Geostatistical Modeling for CO_2 Geostorage: A Look at Weyburn

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The reduction of Greenhouse Gas emissions is a growing concern for many countries and industries. Following the mitigation solutions recommended by the Kyoto Protocol, underground sequestration of CO_2 presents one approach to meet this goal. For this purpose, oil and gas fields offer huge CO_2 storage capacities while preserving the environment. The oil and gas industry has a longstanding practice of commercial gas injection for the purpose of EOR and natural gas storage. This paper takes a closer look at the Weyburn field and considers geostatistical approaches and issues related to modeling for CO2 sequestration. A synthetic model is also shown for illustration.

Introduction

The reduction of Greenhouse Gas (GHG) emissions is a growing concern for many countries and industries. Over the last few decades, many international forums have focused on the concept of sustainable development, including the United Nations (UN) Conference on Human Environment in Stockholm 1972 and the 1992 Earth Summit in Rio de Janeiro (Environment Canada, 2006). While these forums have had some progress in bringing environmental issues to the global public, the Kyoto Protocol of 1997 is the first document committing industrialized countries to reduce their GHG emissions to a level that is 5.2% below 1990 levels.

The Kyoto Protocol is an agreement made under the United Nations Framework Convention on Climate Change (UNFCC). While the protocol was negotiated in 1997, it became legally binding in 2005 when enough countries ratified the agreement to cover at least 55% of the emissions target reduction specified in the protocol. Kyoto Protocol states that countries which ratify this protocol commit to reduce their emissions of six GHGs, or engage in emissions trading if they maintain or increase emissions of these gases.

One such approach towards GHG reductions lies in the potential sequestration of CO_2 gases. For this purpose, oil and gas fields offer huge CO_2 storage capacities while preserving the environment. There are several advantages in using depleted oil and gas reservoirs for CO2 geostorage, for example since the reservoir is depleted therefore large pressure range is available for injection of CO2 this causes storage of significant amount of CO2 without changing the cap-rock integrity. In addition, the static, dynamical and geological properties of the reservoir and also the existing drilled production and injection wells cause the project to be optimized economically (Gallo, Y. L. 2002).

CO_2 Geostorage

Carbon Dioxide (CO_2) storage is one of the ways to reduce the amount of GHG in the atmosphere. There are several options for CO_2 storage i.e. geostorage and ocean storage. CO_2 Geostorage is one of the suitable ways for storage because abandoned oil and gas reservoirs are already available and gas injection technology already exists; CO_2 can be trapped for millions of years in suitable geological formations, different geologic formations which are useful for CO2 geostorage are listed below with their advantages. Table 1 shows different locations all around the world for CO_2 Geostorage;

- *Oil & Gas Fields:* The examples for this type of Geostorage is depleted Oil and Gas Reservoirs or in the case of CO_2 injection for the purpose of enhanced oil recovery (EOR), in the EOR case the storage costs are offset by the sale of additional oil and gas, e.g. Weyburn Oil Field, Saskatchewan, Canada. Oil and Gas reservoirs are known to have a geologic seal that trapped hydrocarbons. One of the important factors that depleted oil and gas reservoir have in comparison to other sites for CO_2 Geostorage is that there are a lot of data available such as geophysical, petrophysical, …in other hand we are dealing with a mature field.

- *Saline Formations (Deep Saline Aquifers):* This site has large potential storage for geostoring CO_2. In compare to oil and gas field, saline formations are spread widely around the world but in compare to oil and gas fields there are less data available for this kind of formation, e.g. Sleipner Field, North Sea.

- *Unminable Coal Seams (Coalbed Methane):* In coalbeds CO_2 injection and sequestration is one of the best way to extract methane from the coalbeds therefore this method can be named enhanced coalbed methane recovery (ECBM), the storage of CO_2 and extraction of methane is done by adsorption mechanism.

A part of the storage of CO_2 in these reservoirs involves one of three common trapping mechanisms: hydrodynamical, solution and/or mineral trapping. Hydrodynamical trapping involves the injection of CO2 as an extra gaseous phase into the reservoir; flow occurs as a result of the pressure gradient. Solution trapping involves dissolution of CO2 in water, oil and/or gas; the type of solution depends on the type of fluids present in the reservoir, the pressure and the temperature. Finally, mineral trapping involves a chemical reaction of CO2 with the reservoir rock which is dependent on the mineral composition of the rock (Gallo, Y. L. 2002).

