CCS-Analytics

Carbon Capture and Storage using Science & Engineering Application of Artificial Intelligence (SEA-AI)

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National Energy Technology Laboratory
Carbon Management Project Review Meeting
August 15 - 19, 2022

Project Overview

- Science & Engineering Application of AI (SEA-AI)
  - Artificial Intelligence & Machine Learning (AI&ML)
  - AI-Ethics
  - Modeling Physics using AI&ML
  - Engineering Applications of AI&ML
- Smart Proxy Modeling
- Engineering Case Study of SEA-AI
  - Carbon Storage using SEA-AI

Artificial Intelligence & Machine Learning

Artificial Intelligence

The Technology that Simulates Human Intelligence by Mimicking Human Brain for Analysis, Modeling, and Decision Making

Machine Learning

The science of making computers to act

(a) without being explicitly programmed

(b) through using Open Computer Algorithms and **Learning** from Data

Machine Learning Algorithms

- Machine Learning Algorithms used for SEA-AI:
  - Artificial Neural Networks
  - Fuzzy Set Theory
  - Genetic Algorithm

AI+ML Algorithms	Mimicking Life and Nature
Artificial Neural Networks	Human Brain's Information Processing
Fuzzy Set Theory	Human Brain's logic
Genetic Algorithm	Optimization through Natural Selection

AI-Ethics

- Ethics of Artificial Intelligence became a research topic due to the creation of **Racism and Sexism** using AI in the past decade.

- Companies such as IBM, Google, Amazon, etc. that unintentionally developed the racism and sexism using AI-models have made efforts to research and address biases in AI-models.

- One solution for addressing bias is to create documentation for the data used to train the AI systems.

MIT Technology Review of AI-Ethics

"The problem of ***bias*** in machine learning is likely to become more significant as the technology spreads to critical areas like medicine and law (***and engineering***), and as more people without a ***deep technical understanding*** are tasked with deploying it.

Some experts warn that algorithmic ***bias is already pervasive in many industries*** and that almost ***no one is making an effort to identify or correct it***".

AI-Ethics in Engineering

- "AI-based Modeling of Physics" is purely based on Fact and Reality through "Actual Measurements".

- "Traditional Physics-based Modeling" includes some of the following items through "Mathematical Equations".
  - Assumptions, Interpretations, Simplifications, Preconceived Notions, and Biases.

- By including data from "Mathematical Equations" to "Actual Measurements" ***You Are Telling AI-based Model "What To Do"***.

Proxy Modeling

- Proxy Model is **a mathematically or statistically defined function that replicates or approximates the response of the full-scale simulation model output for selected input parameters**.

Denney 2010

- Since deployment of the "**full-scale simulation model**" of complex physical phenomena takes a long time even on HPC, the objective of the Proxy Model is to perform numerical simulation in a very short time period.

Proxy Modeling

- Currently, there are two types of Proxy Models for Numerical Simulations:
  - **Traditional Proxy Models**:
    - Generating the Proxy Models using **mathematical** or **statistical** approaches.
  - **Smart Proxy Model**:
    - Generating the Proxy Models using **Artificial Intelligence & Machine Learning** approach.

Smart Proxy Modeling

- Smart Proxy Modeling is ***teaching*** engineering problem solving to an ***open computer algorithm*** using ***data from numerical simulation***

- ***Data from Numerical Simulation*** includes:
  - Data that is used to build the numerical simulation
  - Feature generation that explains (teaches to the machine learning algorithm) the *physics and numerical solution* of the numerical simulation

It is impossible to do this if you are not a Domain Expert in the development of the numerical simulation

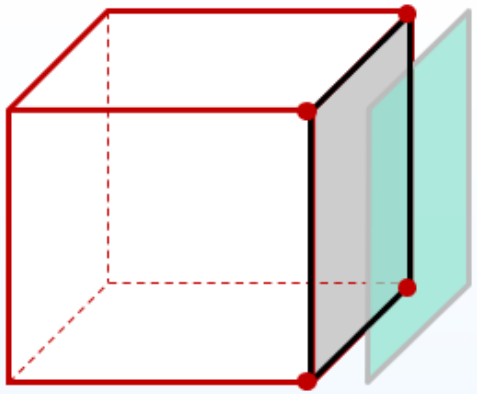
Smart Proxy Modeling

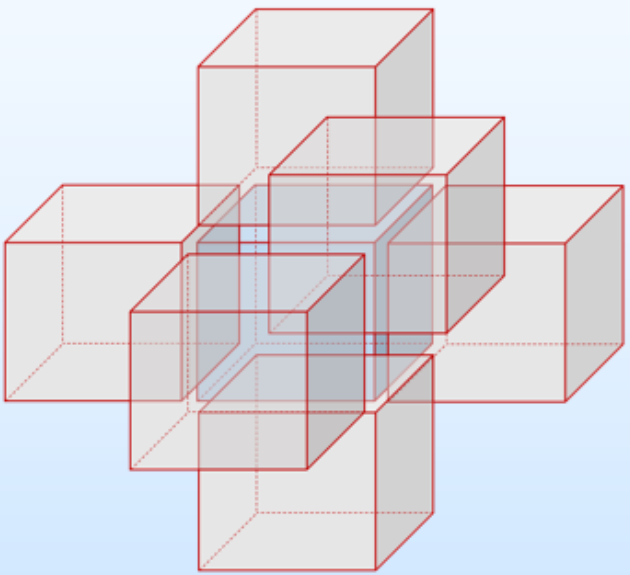
- Smart Proxy Modeling lets the Numerical Simulation easily be used for important characteristics:
  - Reservoir Pressure and CO_2 Saturation distribution in Space and Time for every cell in the Numerical Simulation
  - History Matching
  - Uncertainty Quantification
  - CO_2 Injection Optimization
  - CO_2 Leakage Detection
  - …

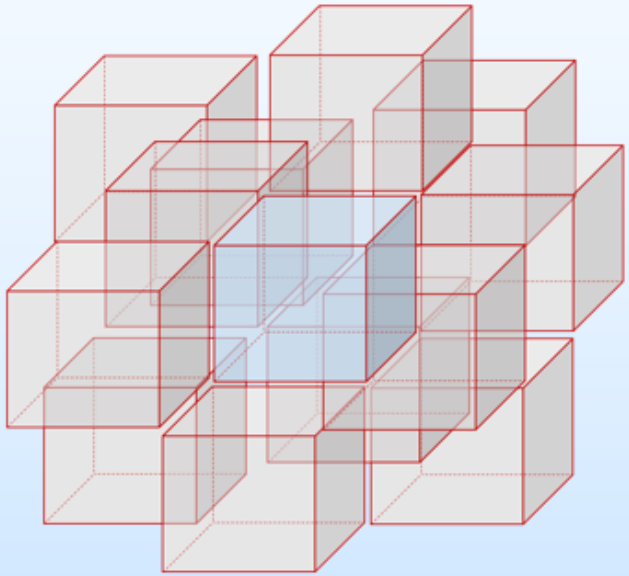
Smart Proxy Modeling

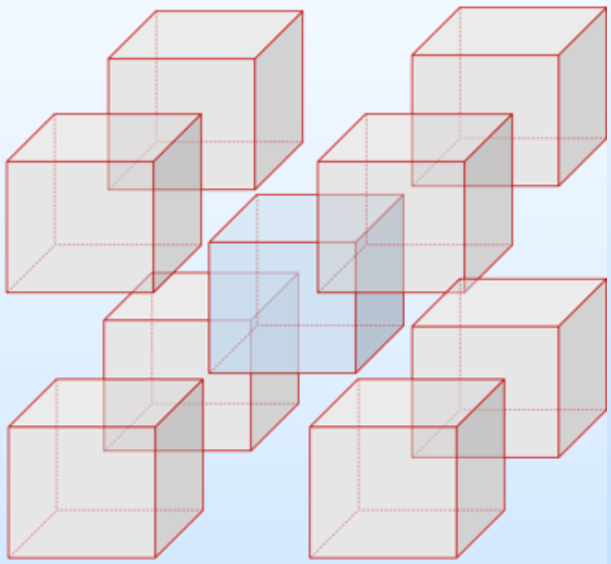
- Smart Proxy Model Development for Numerical Simulation requires:
  - Unlike Traditional Statistics that require hundreds of numerical simulation runs to generate Proxy Model, AI-based Proxy Model (Smart Proxy Model) only requires around 20 numerical simulation runs.

Smart Proxy Model Development



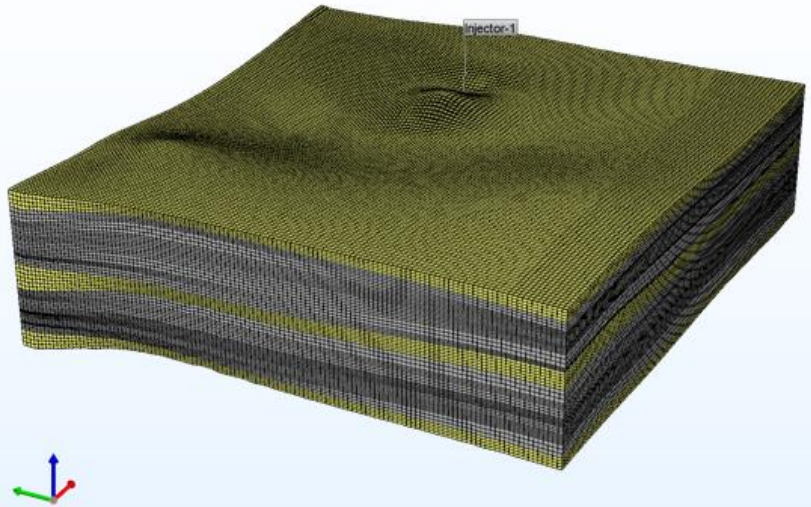




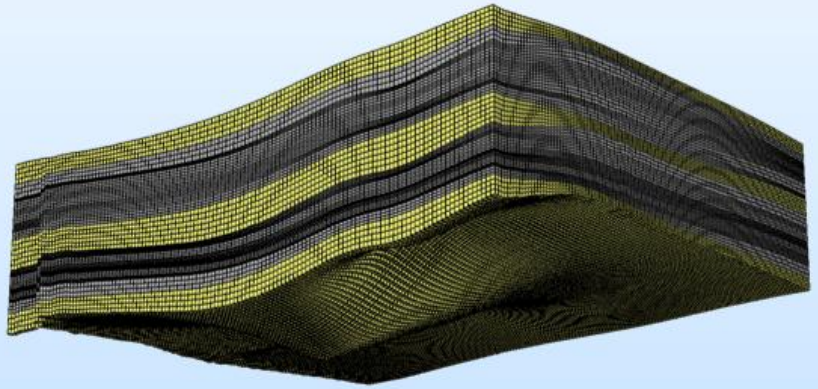


Case Study

CO_2 Storage in Saline Aquifer Numerical Reservoir Simulation



- Heterogeneous Reservoir Characteristics
  - Various Layer Thicknesses
  - Layers are not flat
  - Grid blocks are not the same size

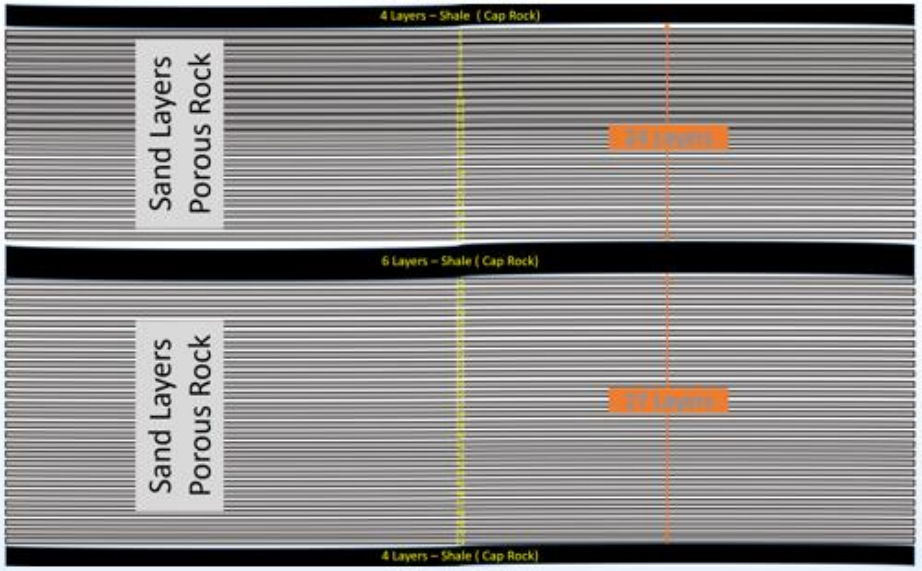


- Saline Aquifer formations (Sands)
- Cap Rocks (Shale)

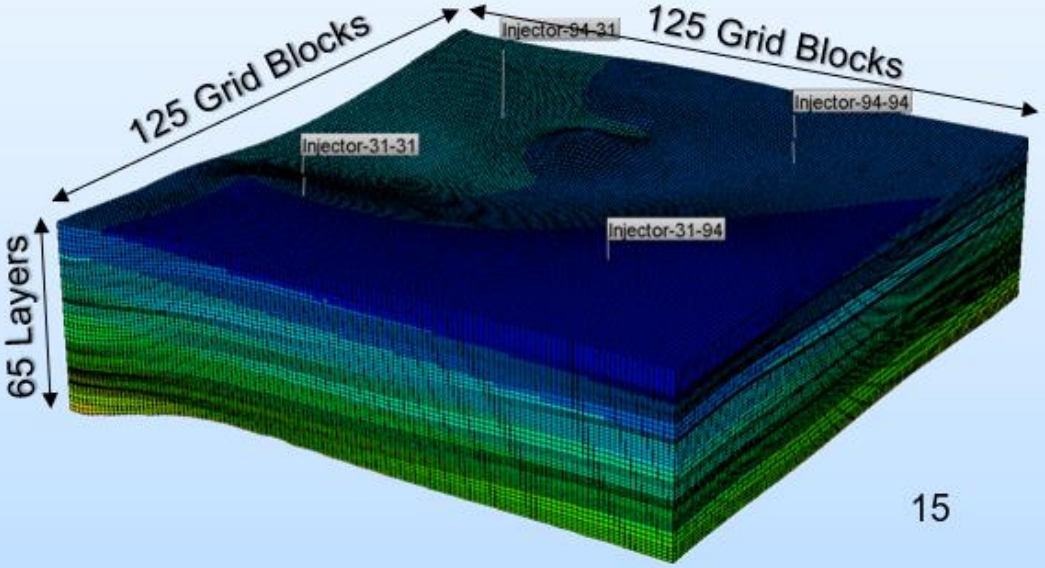
CO_2 Storage in Saline Aquifer

Grid Blocks
125 x 125 x 61 = 1,015,625

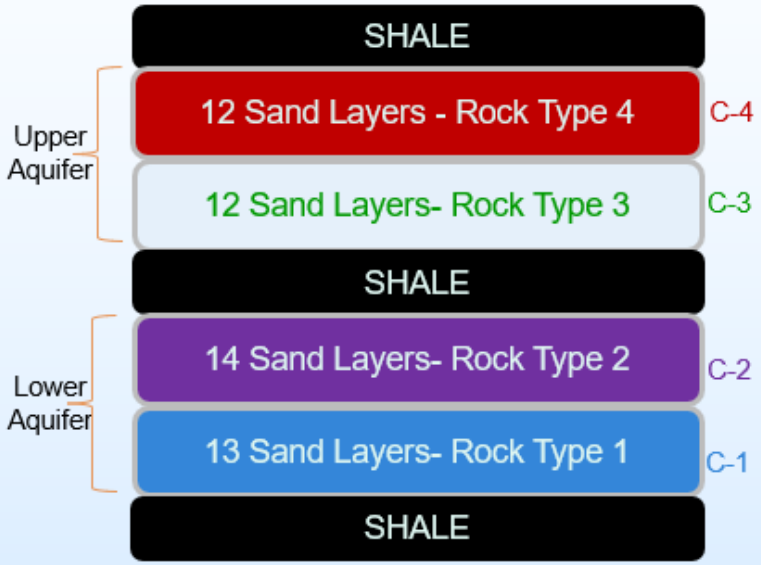
CO_2 is Stored through
4 Injection wells

