

# Site-Scale and Regional-Scale Modeling for Geothermal Resource Analysis and Exploration

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**This work is supported by U.S.  
Department of Energy –  
Geothermal Technologies Office  
(GTO), Machine Learning for  
Geothermal Energy**



Operated by Los Alamos National Security, LLC for the U.S. Department of Energy's NNSA

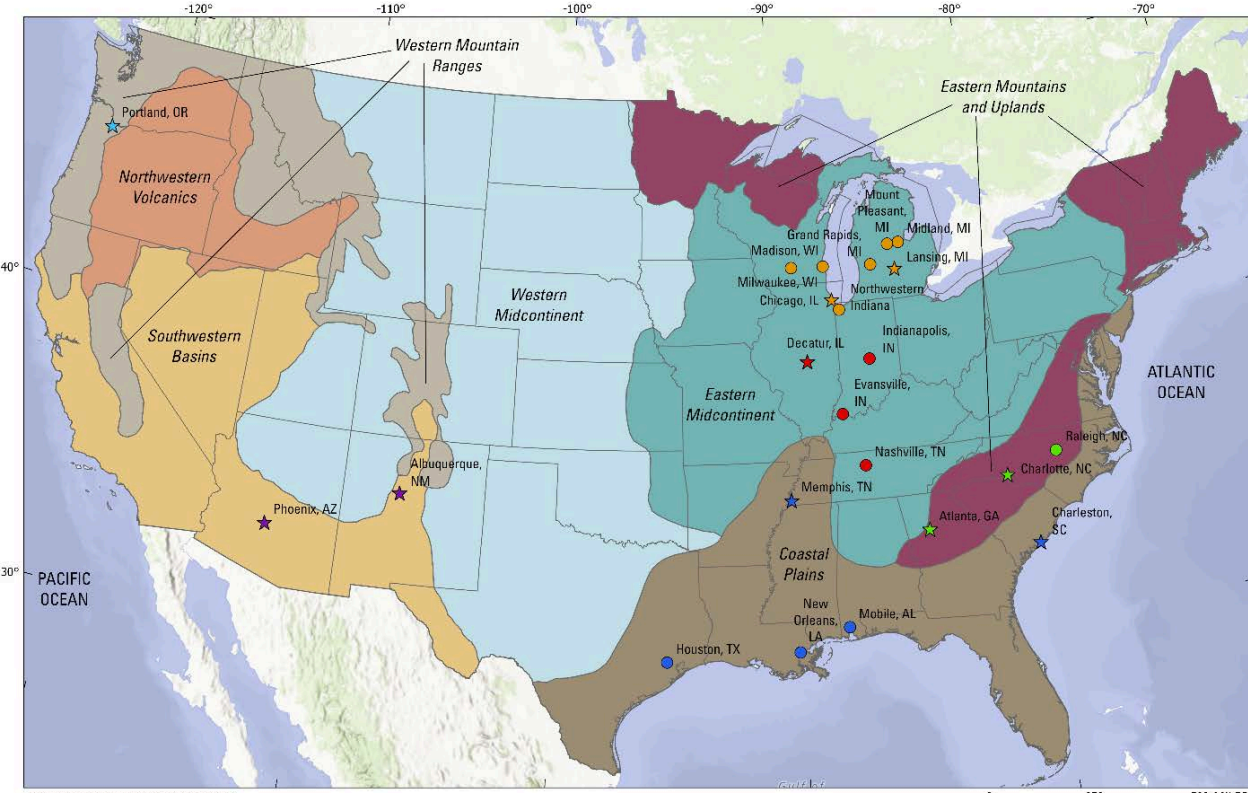
# Outline of the talk

- **Motivation and objectives**
- **Governing equations**
- **Proposed machine learning workflow**
- **Generalized site-scale conceptual model**
- **Preliminary modeling results**
- **Conclusions**
- **Path forward**