There are several advantages for storing CO_2 in depleted oil and gas reservoirs. Firstly, oil and gas reservoirs are proven to hold buoyant fluids therefore it is possible for them to hold CO_2 also. This results in no environmental degradation to the reservoir due to the CO_2. Secondly, CO_2 is a very good solvent for hydrocarbons. Oil and gas reservoirs are well characterized therefore we have good information about seismic to core data, porosity and permeability data, geological data and some knowledge about cap rock integrity. Thirdly, some production wells may be worked over and readily converted to gas injection wells. Others may be used for monitoring CO_2 within the reservoir. Finally, if the field is still in production, a CO_2 sequestration scheme can be used to optimize enhanced oil production (Gallo, Y. L. 2002).

Gallo et. al. (2002) proposed a strategy for selecting a site for geostoring CO2. The strategy contains two main steps which are data gathering and storage investigation. The first step is rather straightforward; information about the reservoir is critical to understanding its suitability as a storage site. The known reservoir information should include exploration, geological aquifer, production history heterogeneity distribution, PVT analysis, location and perforation of the wells, mineralogy and some knowledge about grid size of the reservoir. The second step needs geomechanical modeling for testing the structural integrity, this step also contains determining the trapping mechanisms.

Weyburn Oil Field

The Weyburn field (Figure 1) is located in southeastern Saskatchewan, Canada. The field is discovered in 1954 and has an area of 180 km^2. The oil is at a mean depth of 1450 m. The pay thickness ranges from 5m to over 30m with an average of 10m. From its discovery in 1954 till 1964 the oil was produced by primary recovery. In 1964 the secondary recovery was began by waterflooding the reservoir. Production was declined and in 1986 the vertical infill drilling was performed and caused an increase in production. Horizontal infill drilling was introduced in 1991 and finally CO2 injection began in the fall of 2000 in Phase 1A area. (Figure 2)

Geological Characterization

The oil is produced from the Midale beds of the Mississippian Charles formation, which are part of the Madison Group. The reservoir is divided into a lower Vuggy zone, and an upper Marly zone. The Marly zone is characterized by high porosity and low permeability, whereas the Vuggy zone is characterized by low porosity and high permeability. Net pay in the Marly ranges from 0.1 m to 9.8 m (average 4.3 m). Net porosity ranges from 16% to 38% (average 24%), and net air permeability ranges from 1md to over 100md (average 11.5 md). Net pay in the Vuggy ranges from 0.1 m to 18.6 m, with an average of 6 m. Net porosity values range from 8% to 20% (average 11.2%), and net air permeability ranges from 0.3 md to greater than 500 md (average 14.4 md). The reservoir is overlain by a tight, interbedded anhydrite, dolomite and shale sequence that forms the top seal on the reservoir. The Midale Evaporite caps these beds. Above the Midale Evaporite lays the Ratcliffe and Poplar beds. These beds are progressively eroded off to the north under the Mississippian unconformity. In the northern part of the Weyburn unit these beds are absent. Underlying the reservoir are the Frobisher beds, which are comprised of Marly, Vuggy, and evaporitic zones lithologically and depositionally similar to the overlying Midale beds. The Frobisher Evaporite is present only in the northern half of the field. The original oil water contact for the unit was in the upper part of the Frobisher Vuggy, Figure 3. (Whittaker S. et al. 2004)

Geostatistical Model

We should build the geostatistical model to characterize the Formation Heterogeneity (static reservoir properties, porosity, and permeability) and also to construct the Reservoir Model and create multiple possible realizations using Stochastic Geostatistical Simulation. Monte-Carlo or stochastic approaches are necessary to assess the effects of the uncertainty in simulation of heterogeneity on performance. We will consider two cases in this section, synthetic case and Weyburn Field. The distributional information for the synthetic case is based on the Sleipner field. There are several distinctions between the Sleipner and the Weyburn fields:

- Sleipner is an offshore reservoir in the North Sea, while Weyburn is located on the plains of Midwest Canada.
- Sleipner stores CO_2 in a deep saltwater formation but Weyburn is an Enhanced Oil Recovery project in a carbonate formation.

- Sleipner injects by one horizontal injection well but Weyburn uses both horizontal and vertical wells for gas injection.

Synthetic Example

For reservoir geometry an anticline structure with 4 layers in the field of 1500x3000 was considered. The shape of the synthetic reservoir along with the map of thickness is shown in Figure 4. It is the same reservoir model as in the CMG tutorial. We use the permeability and porosity data from the Sleipner Field as reference distributions (see Figure 5) for sequential Gaussian simulation.

We assumed a simple variogram:

$$\gamma(\mathbf{h}) = 0.10 + 0.90 Sph_{\substack{ah\max=400m \\ ah\min=300m}}(\mathbf{h})$$

Based on the above set up, the following modeling methodology is undertaken:

1. Stratigraphic transformation to a regularized grid assuming an original anticline structure
2. A reference realization is constructed via unconditional sequential Gaussian simulation with the Sleipner reference distribution. Collocated cosimulation of porosity and permeability is performed to generate this reference model.
3. Using the reference model, samples are drawn and used for conditional simulation using the reference histogram and variogram model. Collocated cosimulation is then performed with porosity as the primary variable, and permeability as the secondary variable.
4. Histogram and variogram reproduction is then checked.