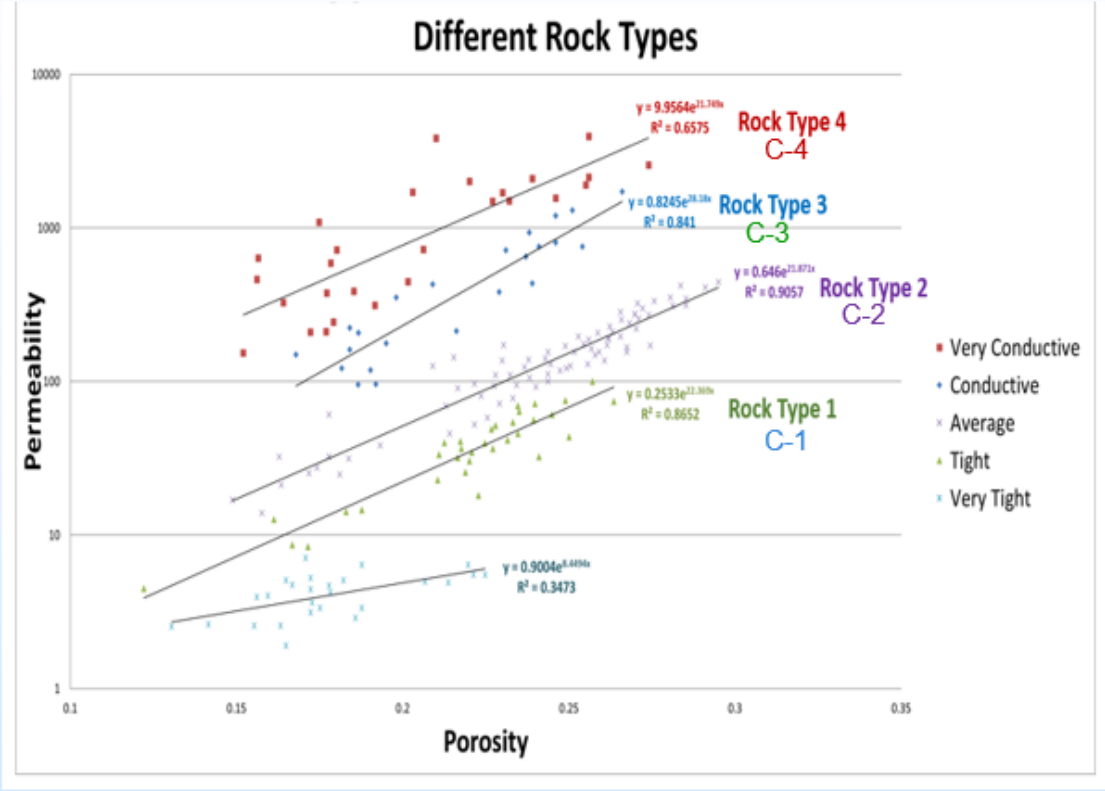


Some of reservoir data are taken from Citronelle field, a saline reservoir located in Mobile County (Alabama, US)



CO_2 Storage in Saline Aquifer

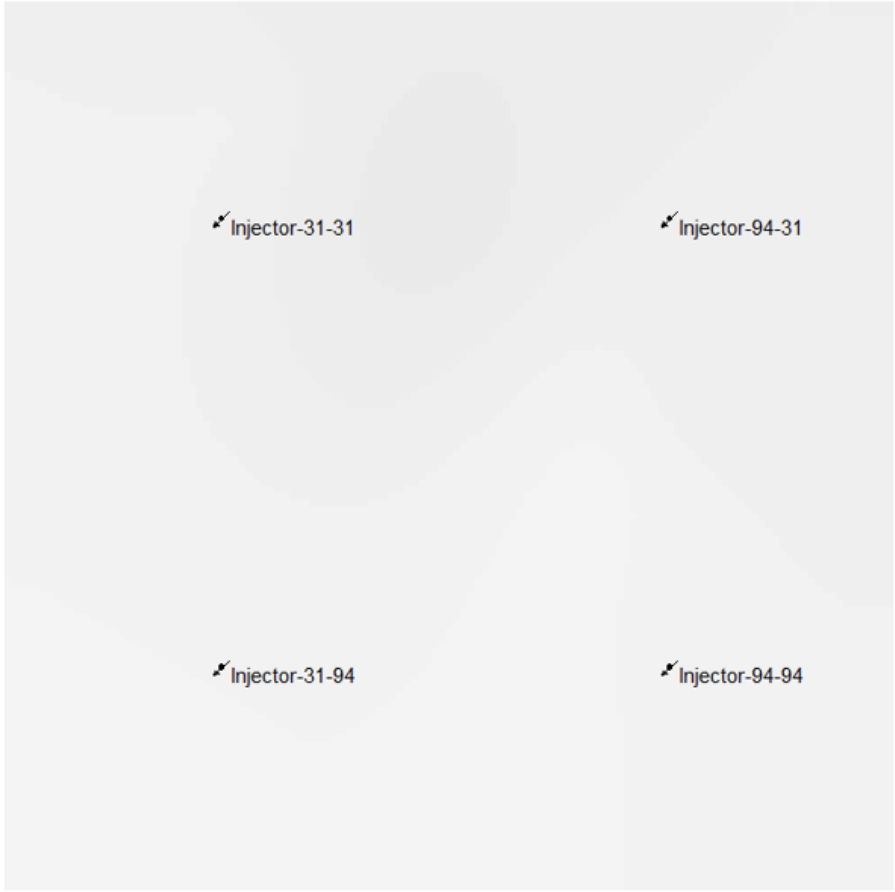




CO_2 Storage in Saline Aquifer

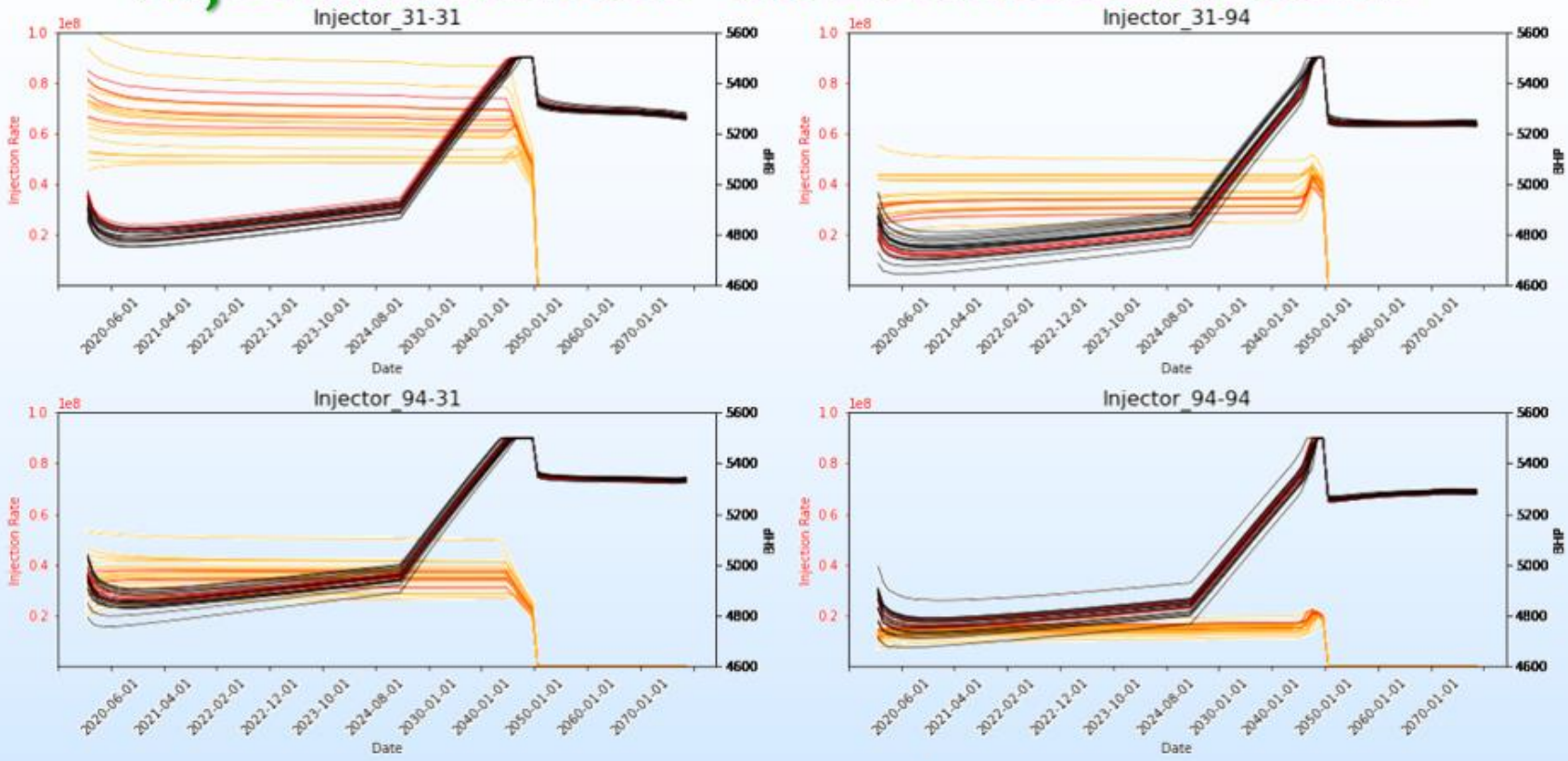
CO_2 Injection Design

- Four CO_2 injector wells
- The injector wells are completed in all 51 sand layers
- The Injectors well will be operating using two constraints.
  - Bottom Hole Pressure
  - Max Injection Rate



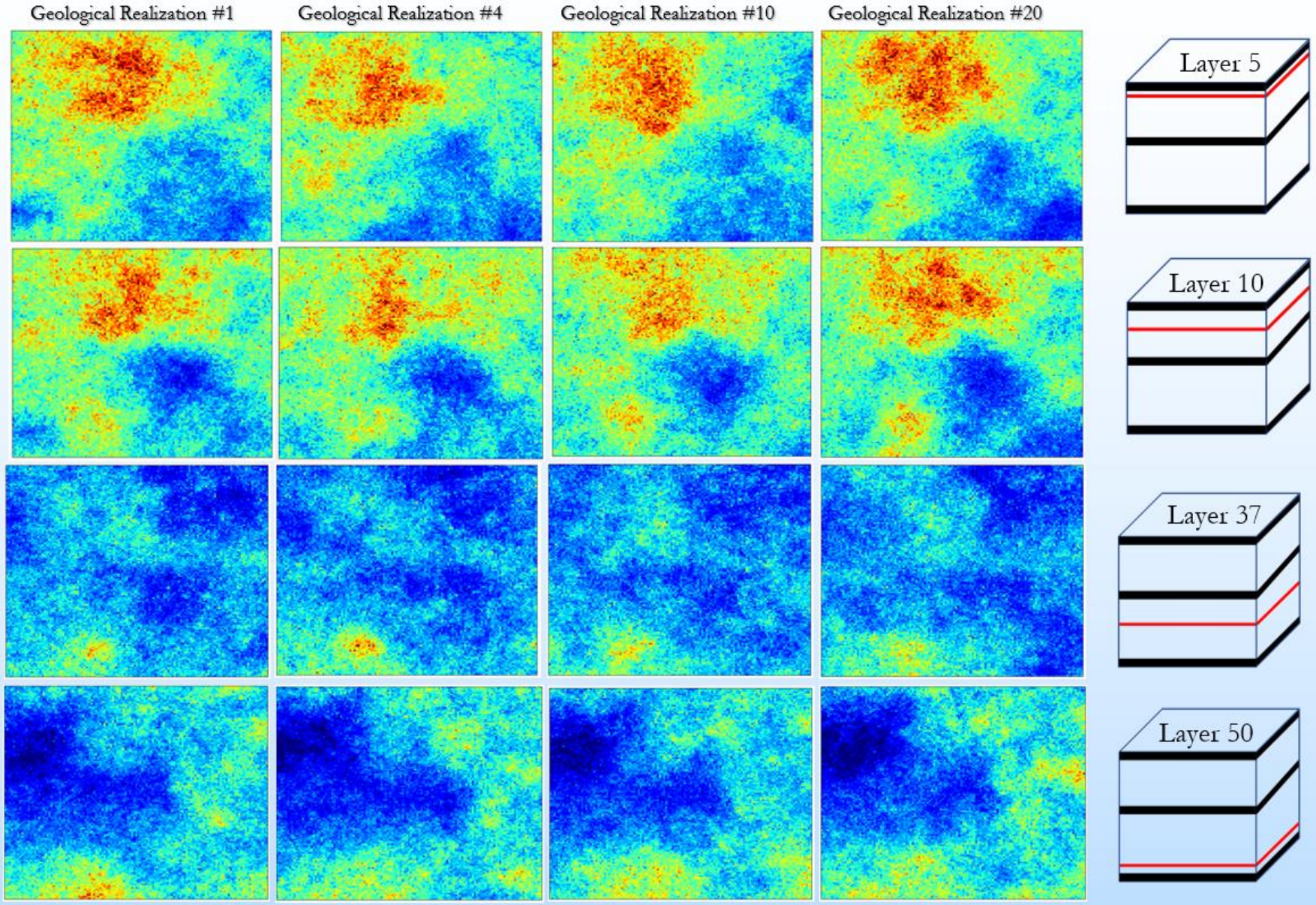
CO_2 Storage in Saline Aquifer

Injection and BHP for 20 Simulation Runs



300 Years of Numerical Reservoir Simulation Model

20 Geological Realizations



CO_2 Storage in Saline Aquifer

Data Used for Smart Proxy Model Development

Smart Proxy Model Development includes Training (80%), Calibration (10%), and Validation (10%)

Data Used for Smart Proxy Blind Validation

Data for Blind Validation is NOT used during Smart Proxy Model Development

Geological Realization #1

Geological Realization #2

Geological Realization #3

Geological Realization #4

Geological Realization #5
Simulation Run 05

Geological Realization #6

Geological Realization #7

Geological Realization #8

Geological Realization #9
Simulation Run 09

Geological Realization #10

Geological Realization #11

Geological Realization #12

Geological Realization #13
Simulation Run 13

Geological Realization #14

Geological Realization #15

Geological Realization #16

Geological Realization #17
Simulation Run 17

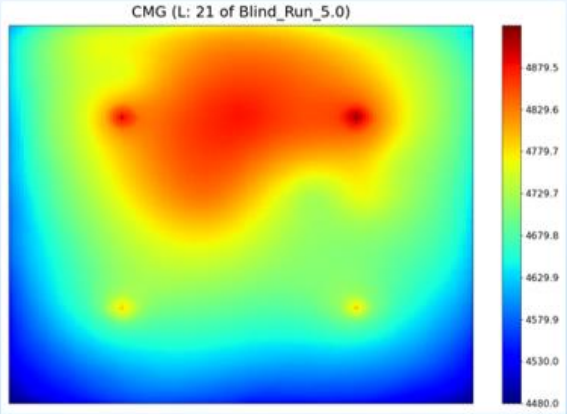
Geological Realization #18

Geological Realization #19

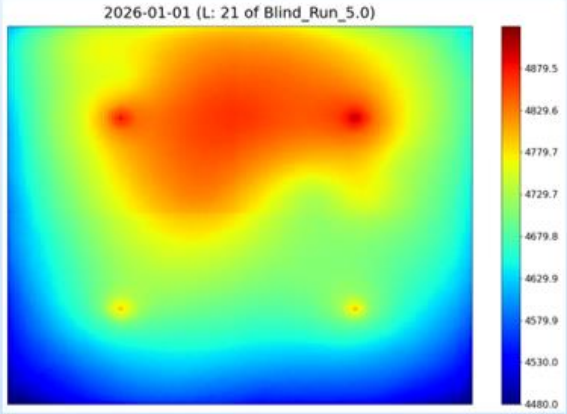
Geological Realization #20

Pressure Distribution at a Specific Time (January 2026) in a Layer (Layer 21) in a Specific Blind Validation Simulation Run (Blind Validation – Run #5)

