Understanding the (co)variance in petrophysical properties of CO_2 reservoirs comprising sedimentary architecture

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ABSTRACT

Scientific evaluation of CO_2 geo-sequestration requires fundamentally understanding the processes associated with CO_2 movement and trapping within reservoirs. Fully understanding these processes requires understanding a diverse set of heterogeneous geologic properties that vary at different scales. Establishing basic relationships between the sedimentary architecture in these reservoirs and the variation in petrophysical attributes that can affect plume dynamics and residual trapping is an important step toward understanding reservoir processes. Highly-resolved data sets at well-characterized research sites can be used to establish these basic relationships. In this vein, the sample (co)variance for petrophysical attributes can be quantitatively and deterministically decomposed according to a hierarchy of textural factors that vary among sedimentary facies. A new hierarchical method for the analysis of (co)variance of petrophysical attributes is adapted for this purpose. The results quantify the magnitude that each factor contributes to the (co)variance, and thus clarify their relative contribution within the factor hierarchy. This leads to a basic understanding of how the sample (co)variance arises within the sedimentary architecture, and of which factors are important in defining it. Such an understanding aids in developing parsimonious reservoir simulation models. The method is illustrated using a highly-resolved data set from the lower Mt. Simon Sandstone reservoir.

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1. Introduction

Evaluating the efficacy of geological sequestration of CO_2 requires understanding subsurface flow dynamics, including CO_2 plume migration and trapping, which, in turn, requires understanding a diverse set of geologic properties of a candidate reservoir. For example, there is considerable interest in the post-injection process of residual trapping of CO_2 within reservoirs (occurring far below caprock). Residual trapping occurs because CO_2 is immobilized by snap-off of CO_2 bubbles at the tail of a CO_2 plume as it buoyantly rises and by entry pressure pinning of the plume below areas where capillary entry pressure exceeds buoyant pressure. These trapping processes could immobilize appreciable amounts of CO_2 within the reservoir and add to the overall efficacy of CO_2 storage (e.g., Juanes et al., 2006; Saadatpoor et al., 2009; Zhou et al., 2010; Gershenzon et al., 2015a; Krevor et al., 2015; Bacon et al., 2016). As shown by Gershenzon et al. (2015a), smaller-scale (decimeter to tens of meters) textural differences in reservoir rock, related to

sedimentary architecture, can exert strong control on residual trapping and other aspects of CO_2 dynamics because of the variation in petrophysical attributes such as capillary entry pressures, intrinsic permeability, saturation relationships with capillary pressure and relative permeability, and porosity. The focus of this article is on understanding and explaining the variance of an attribute through the sedimentary architecture. A new method of decomposing the sample variance or covariance (Soltanian and Ritzi, 2014) is adapted for this purpose, which incorporates indicator variables to represent a hierarchy of sedimentary attributes.

Field studies of sedimentary deposits have created a body of literature on the link between sedimentary architecture and heterogeneity in intrinsic permeability and porosity [e.g., Anderson, 1989, 1991a,b; Davis et al., 1993, 1997; Allen-King et al., 1998, 2015; Barrash and Clemo, 2002; Divine, 2002; Gaud et al., 2004; Biteman et al., 2004; Dai et al., 2005; Ritzi et al., 2013; Soltanian and Ritzi, 2014]. Facies classifications are prevalent in this work. Facies are three-dimensional bodies of sediment whose differentiation provides a useful conceptual framework within which to characterize heterogeneity in attributes of interest within the larger sedimentary deposit. Importantly, facies classifications are not unique. For example, Dai et al. (2005) demonstrated how either

depositional sedimentary facies or textural sedimentary facies could be used to represent spatial heterogeneity in permeability arising in alluvial deposits in the Rio Grande Valley. There is no universal answer to questions over how facies should be defined. A classification should be useful and parsimonious, and these both depend upon context. What is most appropriate in one context may not be most appropriate for another. Our interest is in defining facies classifications useful within the workflow for creating interpretive reservoir simulation models.

The idea behind the approach is illustrated here in the context of understanding and modeling the spatial distribution of petrophysical attributes within sedimentary architecture created by fluvial deposition, though the general approach is not limited in applicability to fluvial architecture. A number of candidate reservoirs suitable for CO_2 sequestration have sedimentary architecture reflecting fluvial deposition in at least part of their stratigraphic sections, such as in the lower Mt. Simon Sandstone (Freiburg et al., 2014); the lower Paaratte Formation (Krevor et al., 2012; Dance and Patterson, 2016); the Victor interval of the Ivishak Formation (Tye et al., 2003); the Morrow Sandstone (Dai et al., 2014; Gallagher, 2014); and the lower Tuscaloosa Formation (Krevor et al., 2012; Lu et al., 2011). These are predominantly composed of sandstone or conglomerate, and their sedimentary architecture comprises multiple scales of heterogeneity ranging from the decimeter to the reservoir scale. The complexity of the sedimentary architecture internal to such reservoirs needs to be included in developing a basic-science understanding of CO_2 injection, migration, and residual trapping.