Figure 6 shows the stratigraphic transformation to a proportional grid (Deutsch, 2002):

$$z_{rel} = \frac{z - z_{cb}}{z_{ct} - z_{cb}} \cdot T$$

where z_{cb} is the correlation base, z_{ct} is the correlation top, z is the real z-coordinate, z_{rel} is the stratigraphic transformed z-coordinate, and T is the average thickness of the layer. Figure 7 shows the stratigraphic back transformation after performing sequential Gaussian simulation. Figure 9 and Figure 9 shows the reference model and one realization of porosity and permeability, respectively. Figure 10 shows the reproduction of the histogram and variogram for porosity and permeability.

Weyburn Field

Available data include porosity and permeability. Figure 11 shows the distribution and cumulative distribution function for permeability (log scale) and porosity (arithmetic scale). Figure 12 shows the scatter plot of permeability and porosity in both original and normal score unit. For this particular case, we were provided with the kriged maps for porosity and permeability for Phase 1A in Weyburn field along with the location of the wells; these are shown in Figure 13 and Figure 14, respectively.

Future Work

The application of geostatistics for CO2 geostorage has been fairly limited. This is not surprising given that interest in CO2 geostorage is a fairly recent development (relative to most other areas of geostatistical application). As such, there are plenty of avenues for future research that can be explored. Specific to this study, the following tasks are identified:

- Gathering all of the required data for Weyburn Phase 1A and completing a geostatistical simulation model for other parameters which are critical for CO_2 geostorage, such as hydraulic conductivity.
- Petrophysical characterization of low permeability seals (top and bottom).
- Giving our model to a compositional flow simulator to check the amount of CO_2 storage for different realizations.

More general research areas that may be particularly relevant for this application area include:

- Fracture modeling of possible sequestration sites. This will inevitably affect the performance of the site in trapping CO_2. There is no doubt that fracture modeling of the region *above* the reservoir will be significant to this type of investigation.
- Spatiotemporal modeling for data integration. Monitoring the performance of a site will require a constant sampling program to ensure that CO_2 traps are efficient. We already know that geochemical data are being recorded at Weyburn over various time periods. The incorporation of this information in an uncertainty assessment of the field would be valuable.

References

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Table 1: Sites where CO_2 geostorage has been done, is currently in progress or is planned. (Source: *IPCC Special Report-Carbon Dioxide Capture and Storage*, Metz et al)

Project name	Country	Injection start (year)	Approximate average daily injection rate (tCO_2 day^{-1})	Total (planned) storage (tCO_2)	Storage reservoir type
Weyburn	Canada	2000	3,000-5,000	20,000,000	EOR
In Salah	Algeria	2004	3,000-4,000	17,000,000	Gas field
Sleipner	Norway	1996	3,000	20,000,000	Saline formation
K12B	Netherlands	2004	100 (1,000 planned for 2006+)	8,000,000	Enhanced gas recovery
Frio	U.S.A	2004	177	1600	Saline formation
Fenn Big Valley	Canada	1998	50	200	ECBM
Qinshui Basin	China	2003	30	150	ECBM
Yubari	Japan	2004	10	200	ECBM
Recopol	Poland	2003	1	10	ECBM
Gorgon (planned)	Australia	~2009	10,000	unknown	Saline formation
Snøhvit (planned)	Norway	2006	2,000	unknown	Saline formation

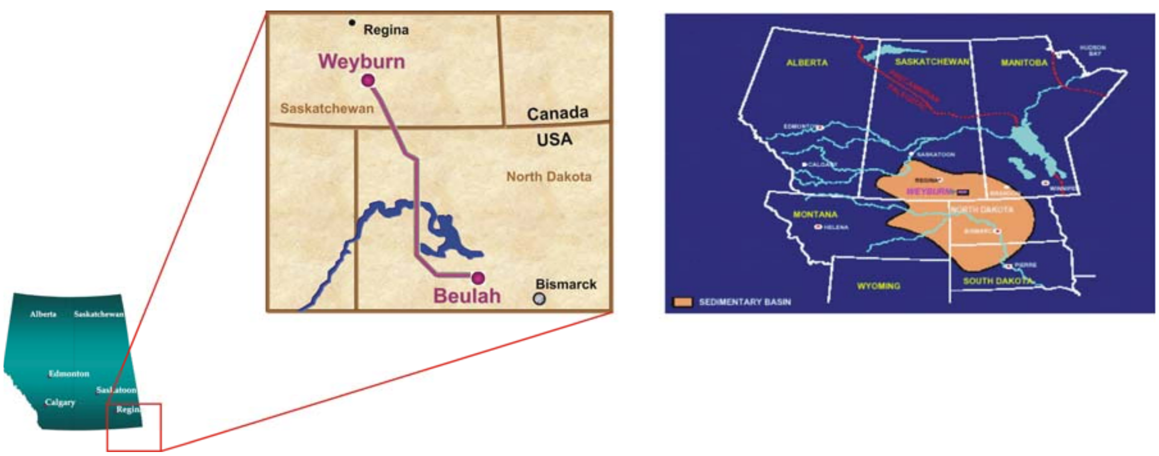

Figure 1: Location of the Weyburn field (Source: Torp T. A. 2005)

