclear but there appears to be a relationship with an inferred unconformity separating the Lower and Middle Mt. Simon. The Middle and Upper Mt. Simon units lack the diagenetic clay coatings and as a result have an abundance of authigenic quartz cement occluding much of the original pore space. As the Mt. Simon experienced normal burial processes, sediments experienced compaction followed by cementation in the form of authigenic quartz and authigenic feldspar. The abundant clay coatings in the Lower Mt. Simon inhibited cements while the Middle and Upper Mt. Simon experienced porosity loss by cementation. Later in burial, post-compaction, feldspars experienced dissolution, which further increased porosity in the form of secondary moldic porosity. Determining secondary porosity in the Mt. Simon is complicated by the abundant pore-bridging illite and should be further investigated along with understanding the origin of clays.

- 3.) Based on mineralogical, diagenetic, and depositional heterogeneities, it is proposed that the deposits composing the Lower Mt. Simon and Argenta Formation are associated with a failed rift basin referred to as the Proto-Illinois Basin, with a depocenter located in northeast-central Illinois. The Middle and Upper Mt. Simon reflect deposition in a slowly evolving Illinois Basin during the Sauk Transgression. Further studies of unit correlation, detrital source, and diagenesis are being completed to test this idea.

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References

Beard, D.C and P.K. Weyl, 1973, Influence of texture on porosity and permeability of unconsolidated sand: AAPG Bulletin, v. 57, p. 349–369.

- Bloch, S., R.H. Lander, and L. Bonell, 2002, Anomalously high porosity and permeability in deeply buried sandstone reservoirs: Origin and predictability: AAPG Bulletin, v. 86, no. 2, p. 301–328.
- Bowen, B.B., R.I. Ochoa, N.D. Wilkens, J. Brophy, T.R. Lovell, N. Fischietto, C.R. Medina, and J.A. Rupp, 2011, Depositional and diagenetic variability within the Cambrian Mount Simon Sandstone: Implications for carbon dioxide sequestration: Environmental Geosciences, v. 18, p. 69–89.
- Chentnik, B.M., 2012, Characterizing fractures and deformation bands: Implications for long-term CO₂ storage within the Cambrian Mount Simon Sandstone: Journal of Purdue Undergraduate Research, v. 2, no p. 8–15.
- Collinson, C., M.L. Sargent, and J.R. Jennings, 1988, Illinois Basin region, *in* L.L. Sloss, ed., Sedimentary cover—North American craton: U.S.: Boulder, Colorado, Geological Society of America, The Geology of North America, v. D-2, p. 383–426.
- Driese, S. G., Byers, C. W., & Dott Jr, R. H. 1981, Tidal deposition in the basal upper cambrian mt. simon formation in wisconsin. Journal of Sedimentary Research, v. 51, p. 0367-0381
- Duffin, M.E., M. Lee, G. deVries Klein, and R.L. Hay, 1989, Potassic diagenesis of Cambrian sandstones and Precambrian granitic basement in UPH-3 deep hole, Upper Mississippi Valley, U.S.A.: Journal of Sedimentary Petrology, v. 59, p. 848–861.
- Ehrenberg, S.N., 1989, Assessing the relative importance of compaction processes and cementation to reduction of porosity in sandstones: discussion; compaction and porosity evolution of Pliocene sandstones, Ventura Basin, California: discussion: AAPG Bulletin, v. 73, no. 10, p. 1274–1276.
- Ehrenberg, S.N., 1995, Measuring sandstone compaction from modal analysis of thin sections: how to do it and what the results mean: Journal of Sedimentary Research, v. A65, no. 2, p. 369–379.
- Emery, D., Myers, R.J., and Young, R. 1990, Ancient subaerial exposure and freshwater leaching in sandstones: Geology, 18, p. 1178-1181
- Fischietto, N. E., 2009, Lithofacies and depositional environments of the Cambrian Mount Simon Sandstone in the northern Illinois Basin: Implications for CO₂ sequestration: Master's thesis, Purdue University, West Lafayette, Indiana, 114 p.
- Fishman, N.S., 1997, Basinwide fluid movement in a Cambrian paleoaquifer: Evidence from the Mt. Simon Sandstone, Illinois and Indiana, *in* I.P. Montañez, J.M. Gregg, and K.L. Shelton, eds., Basinwide diagenetic patterns: Integrated petrologic, geochemical, and