# Motivation and objectives

- Detailed knowledge of site and regional permeability is critical for geothermal resource analysis and exploration
- The knowledge of reservoir rock permeability is **very limited and sparse**
- Rock permeability needs to be inferred from various types of data streams
- The permeability values of rock formations within prospective geothermal reservoirs are **generally low**
- To develop an economically viable enhanced geothermal systems, the reservoir permeability needs to be enhanced
- Identification of prospective geothermal reservoirs: Two key aspects
  - Elevated heat flux
  - Formation suitable for permeability enhancement and reservoir stimulation
- **OBJECTIVE:**
  - Develop fast, reliable, and reasonably accurate machine learning (ML) models for geothermal resource analysis and exploration

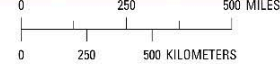
# Geothermal study area in New Mexico (Southwestern Basins)



Albers Equal-Area Conic projection, standard parallels 29°30' N. and 45°30' N., central meridian 96°00' W., latitude of origin 23°00' N. North American Datum of 1983

**EXPLANATION**

<b>Points</b>	<b>Regions</b>
○ Geologic Group Cities	Brackish groundwater region (Stanton et al., 2017)
☆ Modeling in Progress	Coastal Plains
<b>Geologic region</b>	Eastern Midcontinent
★ Basin and Range	Eastern Mountains and Uplands
★ Coastal Plains	Northwestern Volcanics
★ Illinois Basin	Southwestern Basins
★ Michigan Basin	Western Midcontinent
★ Pacific Northwest	Western Mountain Ranges
★ Piedmont	

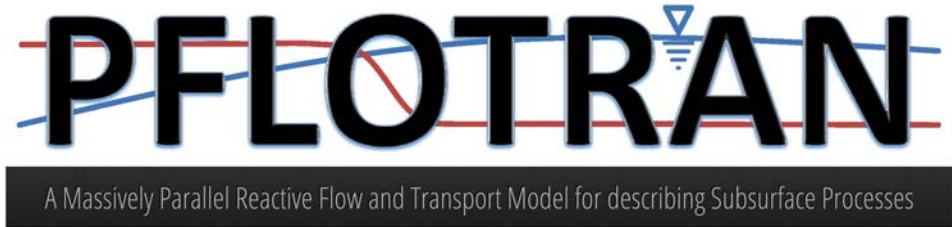


# Governing equations

## Mass conservation equation for single phase saturated flow

$$\frac{\partial(\varphi\rho)}{\partial t} + \text{div}[\rho\mathbf{q}] = Q_{fluid}$$

