

Consequences of Simplified Geologic Models for CO₂ Sequestration: Example from the Powder River Basin, NE Wyoming and SE Montana*

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Search and Discovery Article #80087 (2010)

Posted April 30, 2010

*Adapted for extended abstract prepared for presentation at AAPG/SEG/SPE Hedberg Conference, “Geological Carbon Sequestration: Prediction and Verification,” Vancouver, BC, Canada, August 16-19, 2009

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Introduction

Geologic uncertainty related to the subsurface storage of carbon dioxide centers on establishing storage capacity, evaluating injectivity, and predicting migration paths and rates. Unfortunately, existing simplified geologic models for geologic sequestration fail to retain the multiple scales of heterogeneity that affect these attributes, and, therefore, they cannot be used to assess the geologic uncertainty associated with carbon storage in sedimentary basins. Simplification involves reducing the number of geologic parameters in the model, using large grid cells, and treating geologic storage sites as homogeneous reservoirs. Homogeneous models make it easier to assess important fluid and/or fluid-rock interactions, but they poorly represent the actual reservoir architecture governing subsurface flow. Storage reservoirs contain heterogeneities at multiple scales; this affects fluid migration pathways and rates, which need to be understood at the time scale required for subsurface sequestration (1000 yrs). In this study uncertainty and risk associated with geologic sequestration are being assessed through the generation and application of 3D geologic models that capture multiple scales of reservoir heterogeneity at the basin scale. This research focuses on the static three-dimensional architecture of a portfolio of storage sites considered representative of cratonic sedimentary basins in North America.

Geologic Model

This geologic model incorporates 30,000 wells correlated across the two kilometers-thick and 70,000 km² area of the Powder River Basin (up to 60 picks per well from the Precambrian to top Cretaceous). The workflow involves seven steps: 1) perform basin analysis, petroleum system analysis, and identification of high pore volume storage sites (reservoirs), 2) correlate reservoir class to sedimentary system, 3) perform 1D rock-to-subsurface data calibration, 4) generate stratigraphic framework emphasizing the hierarchy of stratigraphic cycles, 5) define sedimentation regions that characterize changes in sedimentary architecture within and between cycles, 6) use stratigraphic changes in sedimentary architecture to modulate 3D property and heterogeneity distributions, and 7) geostatistically distribute rock properties and generate petrophysical models. This basin-scale model contains five reservoir classes (RCs) that correlate to different Paleozoic and Mesozoic sedimentary systems (step 1) ([Figure 1A](#)). The five RCs represent common sedimentary systems in cratonic sedimentary basins (step 2) and include in decreasing depth: RC1, greenhouse carbonate platform (12 m.y.); RC2, icehouse mixed carbonate/eolian sandstone system (4

m.y.); RC3, sandstone valley-fill encased in marine shale; RC4, deltaic and ramp turbidite sandstone system (8 m.y.) and; RC5, wave-dominated shoreface to shelf sandstone system (4 m.y.) (Figure 1B).

Core and outcrop studies provide essential rock calibration for the geologic models (step 3). Process-based facies analysis helps identify hydrodynamic facies, sedimentary environments, stratigraphic trends and key surfaces for correlation. Hydrodynamic facies are grouped into petrofacies that correlate grain size to core porosity, permeability, and well-log values. This step correlates hydrodynamic facies to rock properties and log values to predict petrofacies in the uncored wells. This important step captures the several orders of magnitude variation in porosity and permeability that the core data reveal. Averaging this data removes the empirical pore-scale heterogeneity from the model.

Stratigraphic cross sections reveal 2D trends within a hierarchical framework of stratigraphic cycles established from basin-wide correlations (step 3) (Figure 2A). From this framework, isochore and lithology maps can be generated, which are iterated with cross-section correlations until a defensible sedimentary pattern is generated that honors both the map pattern and cross-sectional architecture and which can be correlated to sedimentary processes considered characteristic of the sedimentary system. This permits establishing sedimentation regions (step 5), or areal zones with common sedimentary architecture (defined by thickness, lithology, and well-log shape). Cycle strata are then populated with sedimentation regions, which define spatial distributions and trends. If sedimentation regions are not defined, spatially varying rock properties are averaged and smoothly distributed in homogenous layers within the volume.