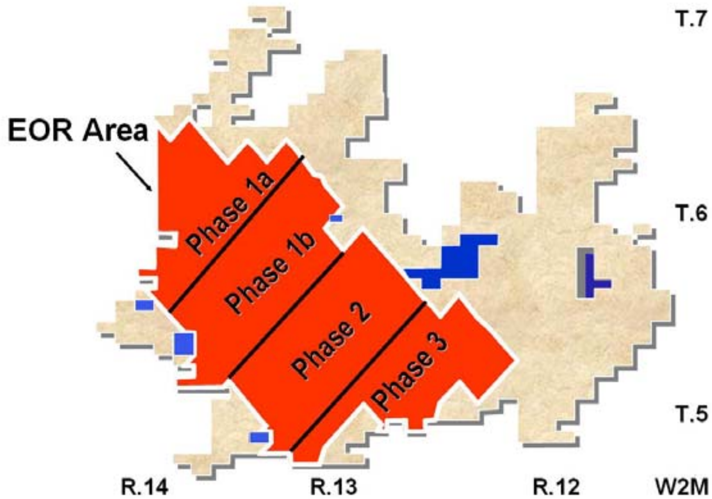

Figure 2: The locations of 3 phases in Weyburn field (Source: Whittaker S. et al. 2004).

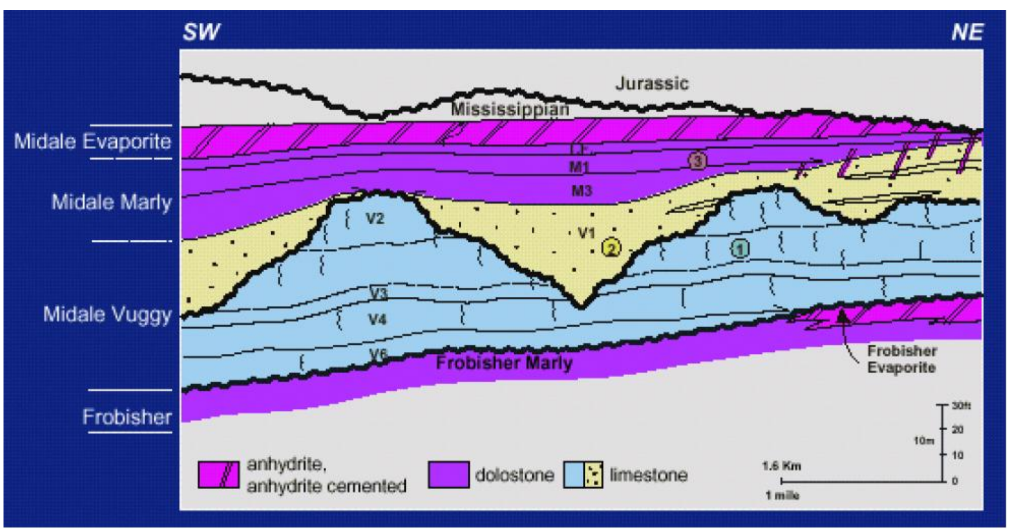

Figure 3: Geological setting of the Weyburn field (Source: Burrowes G. 2001).