- hydrologic considerations: Society for Sedimentary Geology (SEPM), Special Publication, v. 57, p. 221–234.
- Freiburg, J.T., D.G. Morse, H.E. Leetaru, R.P. Hoss, and Q. Yan, 2014, A depositional and diagenetic characterization of the Mt. Simon Sandstone at the Illinois Basin – Decatur Project carbon capture and storage site, Decatur, Illinois, USA: Illinois State Geological Survey, Circular 583, 59 p. and 3 digital appendices.
- Freiburg, J.T., H.E. Leetaru, C.C. Monson, 2015, The Argenta Formation: A newly recognized Cambrian stratigraphic unit in the Illinois Basin: Geological Society of America Abstracts with Programs, v. 47, no. 5, p. 86.
- Hagadorn, J. W., Dott, R. H., & Damrow, D., 2002, Stranded on a Late Cambrian shoreline: Medusae from central Wisconsin. *Geology*, v. 30, no. 2, p. 147-150.
- Heald, M.T., 1956, Cementation of Simpson and St. Peter Sandstones in parts of Oklahoma, Arkansas, and Missouri: *Journal of Geology*, v. 64, p. 16–30.
- Heald, M.T., and G.F. Baker, 1977, Diagenesis of the Mt. Simon and Rose Run sandstones in western West Virginia and southern Ohio: *Journal of Sedimentary Research*, v. 47, no. 1, p. 66–77.
- Heald, M.T., and R.E. Larese, 1974, Influence of coatings on quartz cementation: *Journal of Sedimentary Petrology*, v. 44, p. 1269–1274.
- Hoholick, J.D., T. Metarko, and P. E. Potter, 1984, Regional variations of porosity and cement: St. Peter and Mount Simon Sandstones in Illinois Basin: *AAPG Bulletin*, v. 68, no. 6, p. 753–764.
- Houseknecht, D.W., 1984, Influence of grain size and temperature on intergranular pressure solution, quartz cementation, and porosity in quartzose sandstone: *Journal of Sedimentary Petrology*, v. 54, p. 348–361.
- Houseknecht, D.W., 1987, Assessing the relative importance of compaction processes and cementation to reduction of porosity in sandstones: *AAPG bulletin*, v. 71, no. 6, 633–642.
- Labotka, D.M., S.V. Panno, R.A. Locke, and J.T. Freiburg, 2015, Isotopic and geochemical characterization of fossil brines of the Cambrian Mt. Simon Sandstone and Ironton-Galesville Formation from the Illinois Basin, USA: *Geochimica et Cosmochimica Acta* 165, 342–360.
- Lander, R.H., and O. Walderhaug, 1999, Predicting porosity through simulating sandstone compaction and quartz cementation: *AAPG bulletin*, v. 83, no. 3, p. 433–449.
- Lovell, T.R. and Bowen, B.B., 2013, Fluctuations in sedimentary provenance of the Upper Cambrian Mount Simon Sandstone, Illinois Basin, United States. *The Journal of Geology*, 121(2), pp.129-154.

- Lundegard, P.D., 1992, Sandstone porosity loss—A “big picture” view of the importance of compaction: *Journal of Sedimentary Petrology*, v. 62, no. 2, p. 250–260.
- Kolata, D.R., and J.W. Nelson, 1990, Tectonic history of the Illinois Basin, *in* M.W. Leighton, D.R. Kolata, D.F. Oltz, and J.J. Eidel, eds., *Interior Cratonic Basins*: AAPG, Memoir 51, p. 263–285.
- Kolata, D.R., and J.W. Nelson, 2010, Tectonic history, *in* D.R. Kolata and C.K. Nimz, eds., *The Geology of Illinois*: Illinois State Geological Survey, p. 77-89
- Makowitz, A., and K.L. Milliken, 2003, Quantification of brittle deformation in burial compaction, Frio and Mount Simon Formation sandstones: *Journal of Sedimentary Research*, v. 73, no. 6, p. 1007–1021.
- Medina, C.R., J.A. Rupp, and D.A. Barnes 2011, Effects of reduction in porosity and permeability with depth on storage capacity and injectivity in deep saline aquifers: A case study from the Mt. Simon Sandstone aquifer: *International Journal of Greenhouse Gas Control*, v. 5, no. 1, p. 146–156.
- Mozley, P.S., J.E. Heath, T.A. Dewers, and S.J. Bauer, 2016, Origin of heterogeneity of pore sizes in the Mount Simon Sandstone and Eau Claire Formation: Implications for multiphase fluid flow: *Geosphere*, v. 12, no. 4, p. 1341-1361
- Paxton, S.T., J.O. Szabo, , J. M. Ajdukiewicz, , and R. E. Klimentidis, 2002, Construction of an intergranular volume compaction curve for evaluating and predicting compaction and porosity loss in rigid-grain sandstone reservoirs: *AAPG bulletin*, v. 86, no. 12, p. 2047–2067.
- Pittman, E.D., and R.E. Larese, 1991, Compaction of lithic sands: Experimental results and applications (1): *AAPG Bulletin*, v. 75, no. 8, p. 1279–1299.
- Pittman, E.D., R.E. Larese, M.T. Heald, 1992, Clay coats: occurrence and relevance to preservation of porosity in sandstones: *Society for Sedimentary Geology, Special Publication No. 47*, p. 242–255.
- Pollington, A.D., R. Kozdon, and J.W. Valley, 2011, Evolution of quartz cementation in the Illinois Basin during burial of the Mt. Simon Sandstone: *In situ microanalysis of $\delta^{18}\text{O}$* : *Geology*, v. 39, p. 1119–1122.
- Ritzi, R.W., J.T. Freiburg, and N.D. Webb, 2016, Understanding the (co) variance in petrophysical properties of CO₂ reservoirs comprising sedimentary architecture. *International Journal of Greenhouse Gas Control*, 51, p. 423-434.
- Surdam, R.C., T.L. Dunn, D.B. MacGowan, H.P. Heasler, 1989, Conceptual models for the prediction of porosity evolution with an example from the Frontier Sandstone, Bighorn Basin, Wyoming, *in* Coalson, E.B., S.S. Kaplan, C.W. Keighin, L.A. Oglesby, J.W.