$$\mathbf{q} = -\frac{k(\mathbf{x})}{\mu} \text{grad}[P - \rho g z]$$



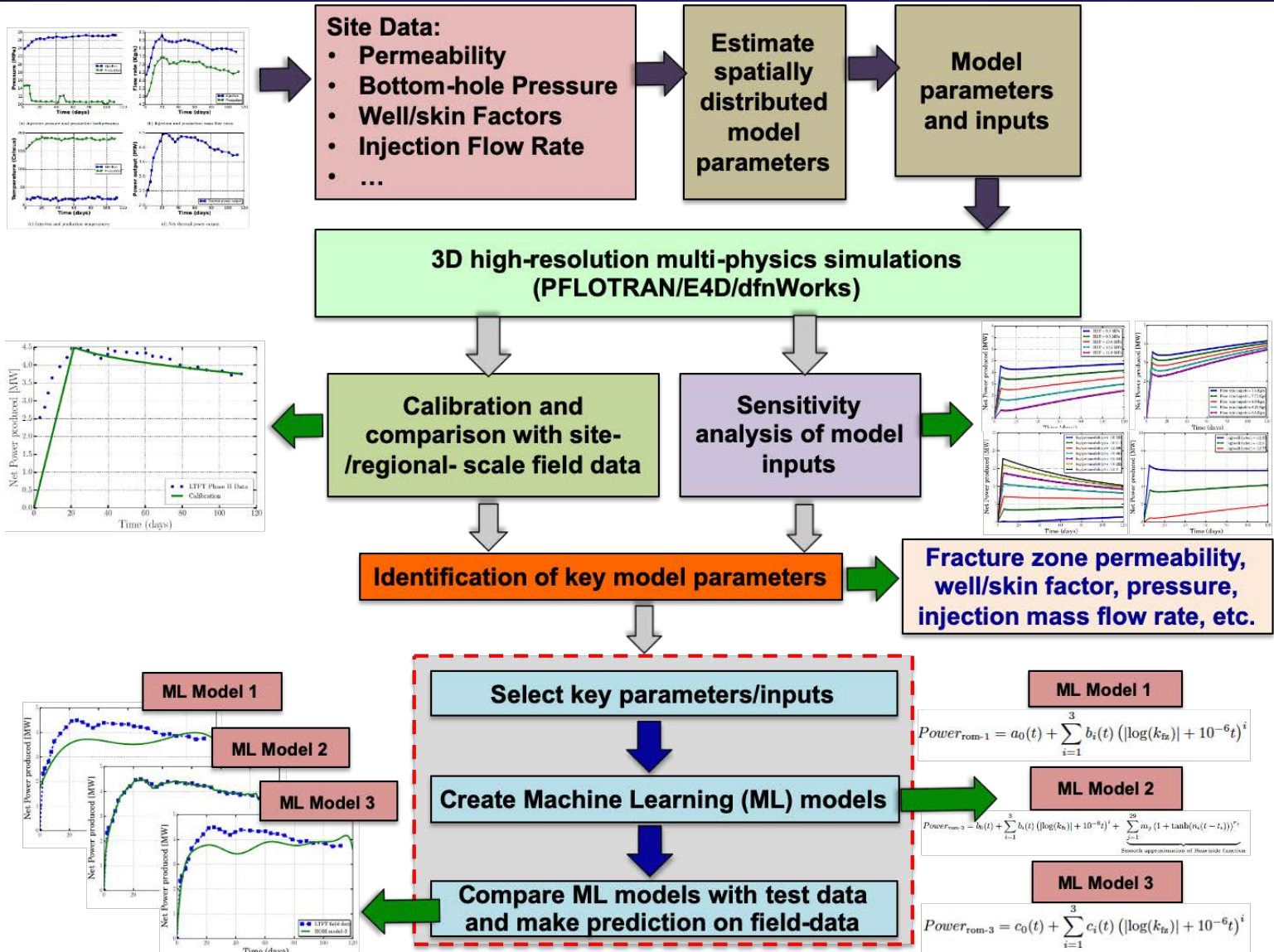
## Governing equations for chemical transport (e.g., lithium, boron)

$$\frac{\partial(\varphi c)}{\partial t} + \text{div}[c\mathbf{q} - \varphi\tau D \text{grad}[c]] = Q_{tracer}$$

## Governing equations for thermal energy conservation

$$\frac{\partial(\varphi\rho U + (1 - \varphi)\rho_{rock} c_{p,rock} T)}{\partial t} + \text{div}[\rho H \mathbf{q} - \kappa_{eff} \text{grad}[T]] = 0$$