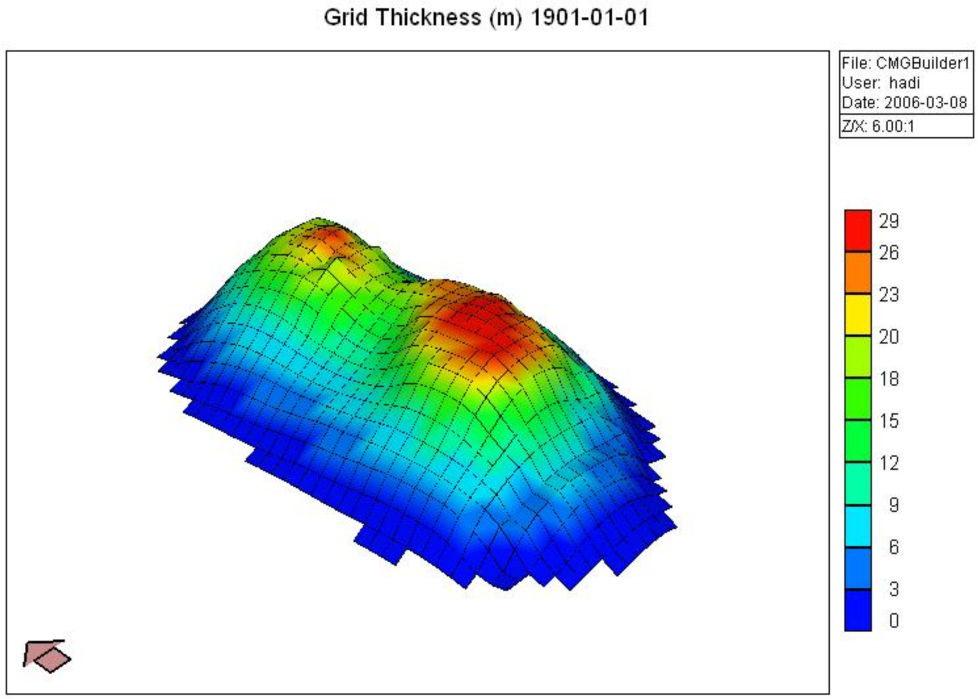

Figure 4: Reservoir geometry and map of thickness for synthetic case.

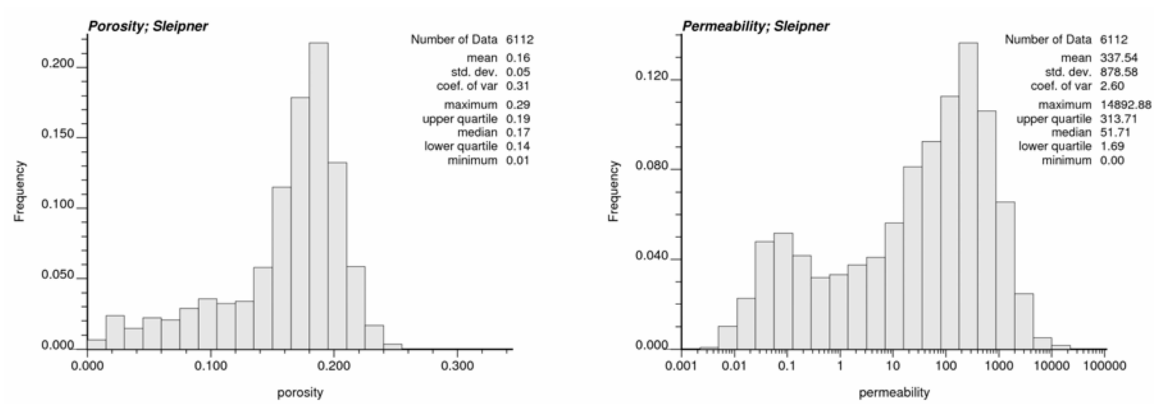

Figure 5: Histogram for porosity (left) and $\log_{10}$ permeability (right) for the Sleipner data as reference distributions.

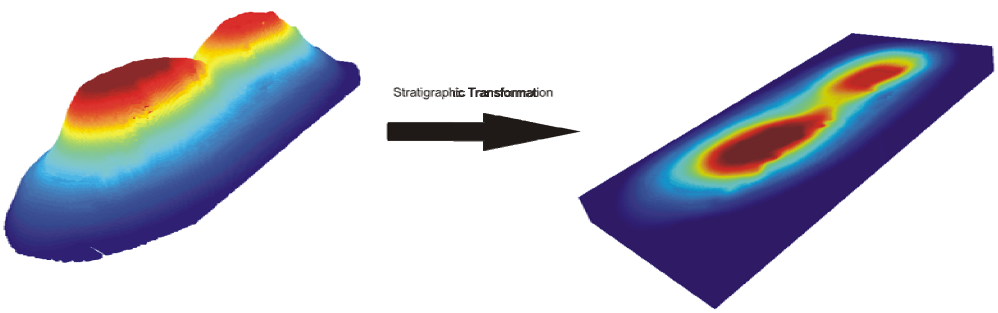

Figure 6: Stratigraphic transformation (the colored values are related to the thickness).