Robinson, eds., Sandstone Reservoirs: Rocky Mountain Association of Geologists, p. 7-21

Wentworth, C.K., 1922, A scale of grade and class terms for clastic sediments: Journal of Geology, v. 30, p. 377-392

Worden, R.H., S. Morad, 2003, Clay minerals in sandstones: Controls on formation, distribution, and evolution, *in* R.H. Worden, and S. Morad, eds., Clay minerals in sandstones: Oxford, UK, Blackwell Science, International Association of Sedimentologists, Special Publication 34, p. 3-41.

Table 1) Sample data and interpretations from thin section modal and lab analyses. Grain-size classes based on Wentworth (1922) and grain-size card from the Canadian Stratigraphic Services.

Table 2) Argenta Formation and Mt. Simon Sandstone averages from ELAN and neutron-porosity logs (Figure 2). Feldspars are reported as all potassium feldspar. Data is recorded every 0.5 ft (15 cm).

Figure 1) Isopach map displaying Mt. Simon Sandstone and Argenta Formation thickness and distribution, Precambrian Basement topography, the location of the Illinois Basin–Decatur Project (IBDP), and locations of wells penetrating the Mt. Simon Sandstone.

Figure 2) Elemental analysis (ELAN) that includes permeability, gamma ray, and neutron-porosity logs through the Mt. Simon Sandstone and Argenta Sandstone from Verification Well #1 at the IBDP site. Whole core (green bar) and rotary sidewall core (tick marks) sample locations are located on the right side of the ELAN log. Units within the Upper, Middle, and Lower Mt. Simon Sandstone are labeled on the logs.

Figure 3) Inputs of grain size (A), initial porosity (B), cement (C), IGV (D), He (helium) porosity (E), and modal porosity (F) vs. depth with an analysis of mean values (red box).

Figure 4) Computed results of COPL (A), CEPL (B), and Icomp (C) vs. depth with analysis of mean values (red box).

Figure 5) Compaction porosity loss (COPL) and cementation porosity loss (CEPL) for the (A) Argenta Formation, (B) Mt. Simon Sandstone Unit A, (C) Unit B, (D) Unit C, (E) Unit D, and (F) Unit E.

Figure 6) Thin section photomicrographs illustrating COPL. Notice sutured grain boundaries (red arrows) and highly consolidated grains with labeled quartz (Q), feldspar (F), lithics (L), and porosity (blue). (A) Sample from the Argenta Formation at a depth of 7023.8 ft (2140.9 m). Notice abundant compacted detrital lithic and quartz grains; (B) Sample from the Lower Mt. Simon Unit A at a depth of 6928.4 ft (2111.8 m). Notice compaction with numerous elongated grains and sutured grain boundaries; (C) Sample from the Lower Mt. Simon Unit B at a depth of 6520 ft (1987 m). A well consolidated fine-grained sandstone with lenses of coarser grains; (D) Sample from the Middle Mt. Simon Unit D at a depth of 5943.7 ft (1811.6 m). Notice highly sutured quartz-grain boundaries.