# Overview of proposed Machine Learning (ML) workflow



# Site-scale model (Fenton Hill, New Mexico) developed based on the proposed ML workflow shows promise

Reference datum: Reservoir top surface is at 3000 m

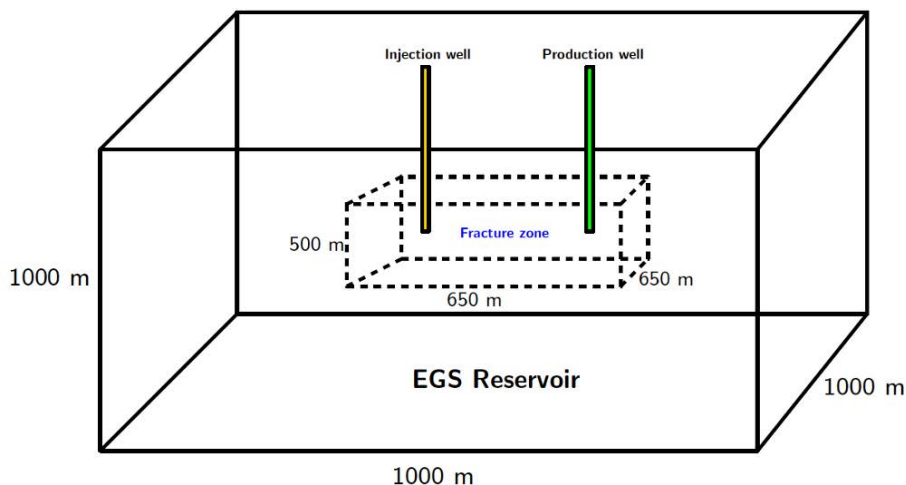
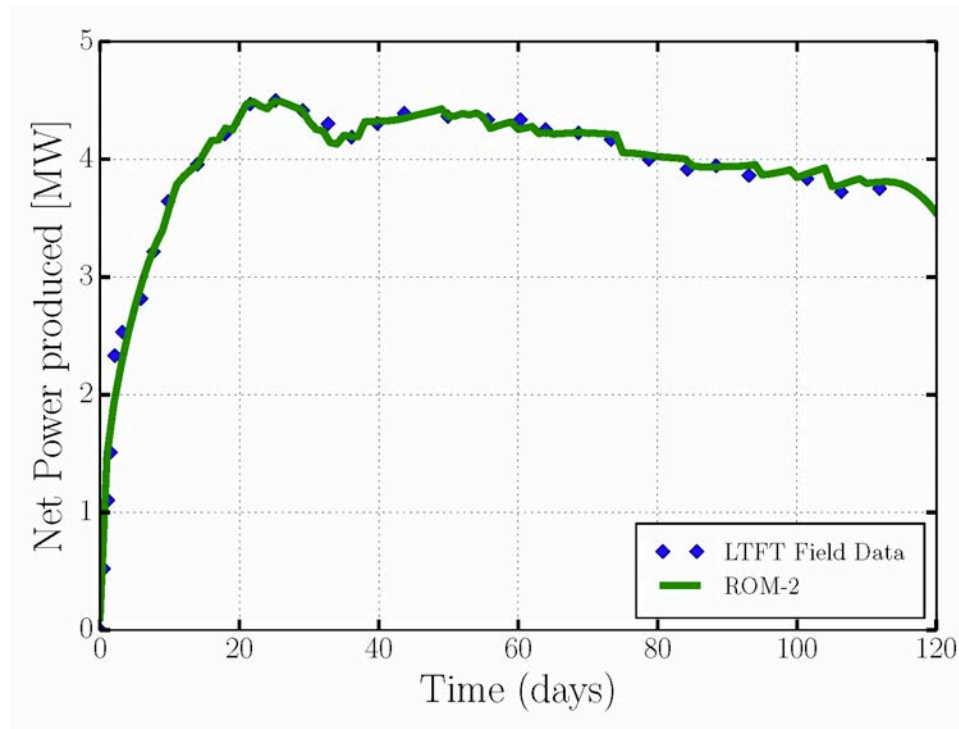