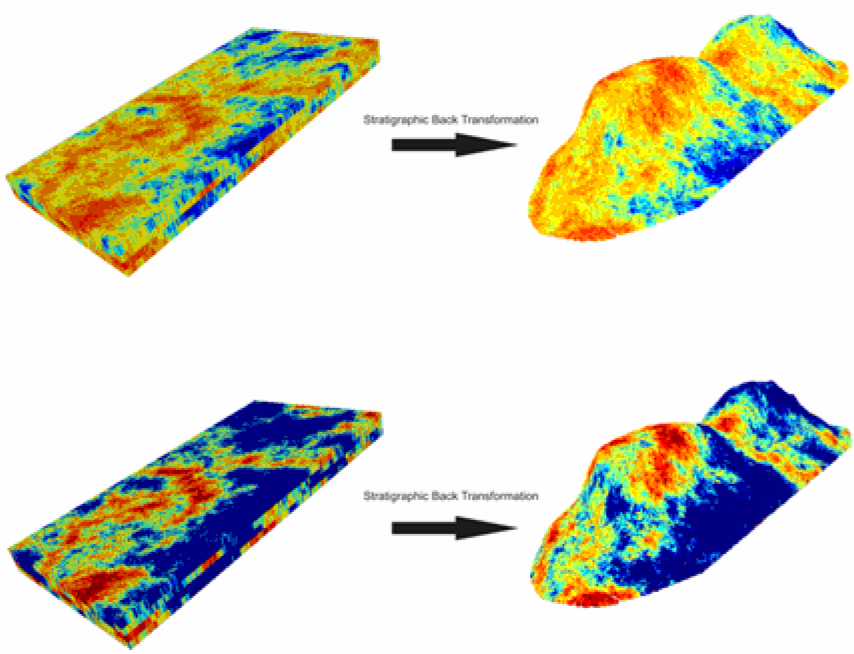

Figure 7: Stratigraphic back transformation after performing sequential Gaussian simulation of porosity (top) and permeability (bottom).

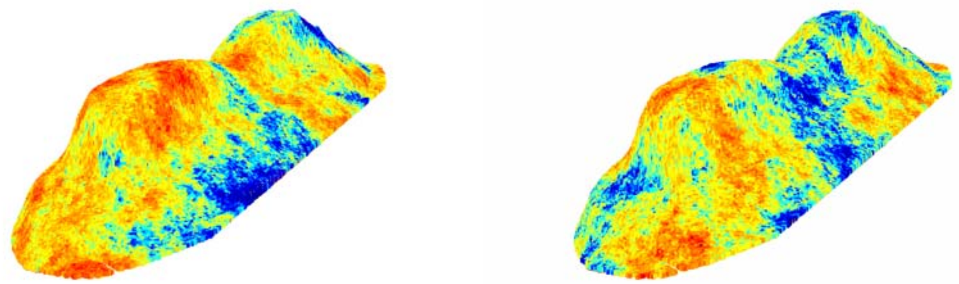

Figure 8: SGS results for porosity (arithmetic scale) for the reference model (left) and a single realization conditioned to 500 wells (right).

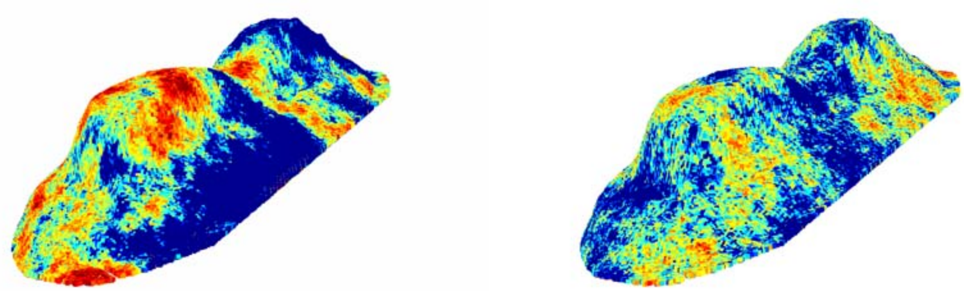

Figure 9: SGS results for permeability (log scale) for the reference model (left) and a single realization conditioned to 500 wells (right).