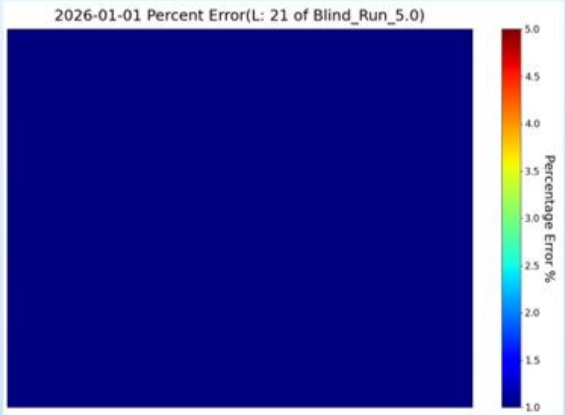
Commercial Numerical Reservoir Simulation - CMG



AI-based Proxy Model Smart Proxy Model

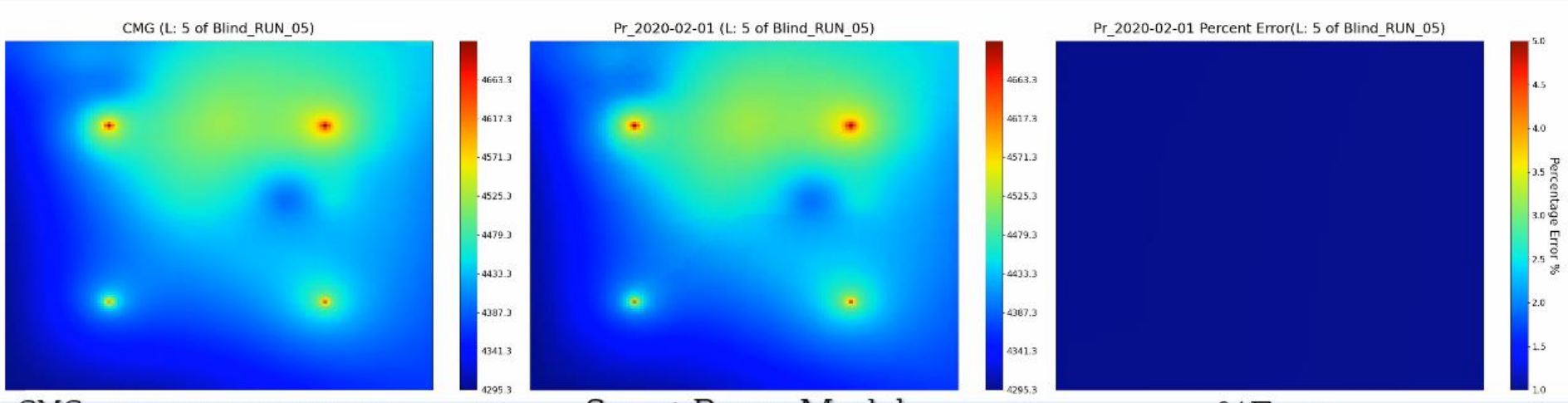


Accuracy of Smart Proxy Model 1% to 5% Error



BLIND RUN #5 – Time-Step Feb. 2020

Reservoir Pressure Distribution Video



CMG - Numerical Reservoir Simulation

Smart Proxy Model

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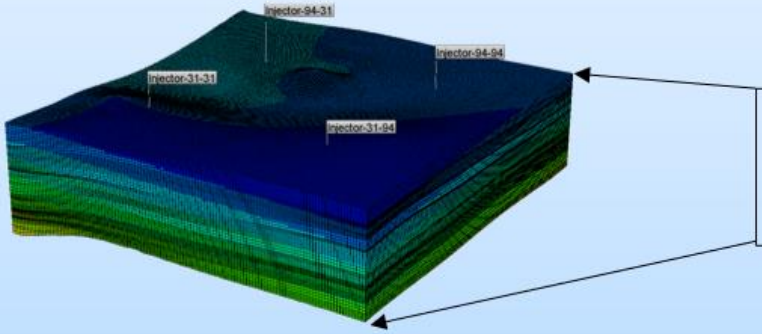
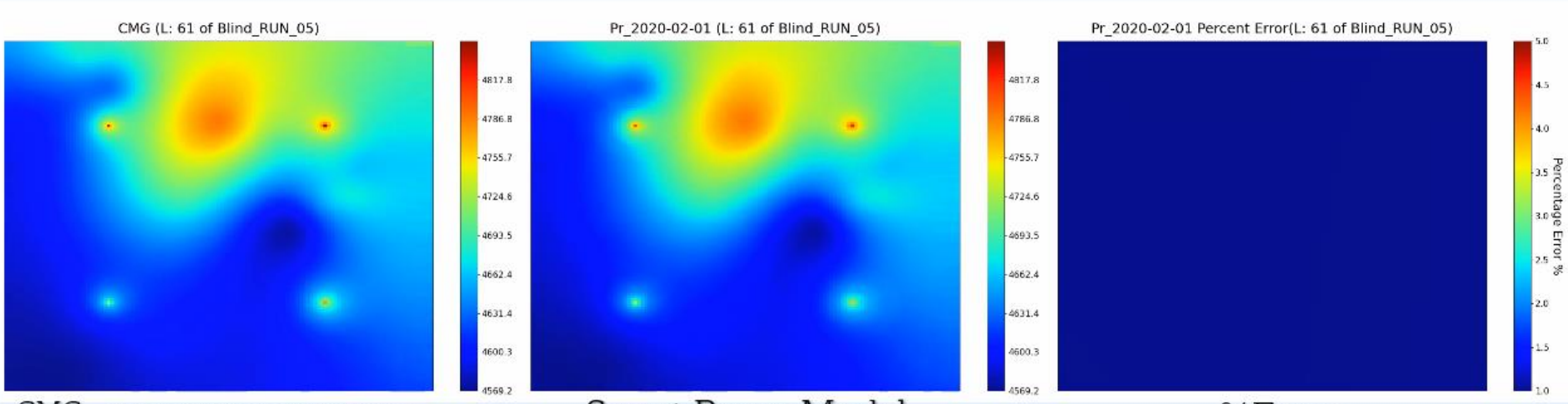


Reservoir Pressure value at every single cell (51 layers) at a certain Time-step

BLIND RUN #5 – Time-Step Feb. 2020

Reservoir Pressure Distribution Video



CMG - Numerical Reservoir Simulation

Smart Proxy Model

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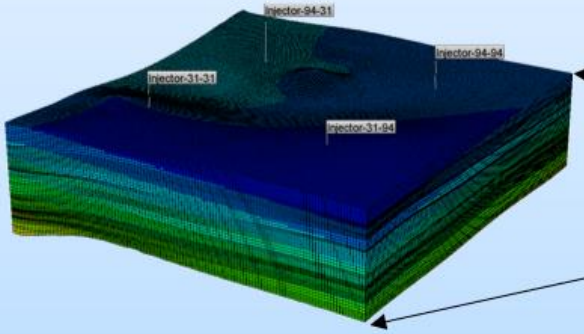
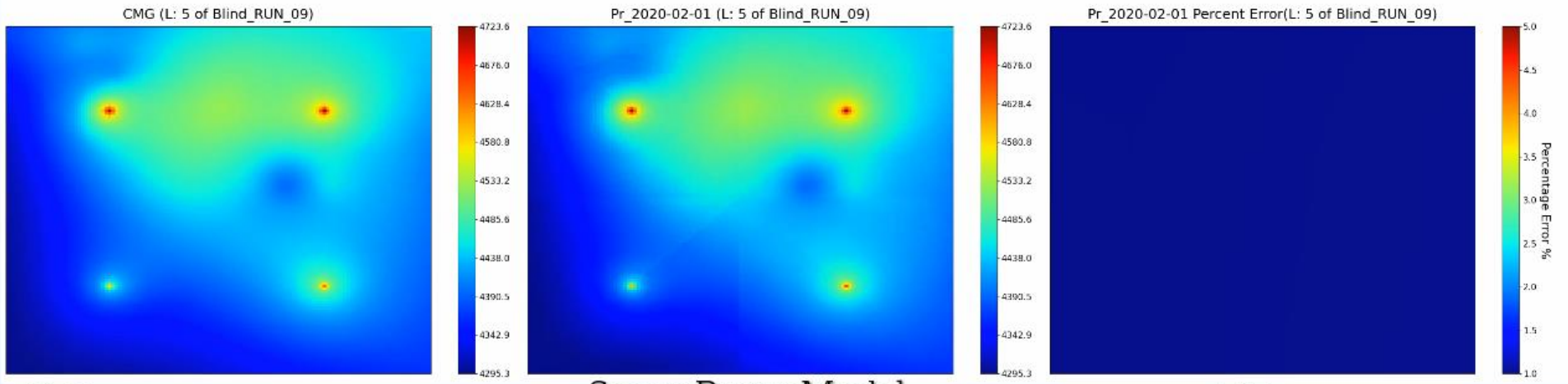


Reservoir Pressure value at every single cell (51 layers) at a certain Time-step

BLIND RUN #9 – Time-Step

Feb. 2020

Reservoir Pressure Distribution Video



CMG - Numerical Reservoir Simulation

Smart Proxy Model

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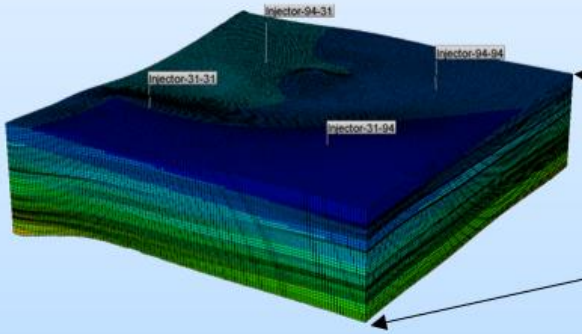
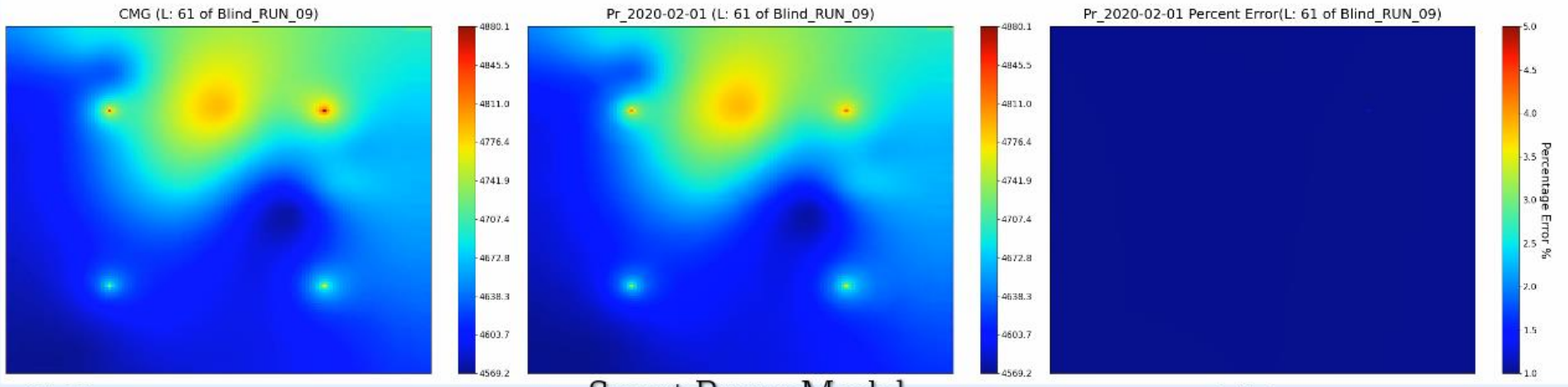


Reservoir Pressure value at every single cell (51 layers) at a certain Time-step

BLIND RUN #9 – Time-Step

Feb. 2020

Reservoir Pressure Distribution Video



CMG - Numerical Reservoir Simulation

Smart Proxy Model

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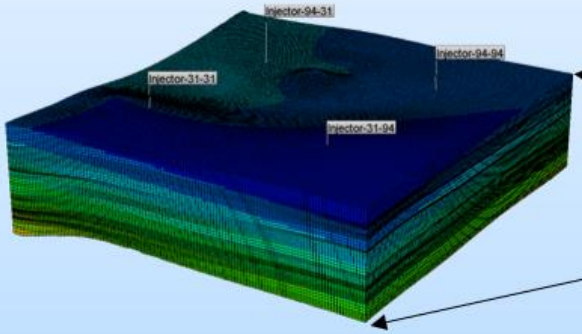
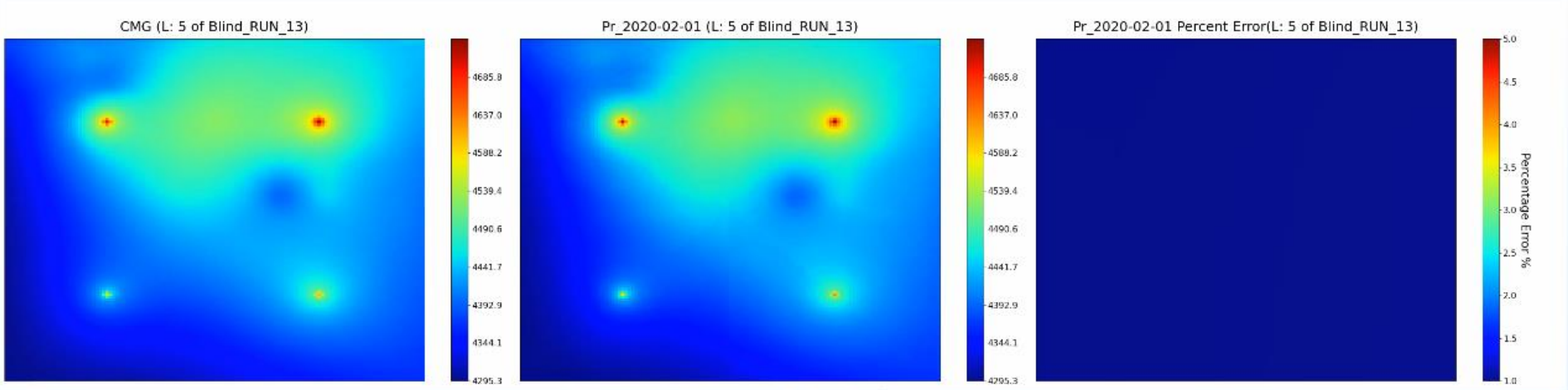