The sedimentary architecture created by fluvial deposition has recently been described and quantified in three-dimensional models (e.g., Lunt, 2002; Lunt et al., 2004; Bridge, 2006; Ramanathan et al., 2010; Guin et al., 2010). As shown in Fig. 1, channel-belt deposits are characterized by a large volume fraction of convex-up compound-bar deposits formed within channels, which comprise unit-bar deposits which, in turn, comprise mostly sets of cross-beds (cross-sets hereafter) formed by migrating dune bedforms, creating a hierarchy of stratification in preserved deposits. Unit bar deposits may also comprise planar- and ripple-laminated strata. When channels are abandoned and filled, concave-up, channel fills are formed comprising finer-grained sediment. This sedimentary architecture is found in modern fluvial settings and in ancient fluvial reservoirs that range in mean grain size from sand (e.g., lower Mt. Simon Sandstone) to gravel (e.g., the Ivishak Formation conglomerate). Importantly, these deposits and reservoirs are dominated by an assemblage of finer- and coarser-grained cross-sets, as illustrated in Fig. 1. Those finer- and coarser-grained sedimentary textures can be a primary factor influencing the variance of a petrophysical attribute such as permeability, and depositional architecture can explain the spatial organization of textural facies that are indeed of primary importance.

Well-developed, digital, geocellular models exist for simulating the depositional architecture of fluvial deposits (e.g., Ramanathan et al., 2010; Hassanpour et al., 2013; Gershenzon et al., 2015a). Because the size of the depositional units scale together with the width of the active channels in which they form (Bridge, 2006), it is possible to adapt these general models to specific deposits. The model units can be scaled to the length scales quantified for a specific reservoir. The grid cells of the different sedimentary units in the digital model can be populated with values for attributes, such as intrinsic permeability, based on a quantification of their statistical distributions specific to the textures of the units (e.g., finer-grained vs. coarser-grained cross-sets) found in a specific reservoir. The workflow in creating a CO_2 simulation model for a specific reservoir might proceed with (1) evaluating reservoir data to define textural facies based on grain size, bedding, and other factors, (2) defining statistical distributions for petrophysical attributes per each

of the textural facies, and (3) mapping values for the attributes from these distributions into the digital geocellular model for sedimentary architecture and using the geocellular model in reservoir simulations (e.g., Gershenzon et al., 2014, 2015a,b).

This article addresses steps 1 and 2 using deterministic statistics (sensu Isaaks and Srivastava, 1988). In this approach, highly-resolved data sets are used to compute sample statistics within a deterministic framework. The general goal is to study real, highly-resolved, sample statistics when well-quantified in naturally-occurring reservoirs, and to understand how the sample statistics are influenced by attributes of the sedimentary architecture. Thus, this area of statistics can be distinguished from other areas that focus on estimation or uncertainty. Here we undertake a deterministic analysis of the sample variance of intrinsic permeability and porosity, and their sample covariance, in a reservoir with highly-resolved data, to see how the sample statistics are controlled by a hierarchy of attributes, including sedimentary grain size and bedding, and also vertical position and diagenetic alteration, and to use that knowledge to create a parsimonious set of textural facies types and statistical distributions for the populations of petrophysical properties that occur within them. These could then be used in the third step of the workflow outlined above (the third step is outside the scope of this article).

To accomplish the deterministic analysis of the sample variance, we use a newer hierarchical approach described below. We illustrate the methodology using a rich data set from the lower Mt. Simon Sandstone, a target CO_2 storage reservoir in the Illinois Basin, USA. The methodology is presented as adapted to a hierarchy of factors defined by this example, and therefore the hierarchy of factors used for study of the lower Mt. Simon is first described.

2. Lower Mt. Simon Sandstone

The Middle Cambrian Mt. Simon Sandstone is a permeable and porous formation that is used for the Illinois Basin-Decatur Project (IBDP), a 1 million metric-ton carbon capture and storage demonstration project located in Macon County, Illinois (Finley, 2014). The IBDP began injecting CO_2 in November 2011 into the lower Mt. Simon Sandstone (Fig. 2) below a depth of 2000 m.

Within the scope of IBDP research, the Mt. Simon Sandstone has been rigorously characterized (Leetaru and Freiburg, 2014; Freiburg et al., 2014). The highest quality reservoir rock is in the lower Mt. Simon, designated as Unit A (Fig. 2a). Unit A can be divided into upper A and lower A, which include braided-fluvial and other sandstone deposits, and which are separated by a thin (~1 m) mudstone that creates a pressure baffle between them (Senel et al., 2014). Our interest has been in characterizing the relatively more permeable upper and lower A units, and not in the mudstone itself. Therefore, we have not included the mudstone in the example analysis below, though it could be included if desired.

A highly resolved data set, used here, comes from a relatively continuous core (vertical interval represented by an ochre stripe in Fig. 2) taken during the drilling of Verification Well #1 (VW1), located 300 m from the injection well. From analyses of this core, Freiburg et al. (2014) provided a highly-resolved textural description of the rock. Related laboratory analyses of 10-cm diameter whole-core samples provided intrinsic permeability and porosity data with 0.3 m (on average) vertical resolution. Capillary entry pressures and other attributes are also important to developing reservoir simulation models; however, data for these attributes do not exist in numbers sufficient for an analysis of their variance. The method we present could be applied in the future if sufficient numbers of data were developed.

The Mt. Simon Unit A deposits are maroon to tan-white sandstones classified as subarkose arenite (between 5%–25% total