The map, section, and well data are integrated to generate a 3D geologic model for each reservoir class. The correlation between facies and rock properties are used to distribute properties based on facies arrangements within and between cycles and regions (step 6). Vertical proportion curves and areal facies proportion maps are used to discretely, geostatistically distribute petrofacies constrained by the architecture in the volume (step 7). These steps are repeated for all reservoir classes to generate the connected 3D pore volume architecture of the whole basin model. This process produces a family of 3D basin-scale petrophysical geological models ready for upscaling and flow simulation.

Though building basin-scale geological models with multiple scales of heterogeneity is resource-intensive, these models represent the only tool available to adequately assess the geologic uncertainty associated with subsurface CO₂ storage. This model provides a simulation-ready dataset that can be used to quantify the effect of connected permeability heterogeneity at different CO₂ retention times (100, 1000, 10000 yrs). It can be used to predict long-term migration path risks at injection ratios of 20%, 50%, and 80% of the basin's total connected pore volume. Future model applications include screening of basin-scale CO₂ storage sites and volume assessments, identification of migration and accelerated flow pathways, characterization of seal integrity, and testing of different upscaling methods and flow simulation algorithms.

This 3D modeling approach assumes that rock property distributions correlate to geologic process. On the other hand, stochastic 2D Monte Carlo methods represent an alternative approach for spatially distributing averaged properties in a model. Model results are easily conditioned to subsurface data using stochastic methods. Because stochastic models are randomly generated, they are not reproducible, nor can they be correlated to the formative geologic processes responsible for their origin (Figure 2B). In other words, conditioning a model to sparse subsurface data does not ensure that it accurately depicts the sedimentary architecture of the reservoir. This highlights the critical need for geologic models with multiple scales of heterogeneity to accurately assess the capacity and complexity of geologic sequestration.