Reservoir Pressure value at every single cell (51 layers) at a certain Time-step

BLIND RUN #13 – Time-Step

Feb. 2020

Reservoir Pressure Distribution Video



CMG - Numerical Reservoir Simulation

Smart Proxy Model

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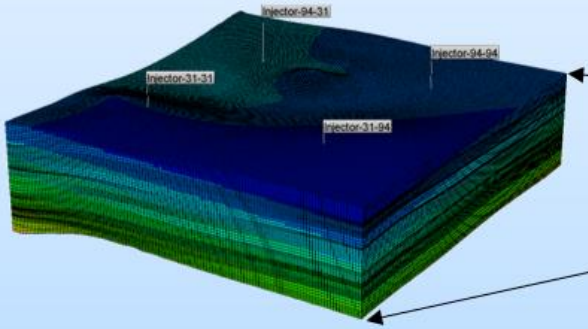
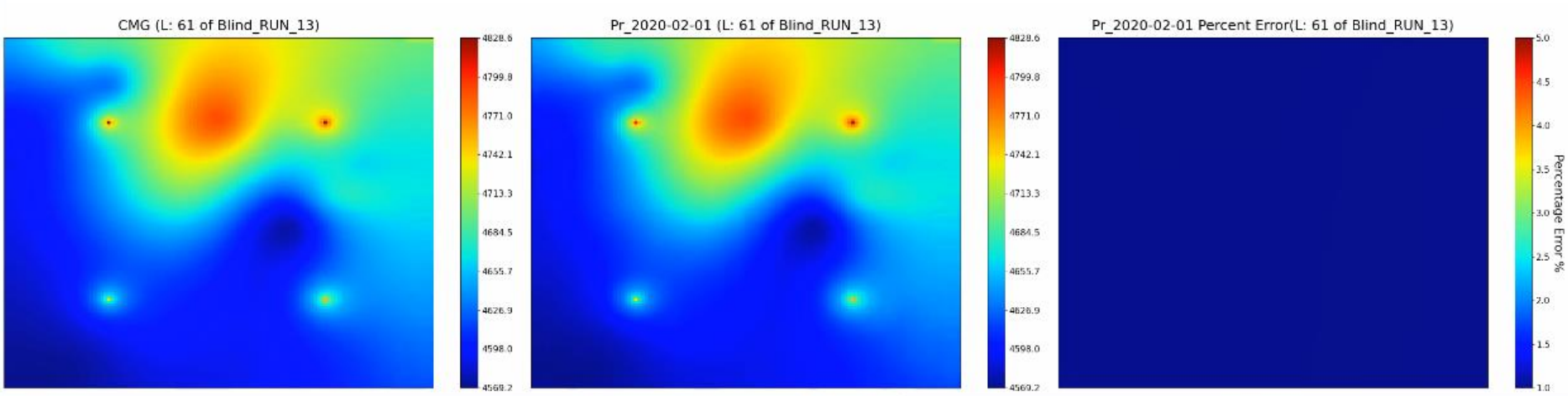


Reservoir Pressure value at every single cell (51 layers) at a certain Time-step

BLIND RUN #13 – Time-Step

Feb. 2020

Reservoir Pressure Distribution Video



CMG - Numerical Reservoir Simulation

Smart Proxy Model

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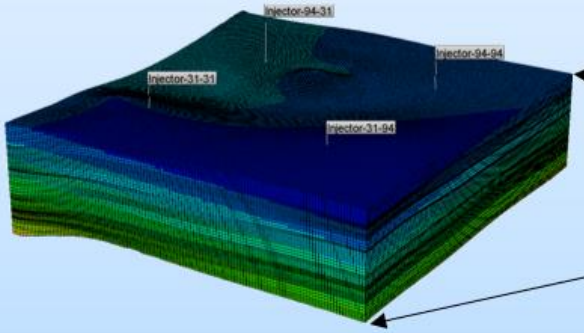
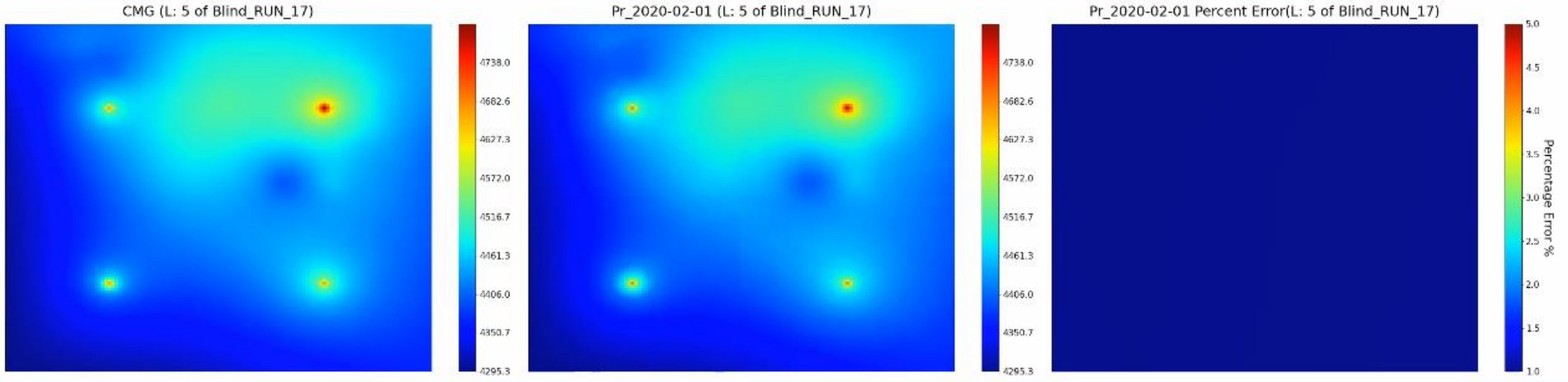


Reservoir Pressure value at every single cell (51 layers) at a certain Time-step

BLIND RUN #17 – Time-Step

Feb. 2020

Reservoir Pressure Distribution Video



CMG - Numerical Reservoir Simulation

Smart Proxy Model

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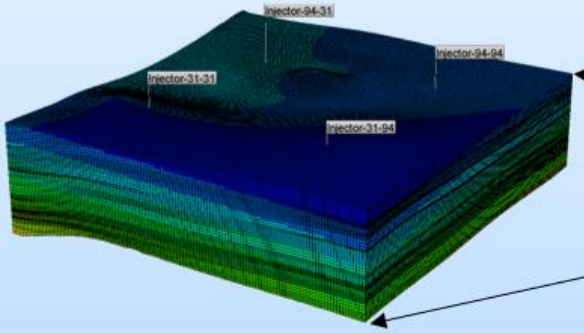
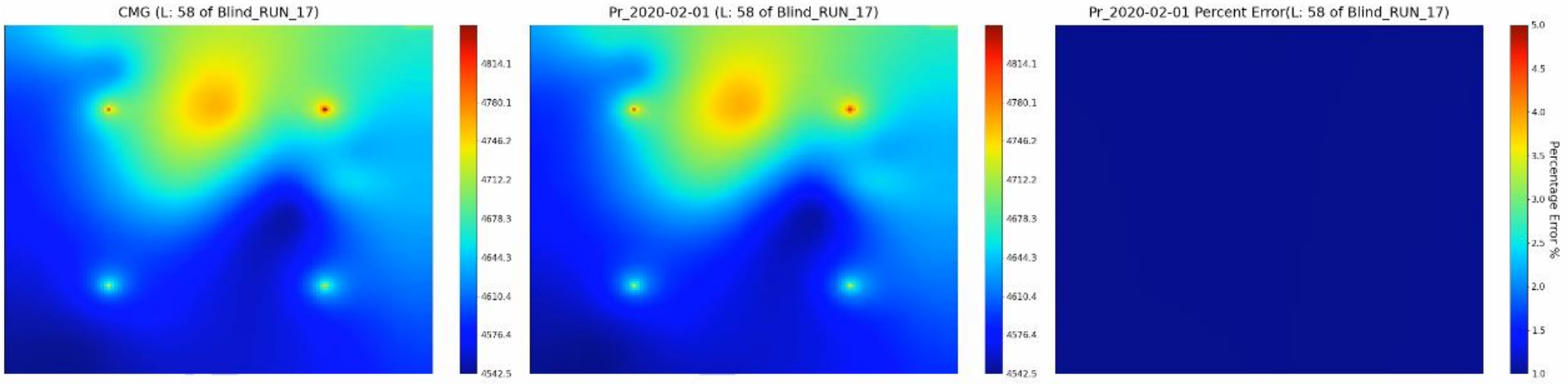


Reservoir Pressure value at every single cell (51 layers) at a certain Time-step

BLIND RUN #17 – Time-Step

Feb. 2020

Reservoir Pressure Distribution Video



CMG - Numerical Reservoir Simulation

Smart Proxy Model

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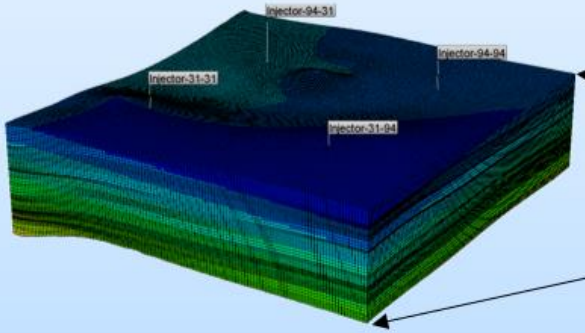
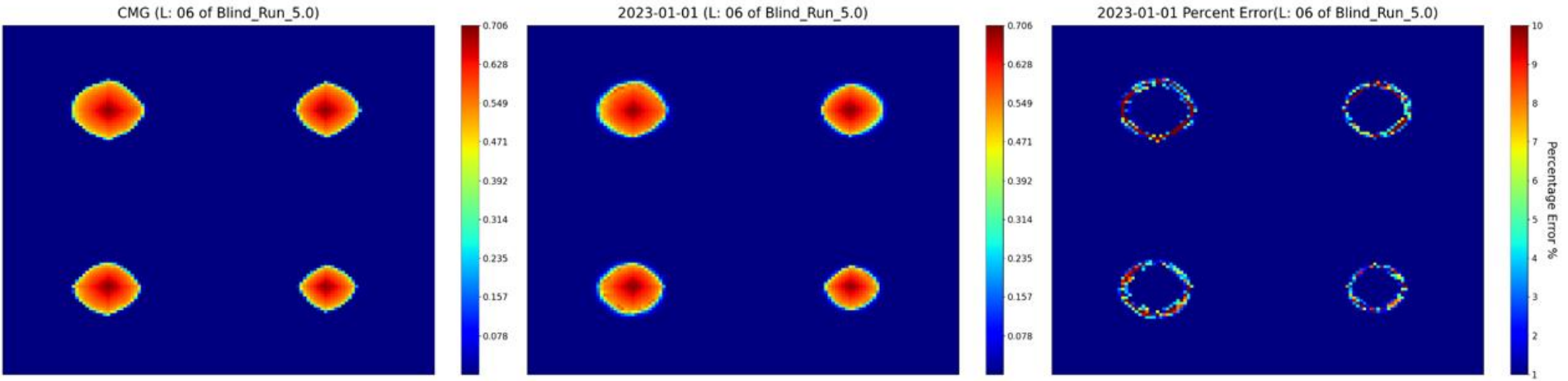


Reservoir Pressure value at every single cell (51 layers) at a certain Time-step

CO_2 Saturation Distribution Video



CMG - Numerical Reservoir Simulation

Smart Proxy Model

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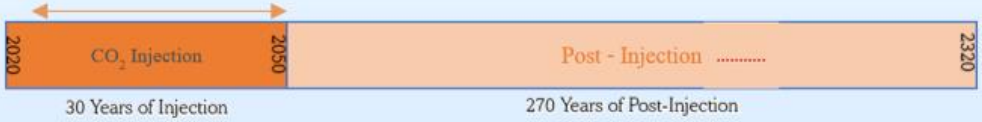
January 2023



Annual Distribution CO_2 Saturation

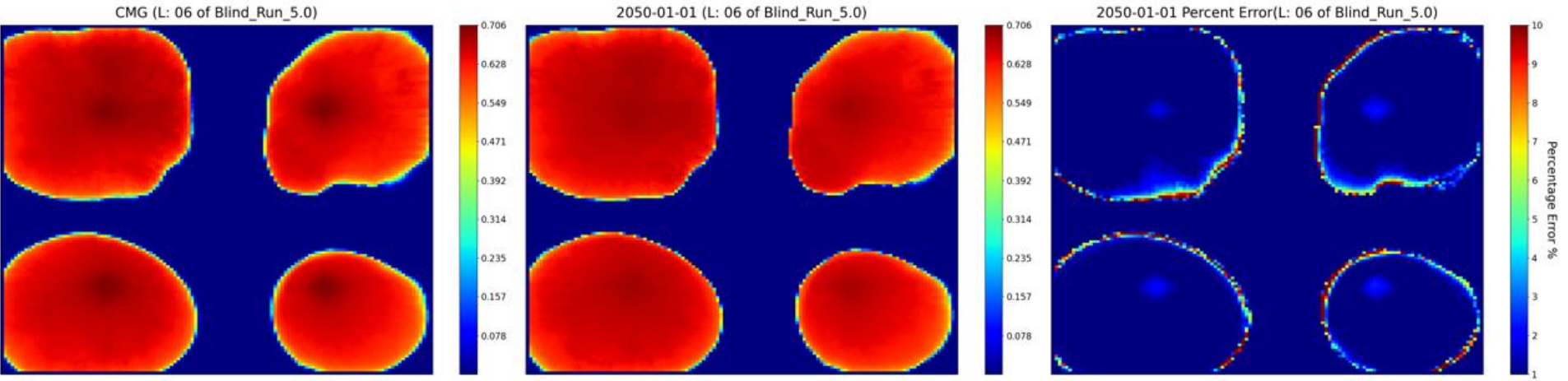
From: January 2023

To: January 2050

Blind Validation

Geological Realization #5, Layer 6

CO_2 Saturation Distribution Video



CMG - Numerical Reservoir Simulation

Smart Proxy Model

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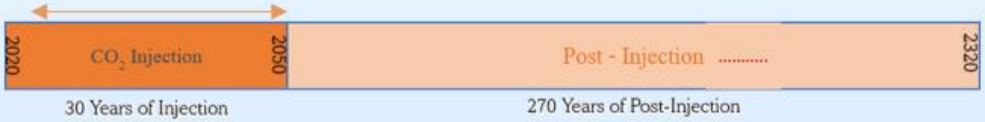
January 2050