Figure 7) Thin section photomicrographs illustrating CEPL with authigenic quartz overgrowths (AQ) on detrital quartz grains (Q), minor feldspar overgrowths (AF) on detrital feldspar grains (F), pore-filling clays (C), and porosity (blue). (A) Sample from the Upper Mt. Simon Unit E at a depth of 5684 ft. Notice the abundant authigenic quartz overgrowths and minor authigenic feldspar overgrowths. (B) Sample from the Middle Mt. Simon Unit D at a depth of 5947.2 ft. Notice the near to complete lack of pore space as a result of pore occluding authigenic quartz cement despite the minor clay coatings over quartz grains. (C) Sample from the Middle Mt. Simon Unit C at a depth of 6266 ft. Pore space is largely occluded by clay minerals. Porosity is more likely preserved in coarser grained laminae compared to finer-grained laminae as a result of grain rotation and reorientation of finer grains.

Figure 8) (A) Thin section photomicrograph from the Lower Mt. Simon Unit A at a depth of 6765 ft (2062 m), showing common clay coatings on detrital quartz (Q) and feldspar grains (F). Notice partial dissolution and alteration of feldspar grains. Clay coating casts (green arrows) indicate feldspar grains that were completely dissolved out. (B) Scanning electron microscope (SEM) photograph of a sample

from the Lower Mt. Simon Unit A at a depth of 6765 ft (2062 m), showing authigenic clay coatings (C) on detrital quartz (Q) and feldspar (F) grains. At least two different diagenetic clays are observed: (I1) an early grain-coating illite that is described as more laminar or sheet-like, and (I2) a later hairy illite growing on I1 illite. Feldspars appear to be altering to I1 illite. (C) Scanning electron microscope photograph of a sample from the Lower Mt. Simon Unit A at a depth of 6765 ft (2062 m), showing partial dissolved feldspar (F) altered to clay minerals (C). Arrow indicates clay cast of partially dissolved out feldspar grain. D) Scanning electron microscope photograph of a sample from the Argenta Formation at a depth of 7038 ft (2145 m). Notice the abundant pore-filling kaolinite (K) among detrital quartz (Q) grains.

Table 1) Sample data and interpretations from thin section modal and lab analyses.

Averages	Unit E	Unit D	Unit C	Unit B	Unit A	Argenta
Samples (n)	30	20	17	21	81	11
COPL	13.71	18.84	14.33	25.29	21.32	21.21
CEPL	18.18	17.81	18.39	7.72	9.54	9.86
I_{comp}	0.43	0.51	0.43	0.76	0.69	0.66
P_i	36.46	38.18	35.08	37.13	36.84	33.05
IGV	25.83	23.26	24.13	15.72	19.51	14.55
Thin Section Porosity	5.79	1.88	2.61	5.48	7.51	2.36
Lab He porosity (%)	11.10	7.62	11.43	16.84	16.27	7.54
Total quartz (%)	82.15	91.72	85.11	80.87	65.99	82.73
Authigenic quartz (%)	11.38	15.97	6.23	3.08	3.25	4.54
Polycrystalline quartz (%)	n/a	1.25	13.24	1.98	8.93	15.07
Total Feldspar. (%)	5.73	1.21	8.42	4.87	12.34	2.77
Authigenic Feldspar. (%)	3.21	0.29	1.58	0.38	0.72	0.01
Lithics (%)	0.25	0.26	1.47	2.14	6.13	4.36
Clay (%)	6.08	4.93	6.62	6.79	8.02	7.64
Sorting Class	Moderate to well sorted	Well to moderately sorted	Moderate to poorly sorted	Well to moderately sorted	Well to moderately sorted	Moderate to poorly sorted
Grain Size Class	Medium lower to fine upper	Fine upper to lower medium	Medium lower to coarse lower	Fine upper to fine lower	Medium upper to fine upper	Fine upper to lower medium
Depositional Environment	Shallow Marine	Eolian	Fluvial	Eolian	Fluvial	Shallow Marine

Table 2) Argenta Formation and Mt. Simon Sandstone averages from ELAN and neutron-porosity logs (Figure 2). Data is recorded every 0.5 ft (15 cm).

Averages (%)	Unit E	Unit D	Unit C	Unit B	Unit A	Argenta
Quartz	85.98	93.09	80.40	86.00	73.96	75.84
Feldspar	10.63	2.74	12.20	8.93	17.57	6.66
Clay Total	3.34	4.06	7.29	4.93	8.11	10.07
Chlorite	0.04	0	0	0.03	0.29	0
Illite	2.90	3.52	7.08	3.30	5.32	10.05
Kaolinite	0.40	0.54	0.21	1.61	2.50	0.02
Calcite/Dolomite	0	0	0	0.03	0.29	0
Pyrite	0.05	0.10	0.11	0.11	0.08	0.22
Porosity	10.15	8.21	9.09	15.08	17.65	8.89

Figure 1

Figure 2

Verification Well #1

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7
A

Figure 8