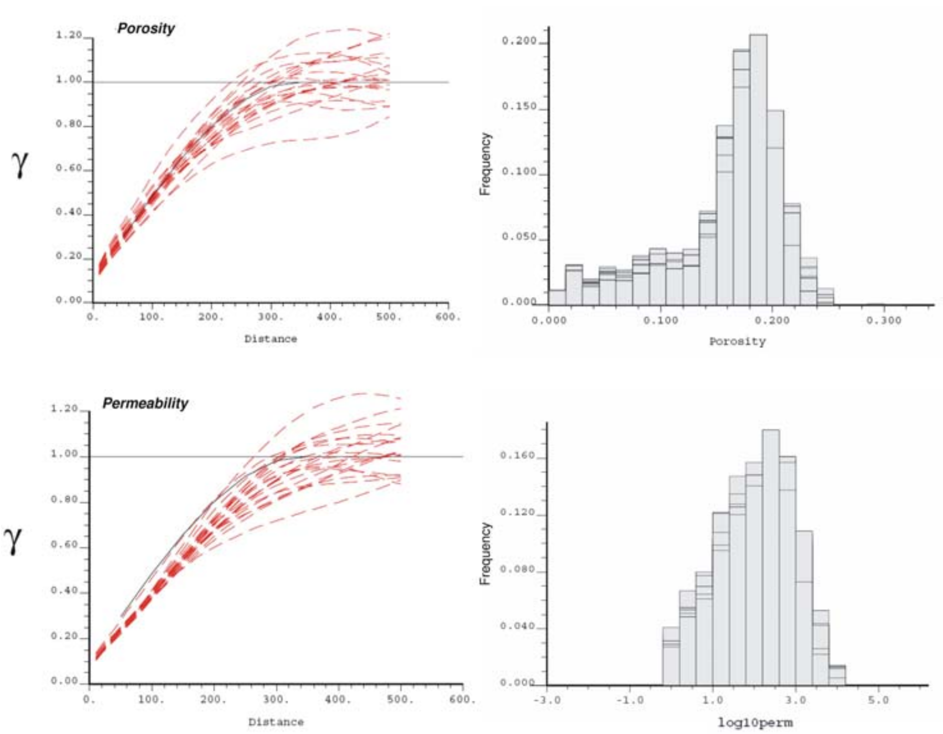

Figure 10: Variogram and histogram reproduction for porosity and permeability modeling for the synthetic case.

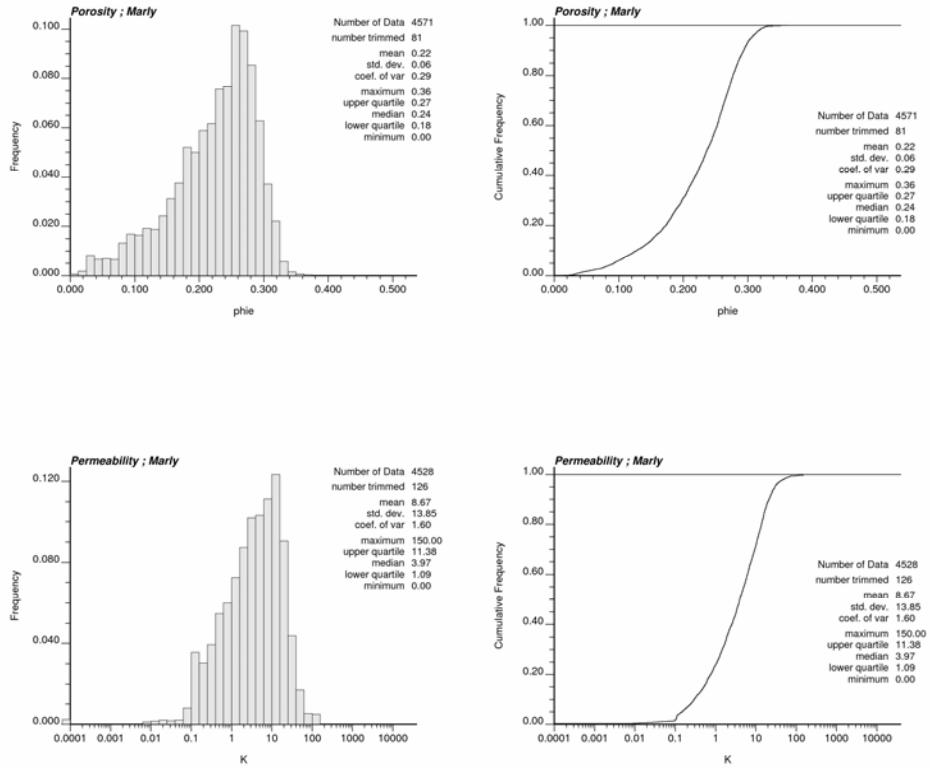

Figure 11: Probability density function and cumulative distribution function for porosity permeability for the Weyburn data.

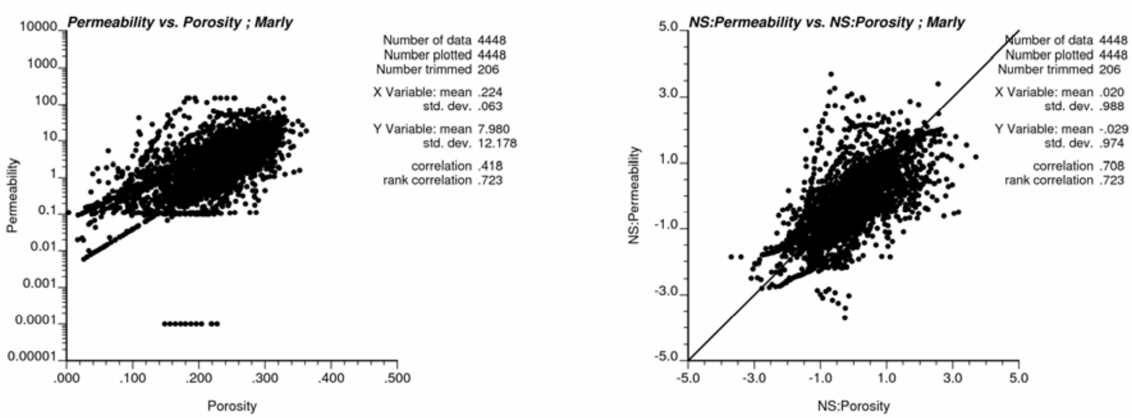

Figure 12: Scatter plots of permeability versus porosity in original and normal score units for the Weyburn data