Annual Distribution CO_2 Saturation

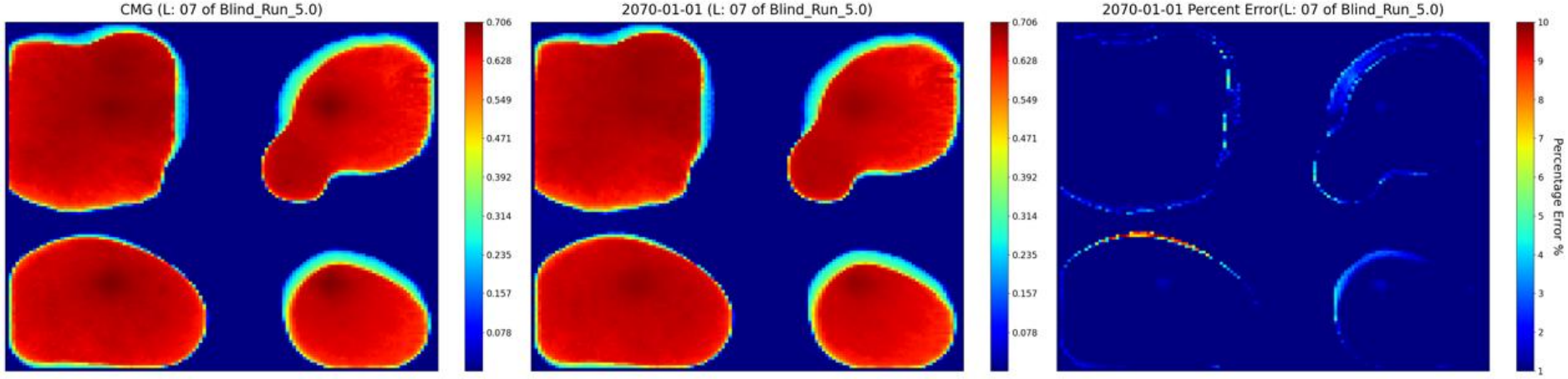
From: January 2023

To: January 2050

Blind Validation

Geological Realization #5, Layer 6

CO_2 Saturation Distribution Video



CMG - Numerical Reservoir Simulation

Smart Proxy Model

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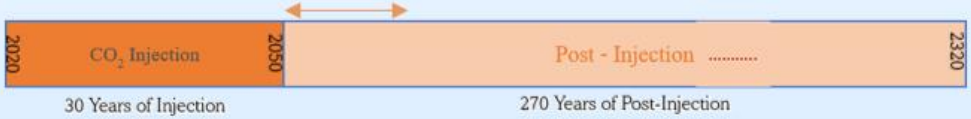
January 2070



Annual Distribution CO_2 Saturation

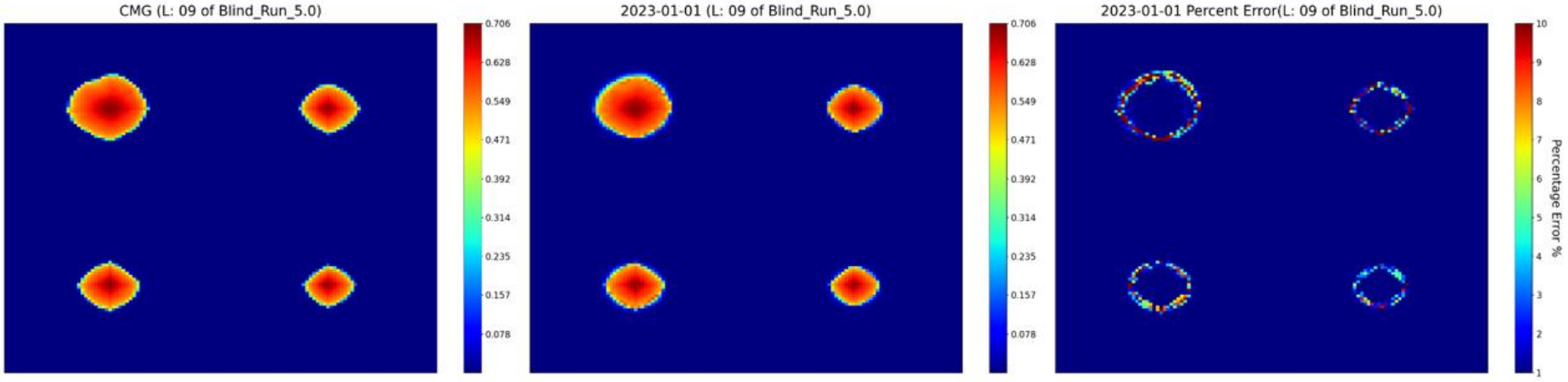
From: January 2051

To: January 2070

Blind Validation

Geological Realization #5, Layer 7

CO_2 Saturation Distribution Video



CMG - Numerical Reservoir Simulation

Smart Proxy Model

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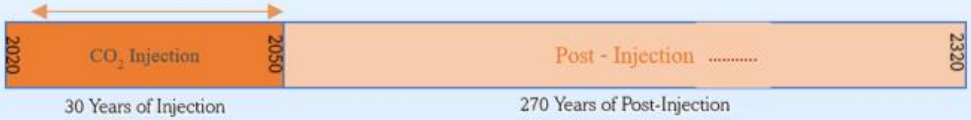
January 2023