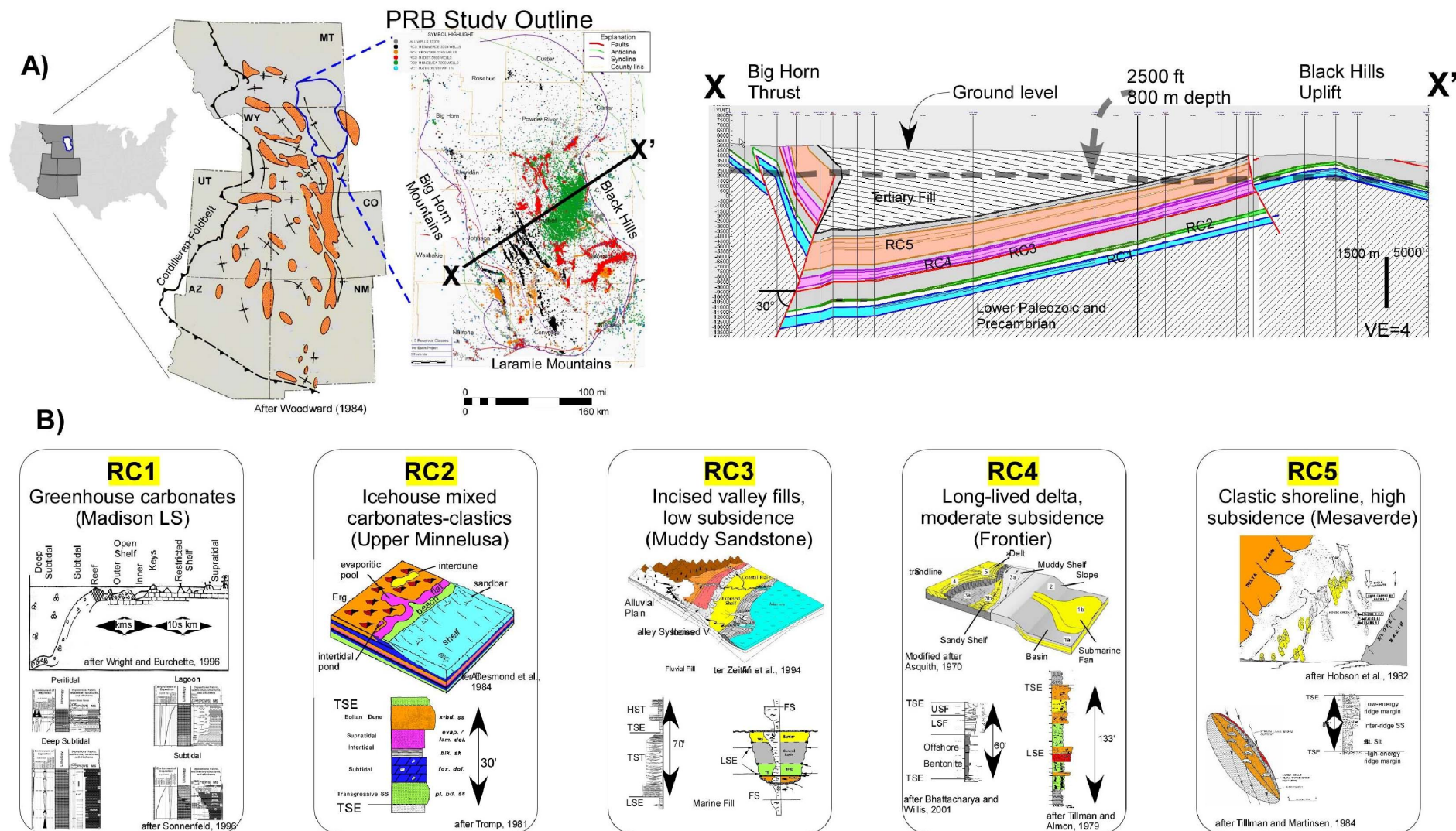
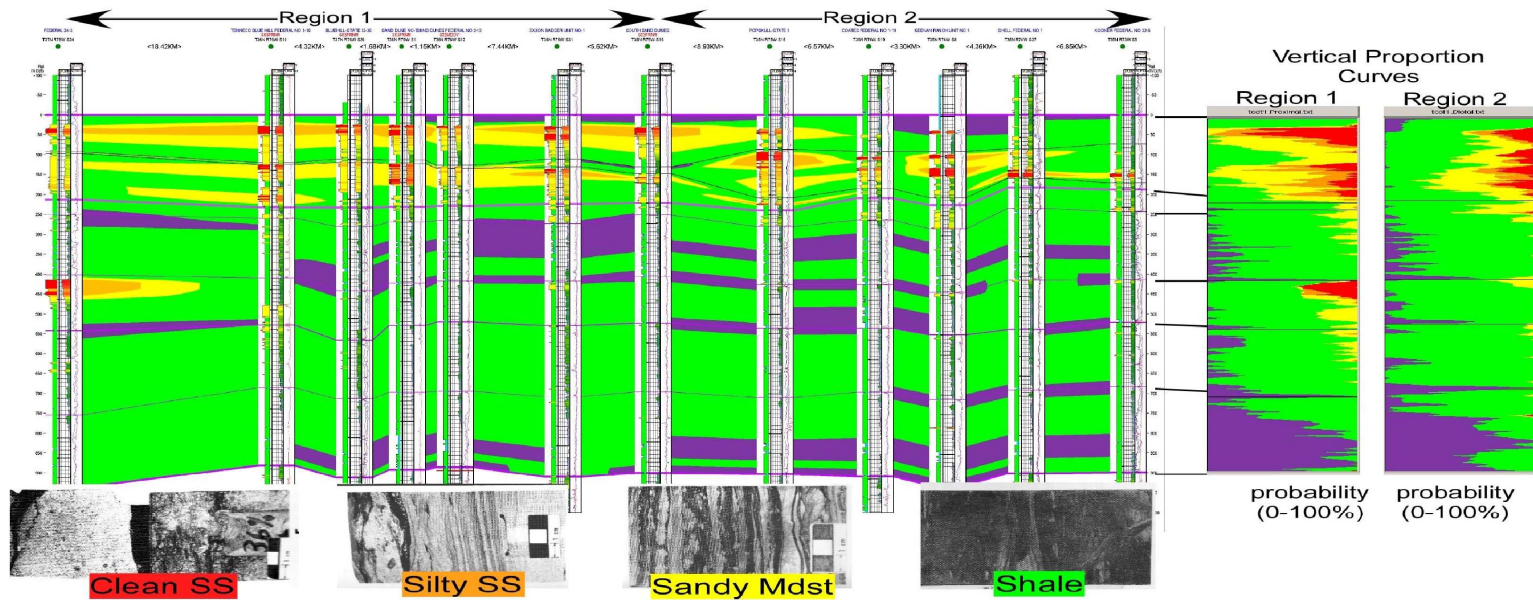
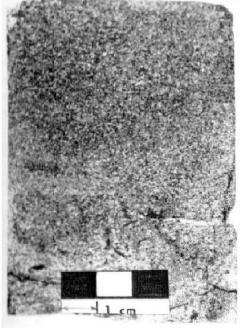