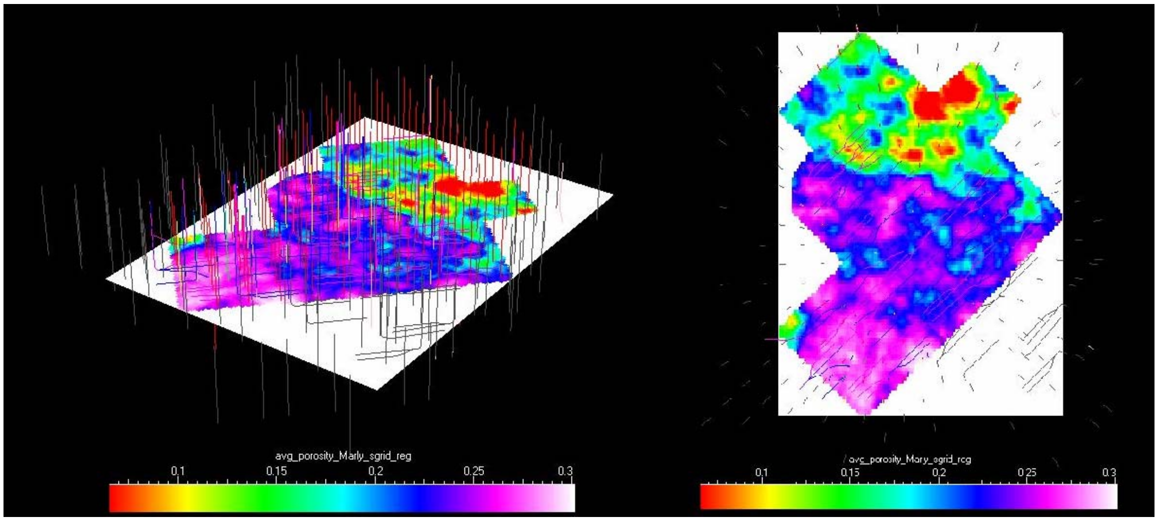

Figure 13: Porosity map for phase1A in Weyburn field.

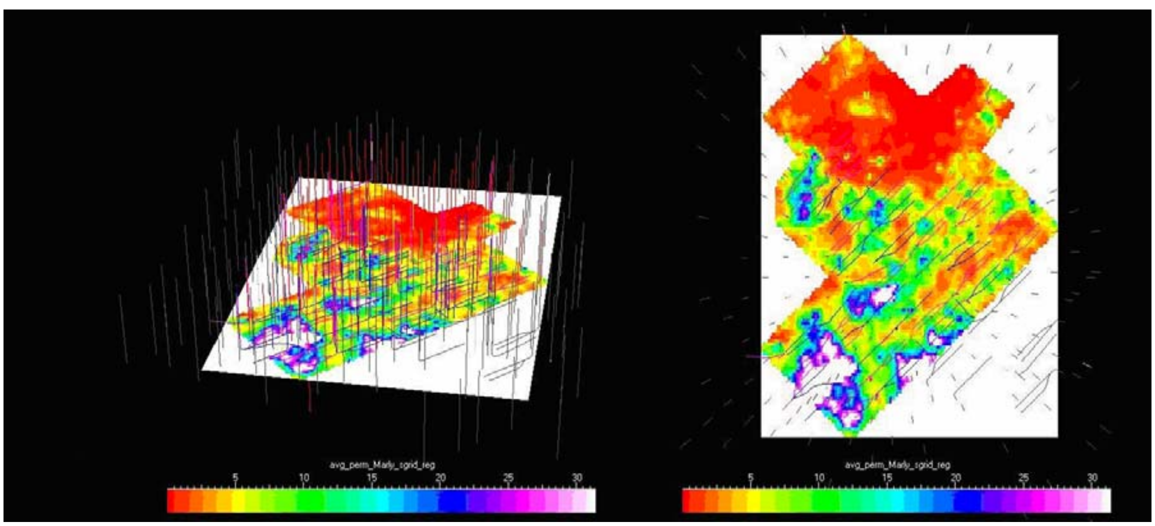

Figure 14: Permeability map for phase1A in Weyburn field.