Annual Distribution CO_2 Saturation

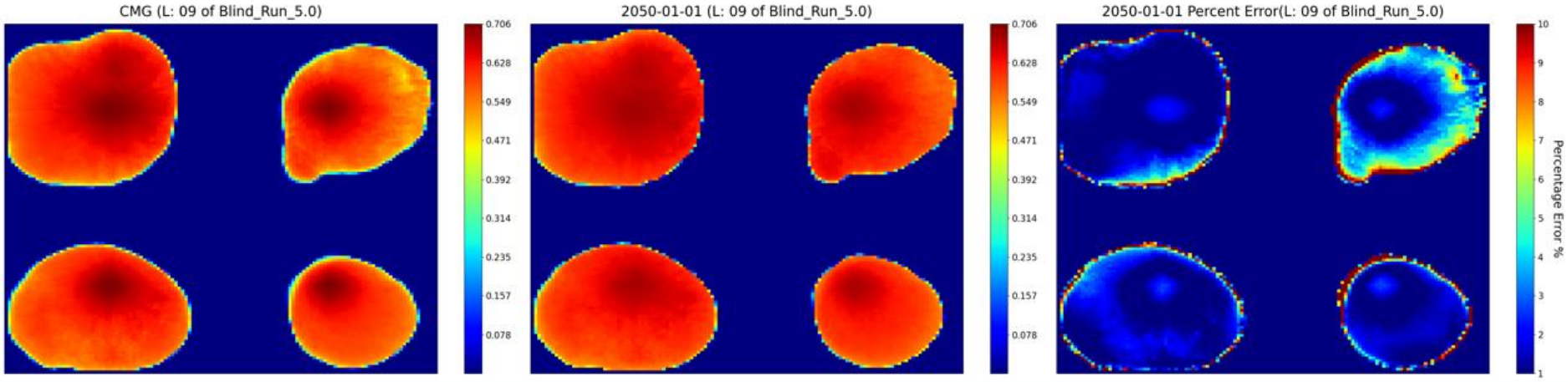
From: January 2023

To: January 2050

Blind Validation

Geological Realization #5, Layer 9

CO_2 Saturation Distribution Video

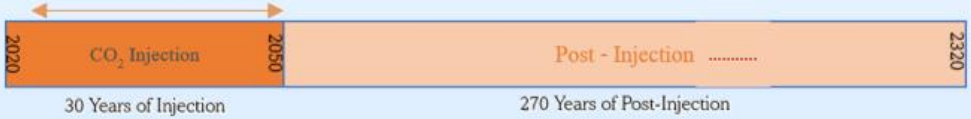


CMG - Numerical Reservoir Simulation

Smart Proxy Model

%Error

January 2050



Annual Distribution CO_2 Saturation

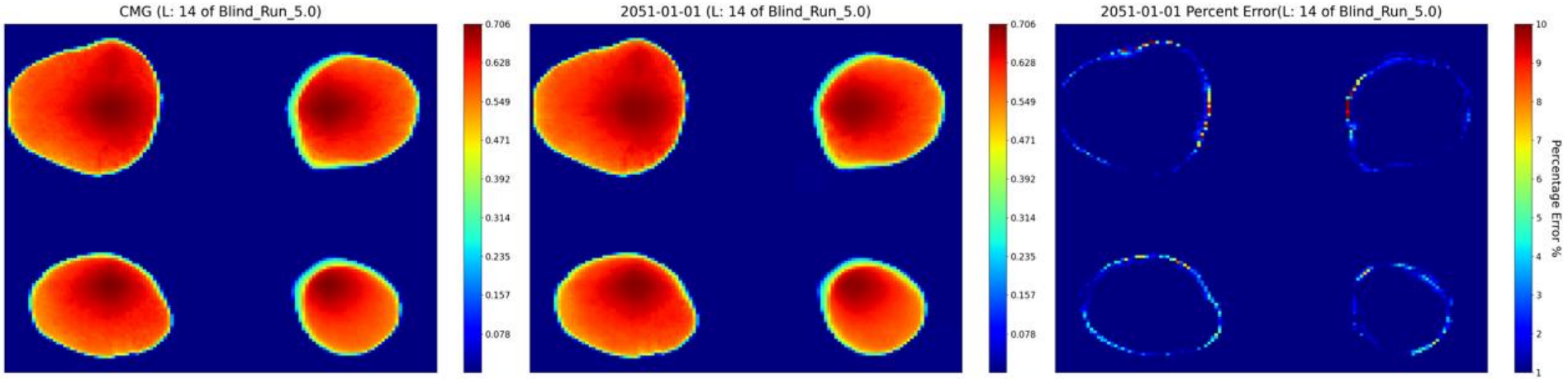
From: January 2023

To: January 2050

Blind Validation

Geological Realization #5, Layer 9

CO_2 Saturation Distribution Video

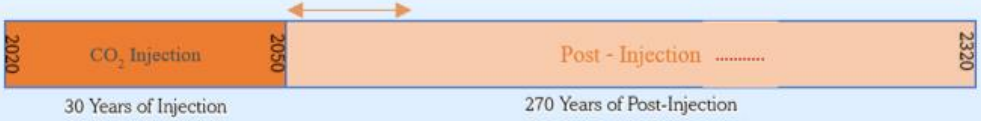


CMG - Numerical Reservoir Simulation

Smart Proxy Model

%Error

January 2051



Annual Distribution CO_2 Saturation

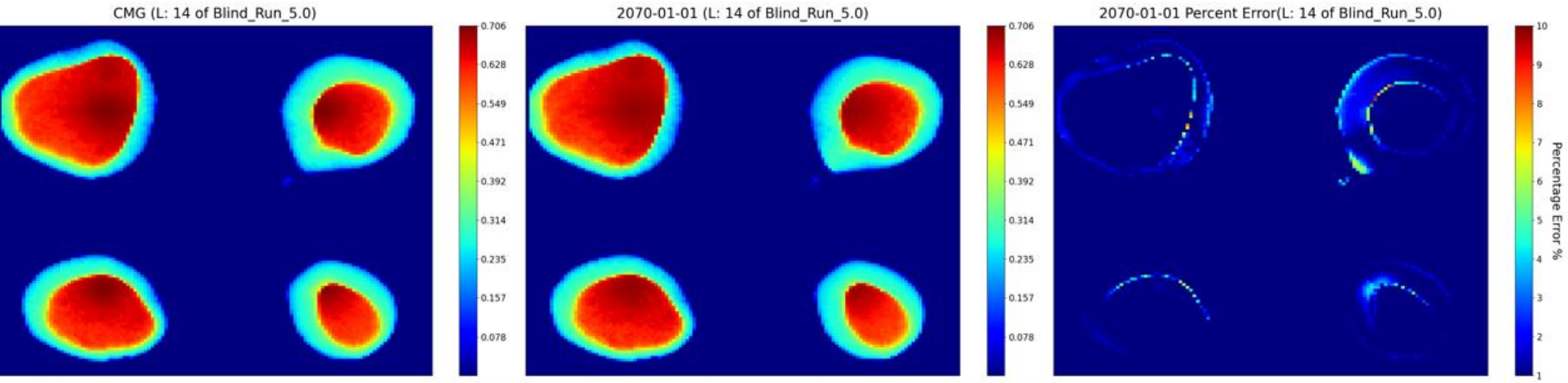
From: January 2051

To: January 2070

Blind Validation

Geological Realization #5, Layer 14

CO_2 Saturation Distribution Video

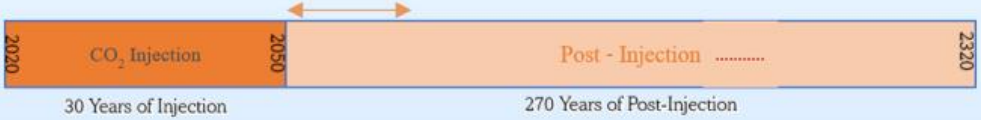


CMG - Numerical Reservoir Simulation

Smart Proxy Model

%Error

January 2070



Annual Distribution CO_2 Saturation

From: January 2051

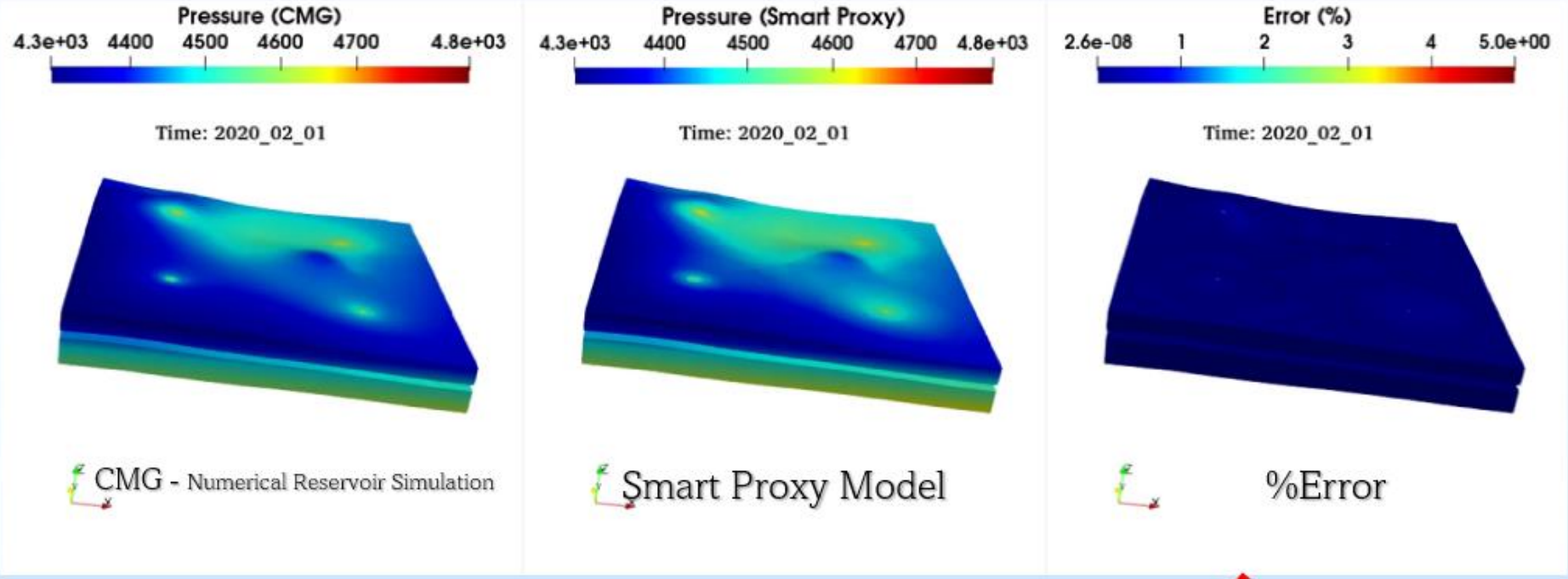
To: January 2070

Blind Validation

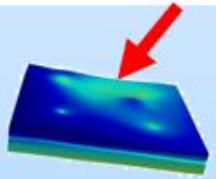
Geological Realization #5, Layer 14

BLIND RUN #5 – 3-D in Space & Time

Dynamic Reservoir Pressure

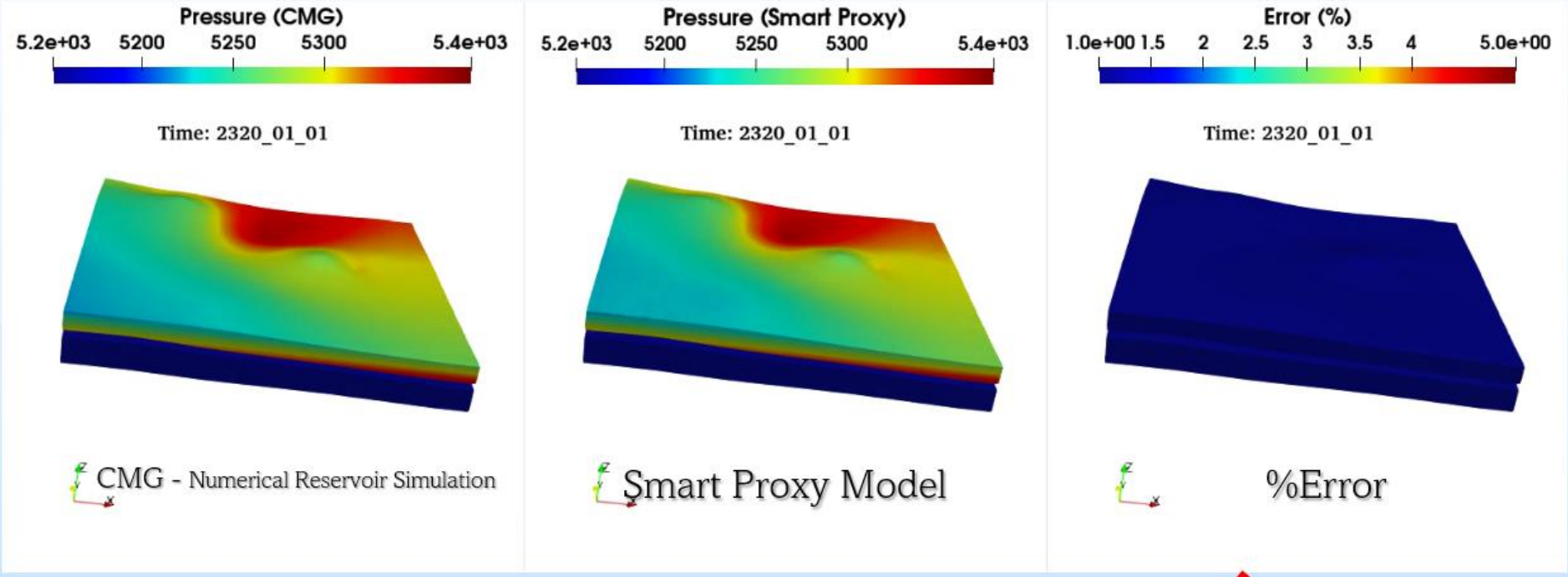


Looking from the Top

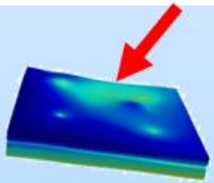


BLIND RUN #5 – 3-D in Space & Time

Dynamic Reservoir Pressure

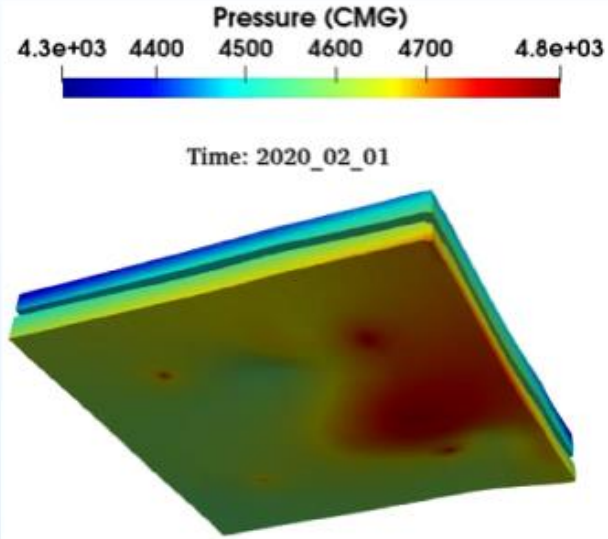


Looking from the Top

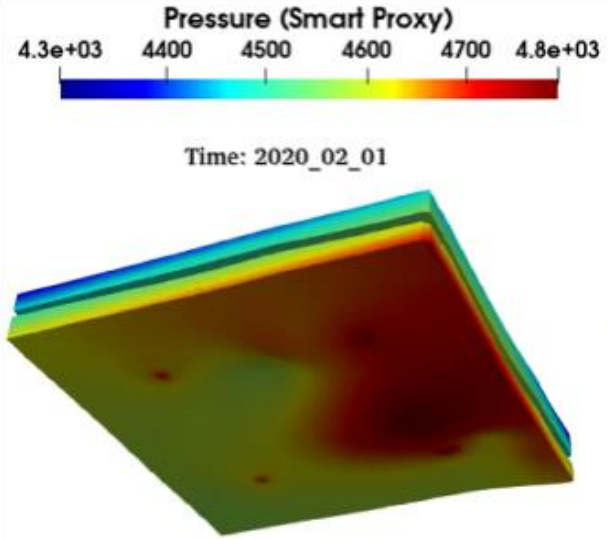


BLIND RUN #5 – 3-D in Space & Time

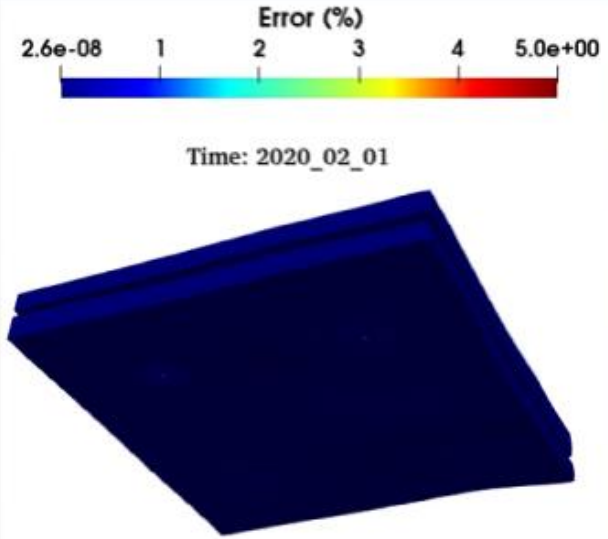
Dynamic Reservoir Pressure



CMG - Numerical Reservoir Simulation



Smart Proxy Model



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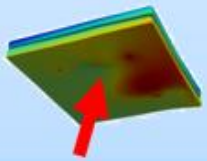
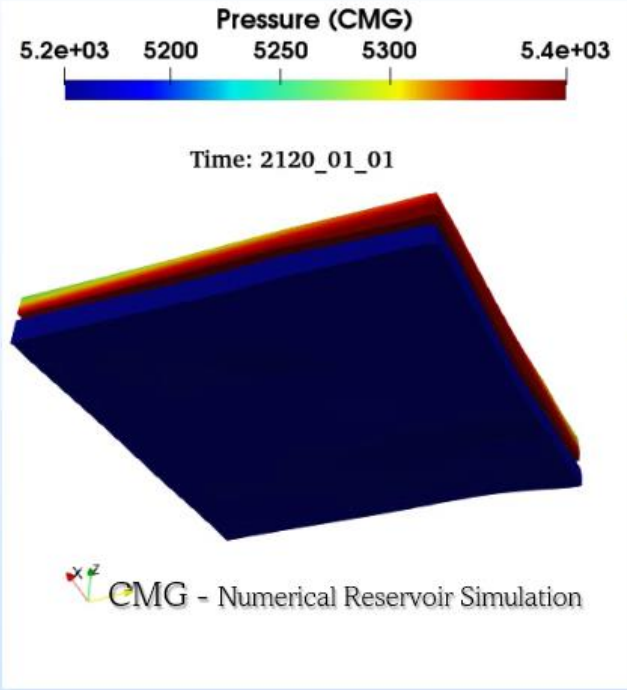
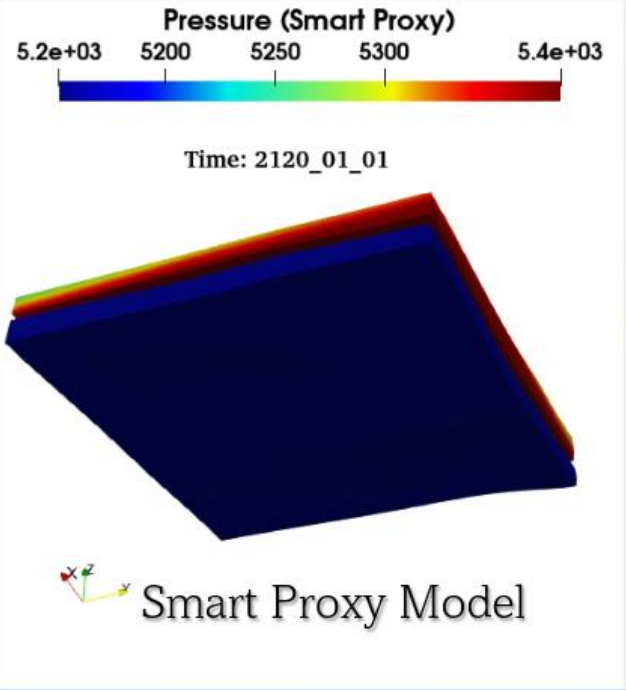
Looking from the Bottom