Figure 1. Basin screening and storage interval characterization of this study. A) typical large onshore cratonic basin near point sources of carbon emissions was selected. Within this 60,000 km³ (37,500 mi³) basin, five reservoir classes were selected (stratigraphic successions with large pore volume reservoirs associated with a set of sedimentary systems) (RC1-5). Five Reservoir Classes (RCs) describe the principal pore volume intervals in the basin. Characterizing these enables assessing storage and connectivity related to carbon sequestration.

A) Geodetail: Facies predictions constrain distribution of properties in 2D



$\Phi = 7\%$,
 $K = 3 \text{ mD}$
 Sand Facies



B) Geoaverage: Lithology prediction is smoothed across large distance

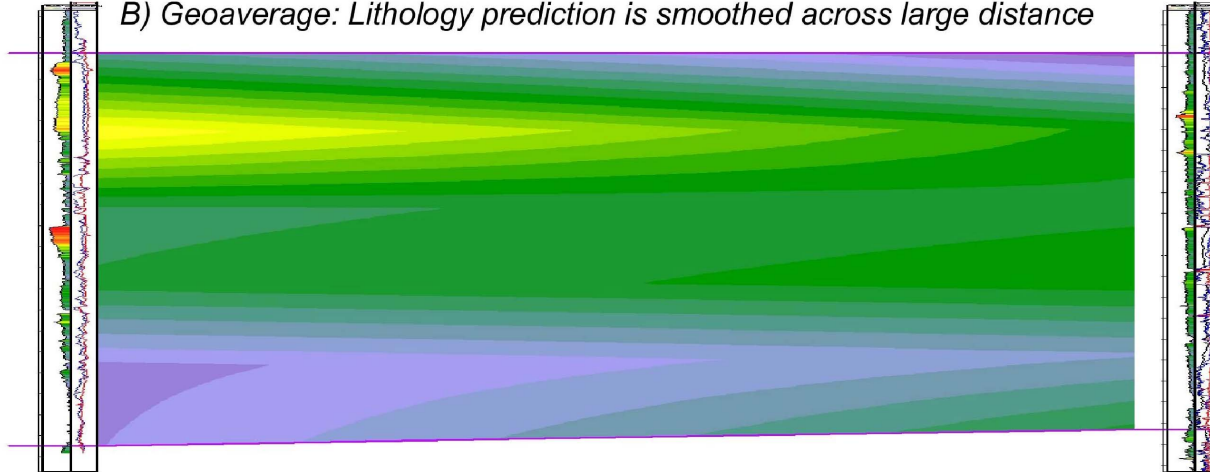


Figure 2. The consequences of averaging geology. A) 50-km (30-mile) transect down depositional dip in RC4 shows the importance of high-resolution stratigraphy and discretizing the area into regions. B) Same distance is represented by two wells, where lithology is interpreted from gamma ray at 65-mi (200-ft) cell thickness