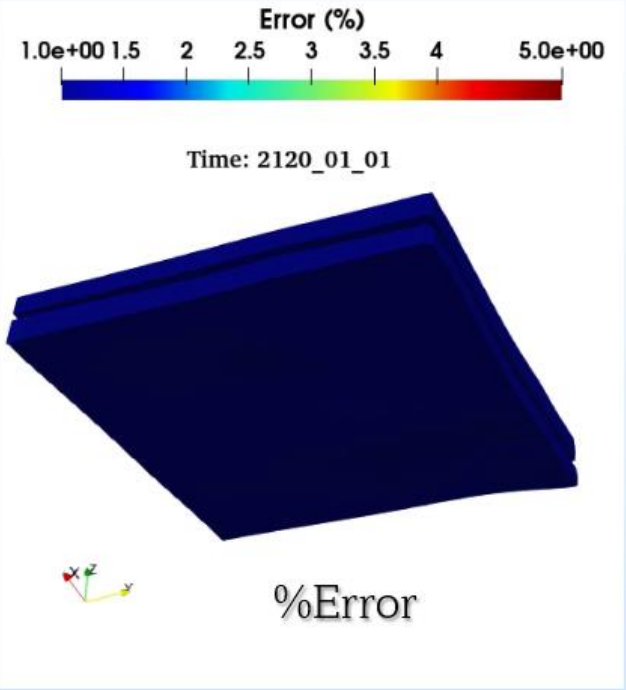


BLIND RUN #5 – 3-D in Space & Time

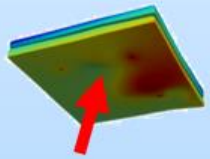
Dynamic Reservoir Pressure





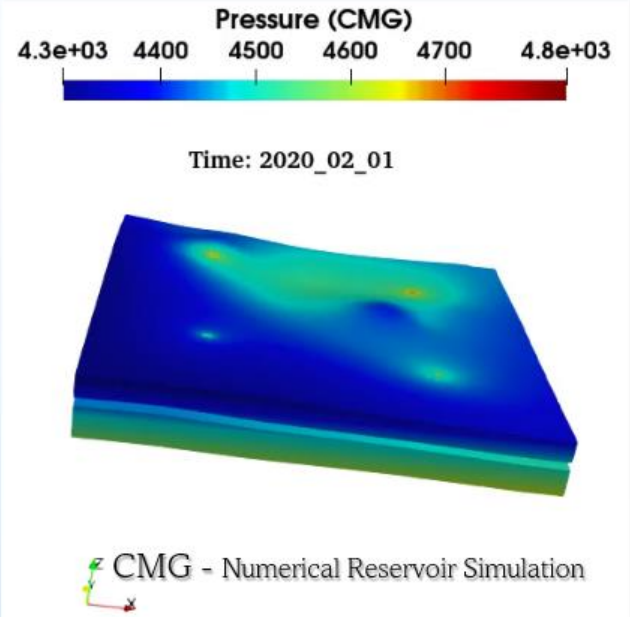


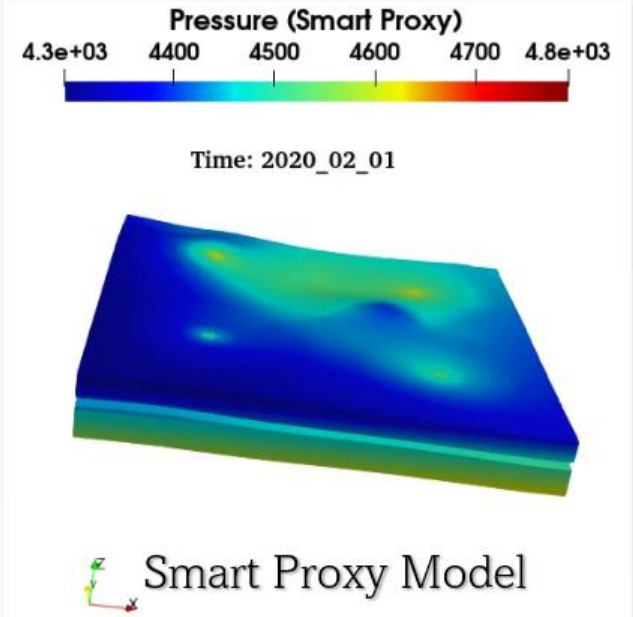
Looking from the Bottom

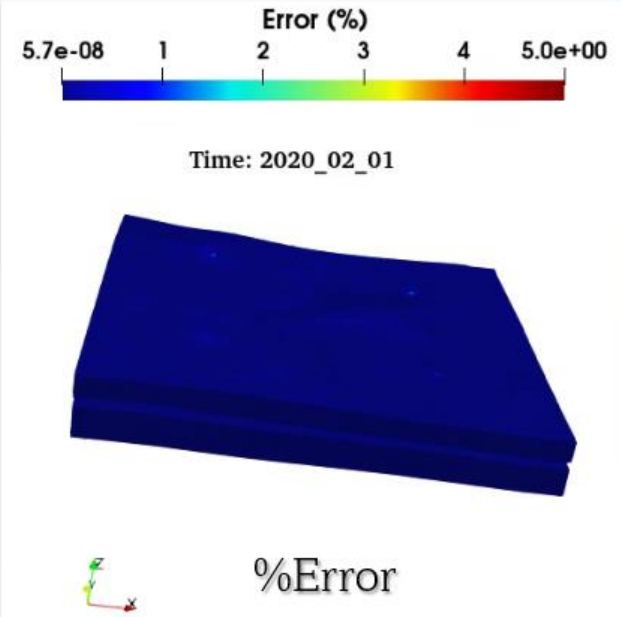


BLIND RUN #13 – 3-D in Space & Time

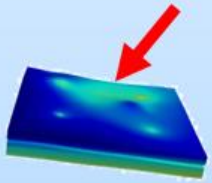
Dynamic Reservoir Pressure





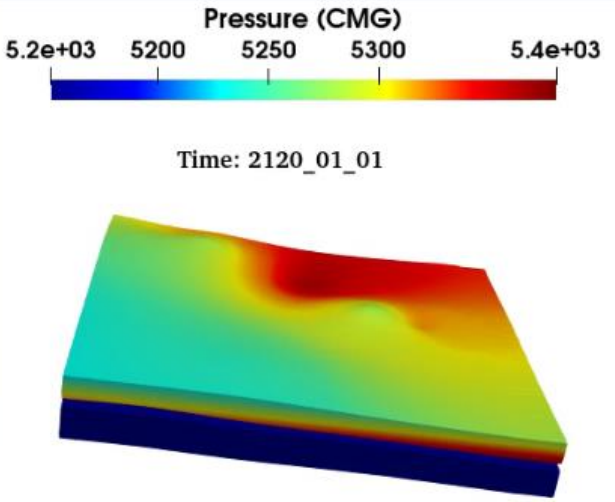


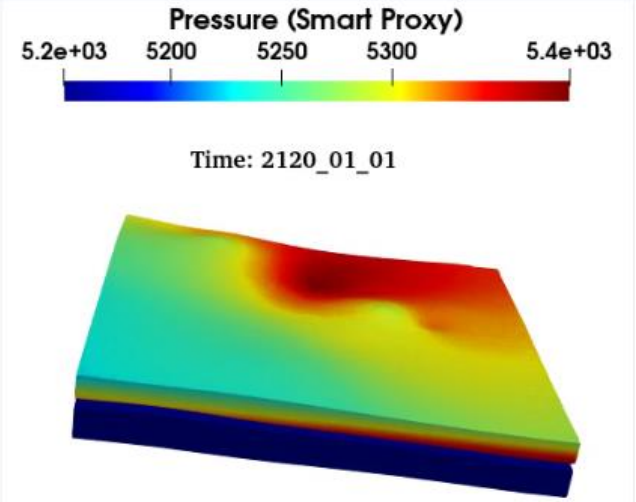
Looking from the Top

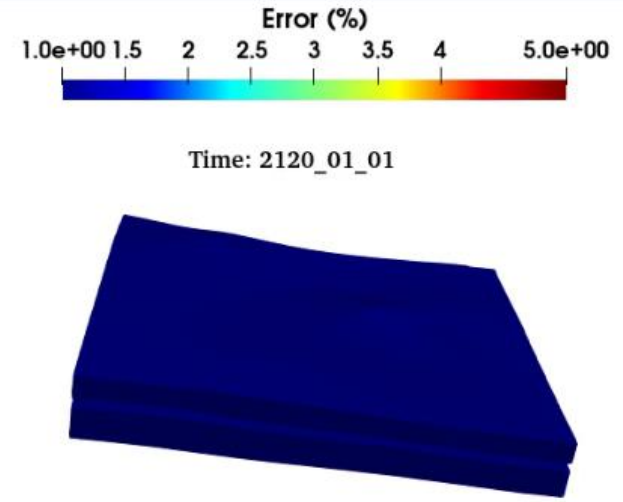


BLIND RUN #13 – 3-D in Space & Time

Dynamic Reservoir Pressure







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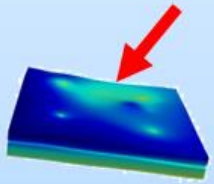
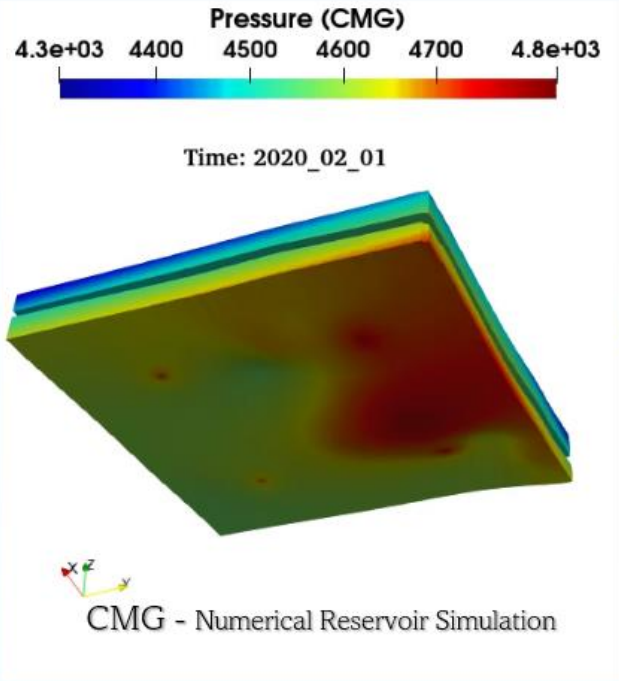
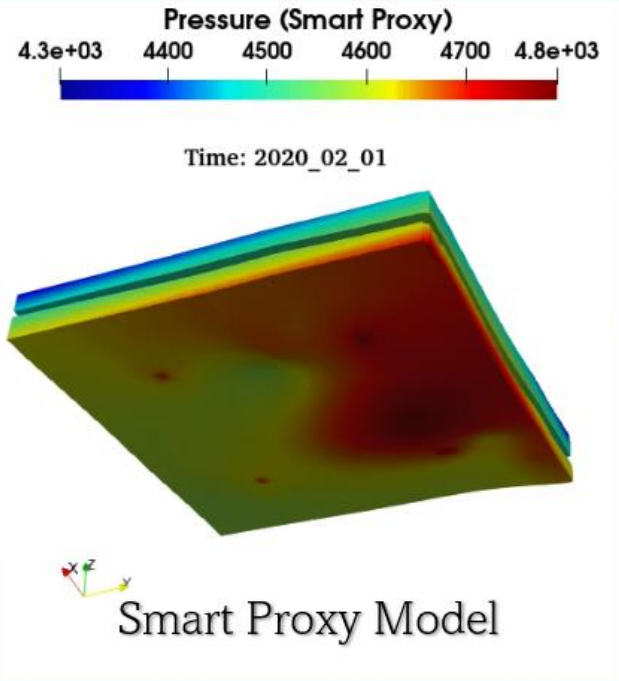


BLIND RUN #13 – 3-D in Space & Time

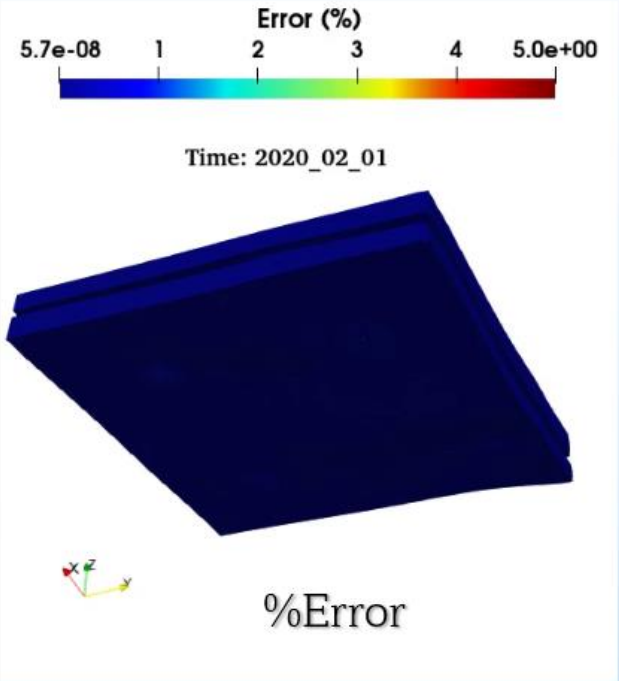
Dynamic Reservoir Pressure



CMG - Numerical Reservoir Simulation



Smart Proxy Model



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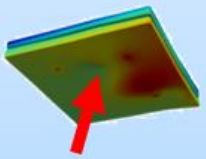
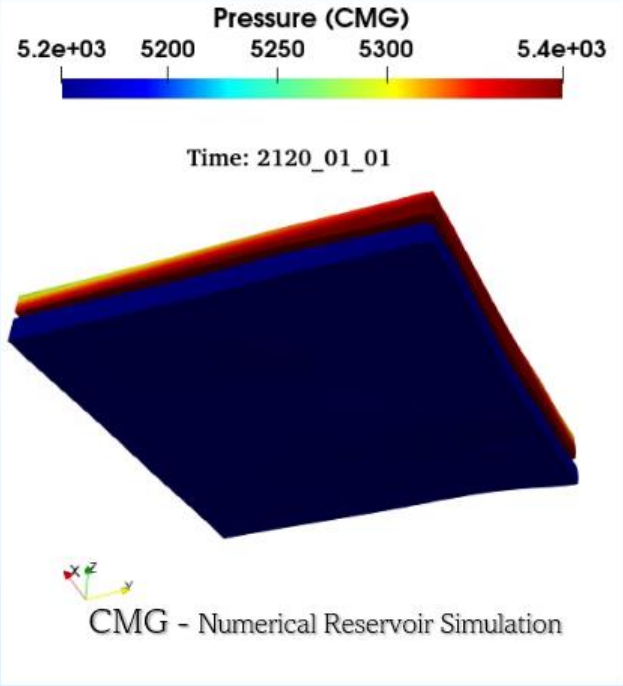
Looking from the Bottom

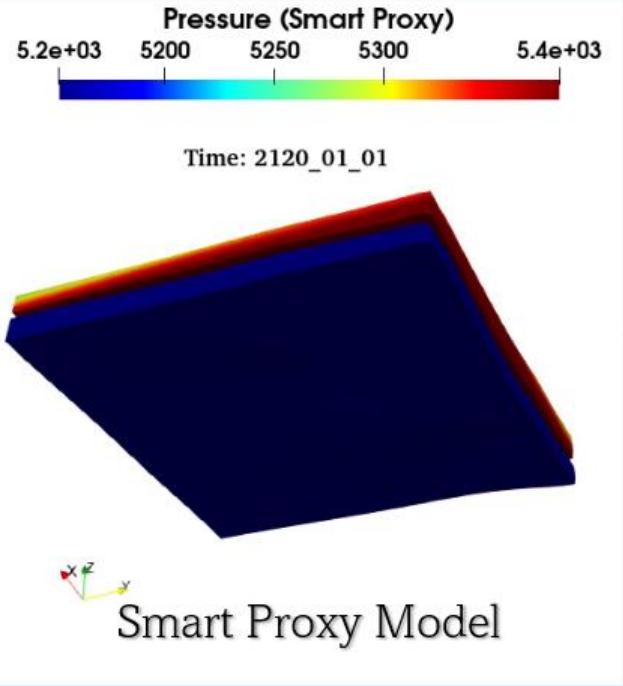


BLIND RUN #13 – 3-D in Space & Time

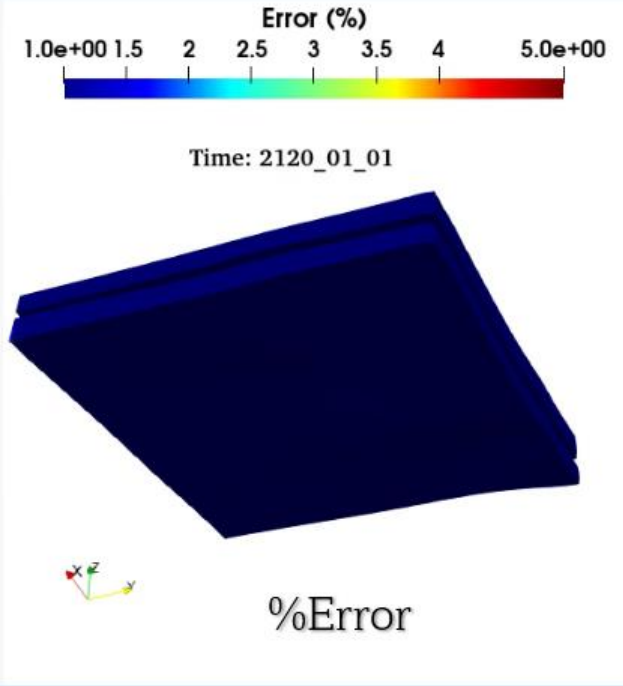
Dynamic Reservoir Pressure



CMG - Numerical Reservoir Simulation



Smart Proxy Model



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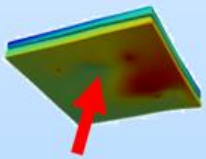
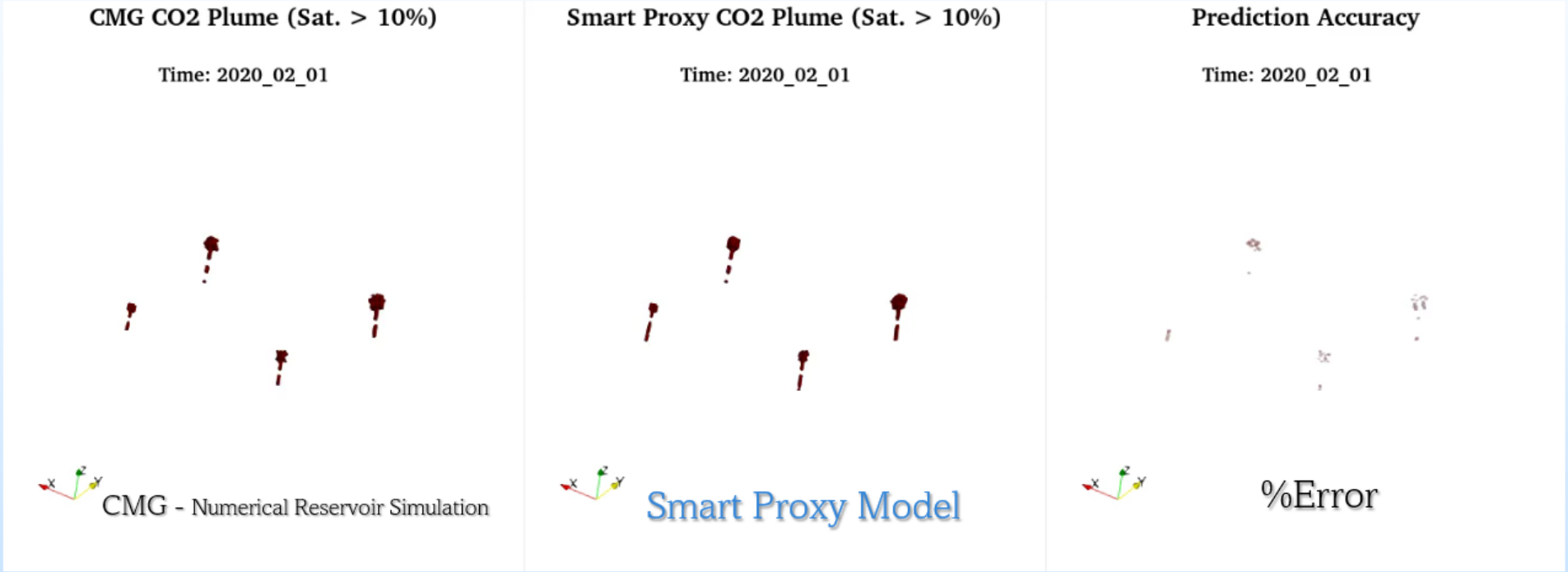
Looking from the Bottom

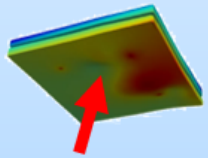


BLIND RUN #5 – 3-D in Space & Time

Dynamic CO_2 Saturation

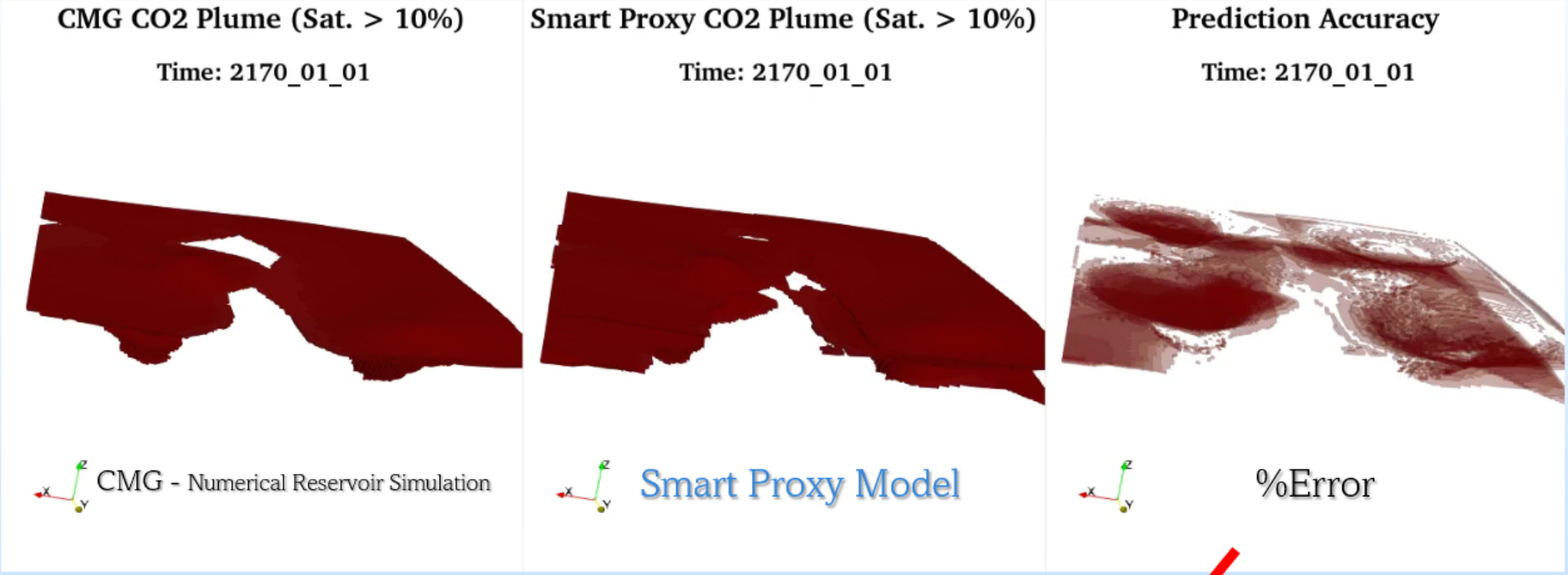


Looking from the Bottom

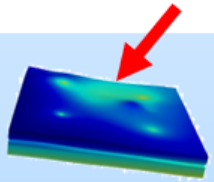


BLIND RUN #5 – 3-D in Space & Time

Dynamic CO_2 Saturation



Looking from the Top



BLIND RUN #5 – 3-D in Space & Time

Dynamic CO_2 Saturation

CMG CO2 Plume (Sat. > 10%)

Time: 2020_02_01

CMG - Numerical Reservoir Simulation

Smart Proxy CO2 Plume (Sat. > 10%)

Time: 2020_02_01

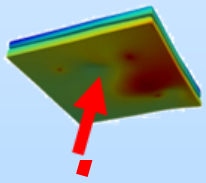
Smart Proxy Model

Prediction Accuracy

Time: 2020_02_01

%Error

Looking from the Bottom

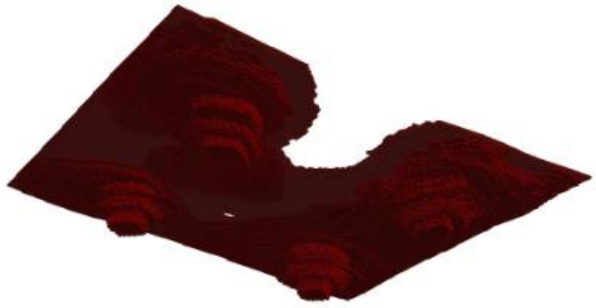


BLIND RUN #5 – 3-D in Space & Time

Dynamic CO_2 Saturation

CMG CO2 Plume (Sat. > 10%)

Time: 2320_01_01



CMG - Numerical Reservoir Simulation

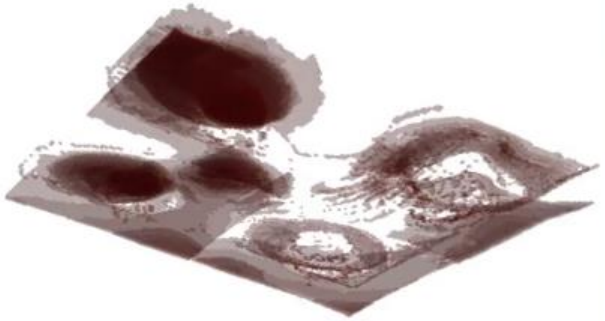
Smart Proxy CO2 Plume (Sat. > 10%)

Time: 2320_01_01

Smart Proxy Model

Prediction Accuracy

Time: 2320_01_01



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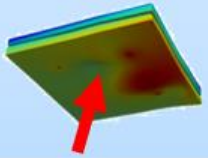
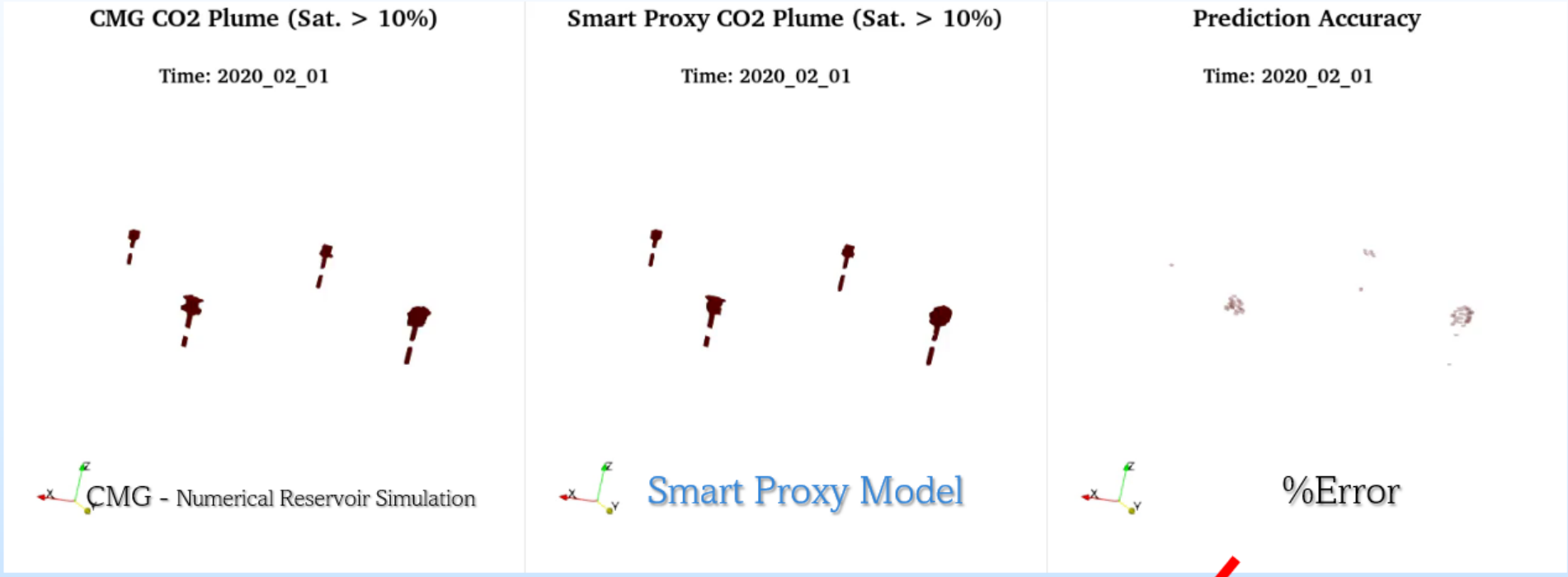
Looking from the Bottom

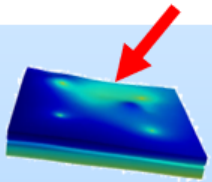


BLIND RUN #13 – 3-D in Space & Time

Dynamic CO_2 Saturation

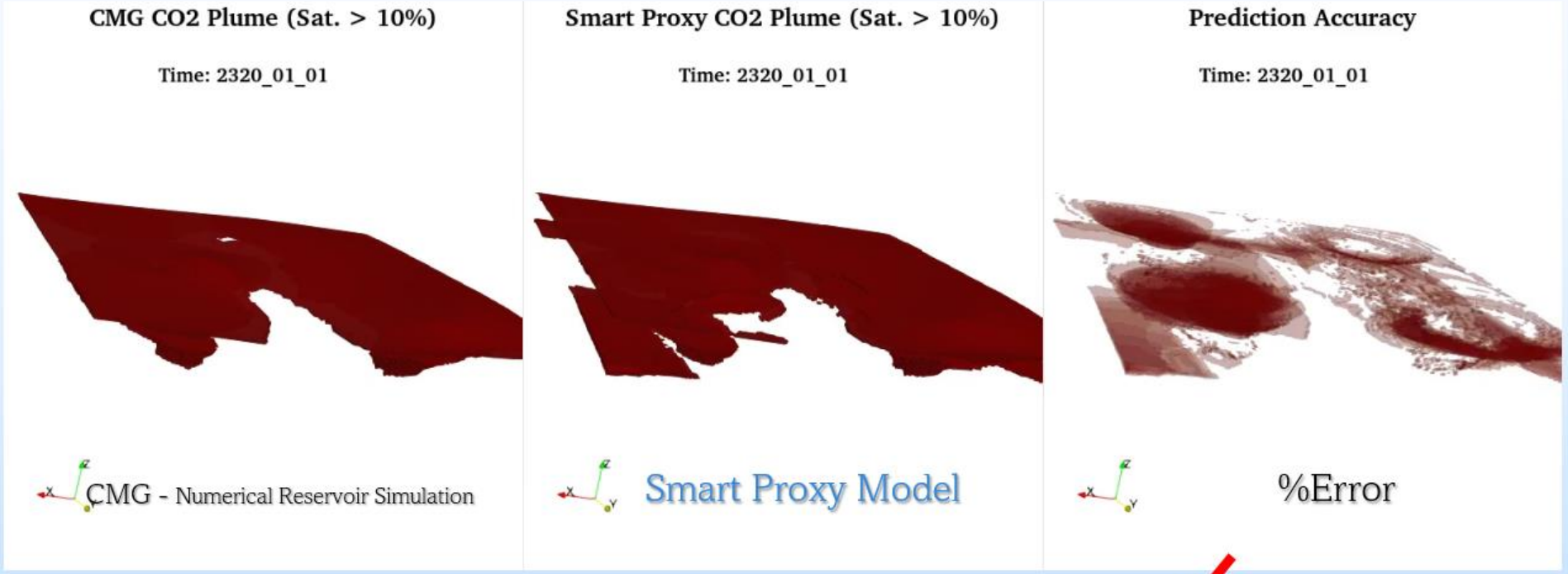


Looking from the Top

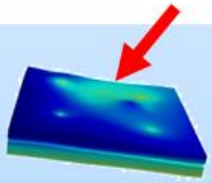


BLIND RUN #13 – 3-D in Space & Time

Dynamic CO_2 Saturation

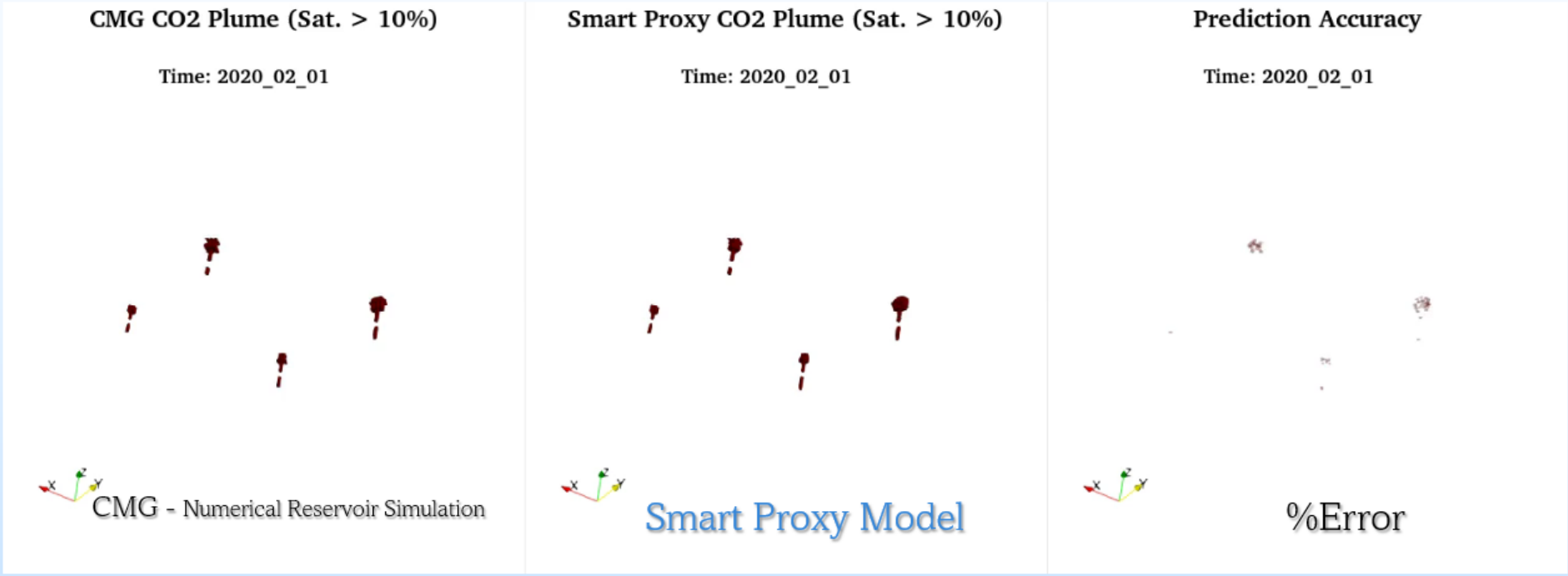


Looking from the Top

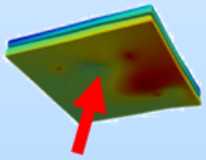


BLIND RUN #13 – 3-D in Space & Time

Dynamic CO_2 Saturation



Looking from the Bottom



BLIND RUN #13 – 3-D in Space & Time

Dynamic CO_2 Saturation

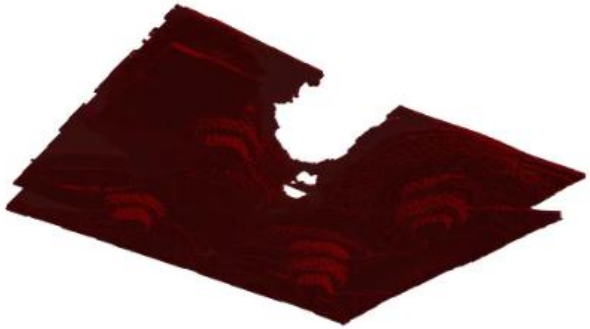
CMG CO2 Plume (Sat. > 10%)

Time: 2170_01_01

CMG - Numerical Reservoir Simulation

Smart Proxy CO2 Plume (Sat. > 10%)

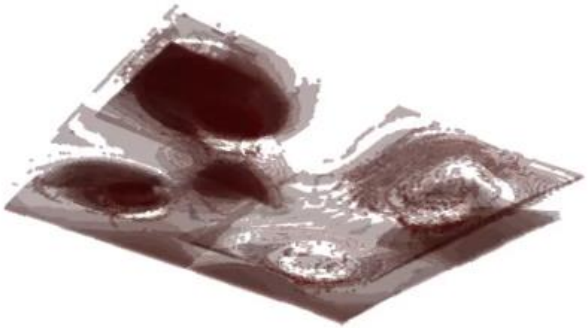
Time: 2170_01_01



Smart Proxy Model

Prediction Accuracy

Time: 2170_01_01



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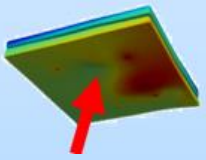
Looking from the Bottom