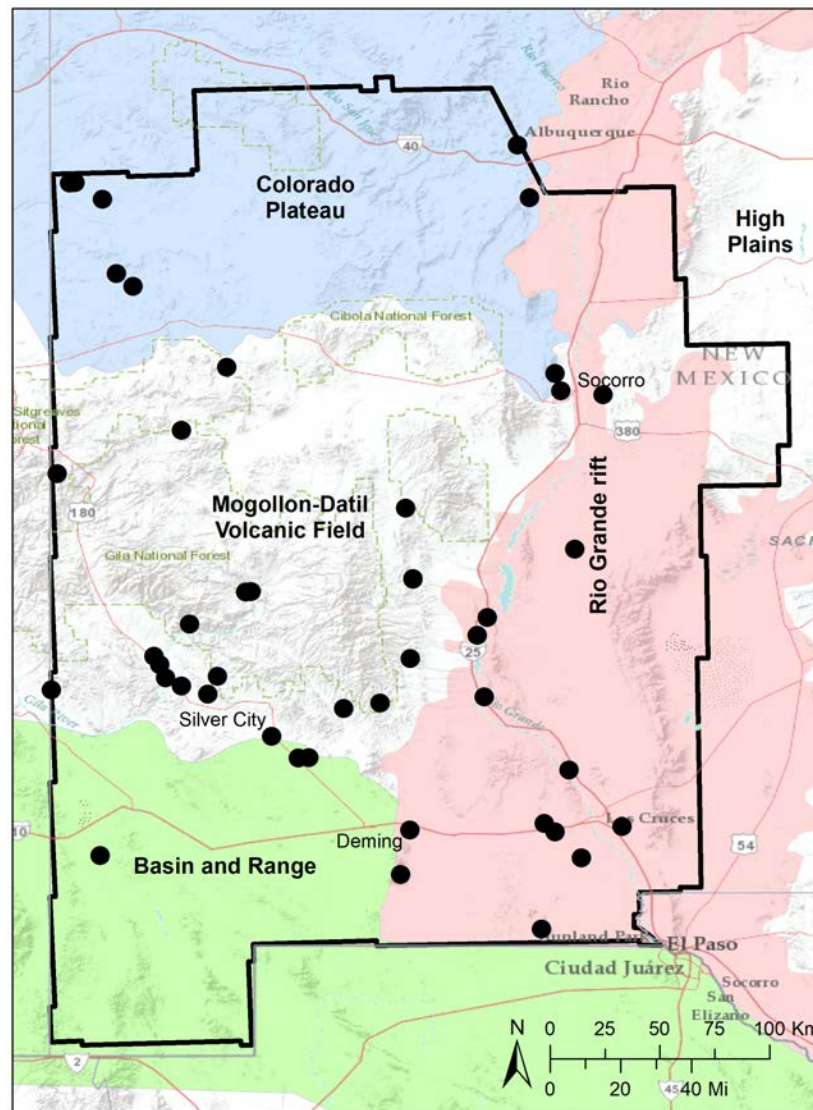
Figure : Conceptual model: EGS reservoir and fracture zone dimensions



M. K. Mudunuru, et al., (2017). Regression-based reduced-order models to predict transient thermal output for enhanced geothermal systems. *Geothermics*, 70, 192-205.

- **Datasets used for calibration and ML model development**
  - Injection and production
  - Reservoir and site-scale characteristics
- **1 million mesh cells on 64 processors**
- **~3000 PFLOTRAN model realizations**

# Modeling region: Southwest New Mexico



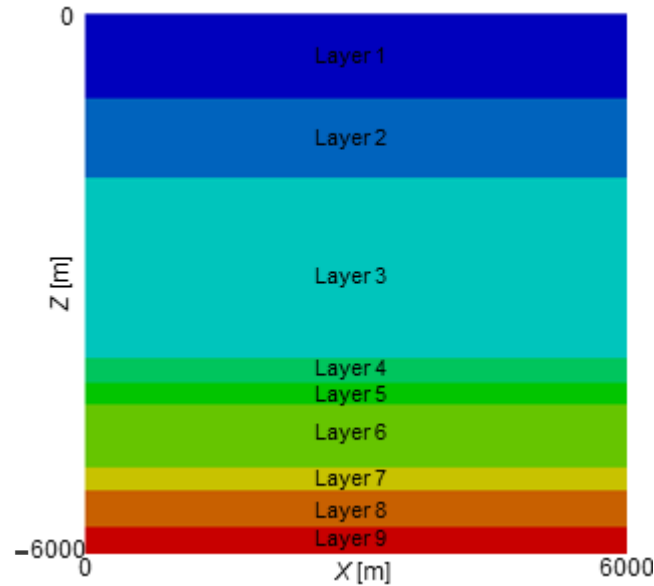
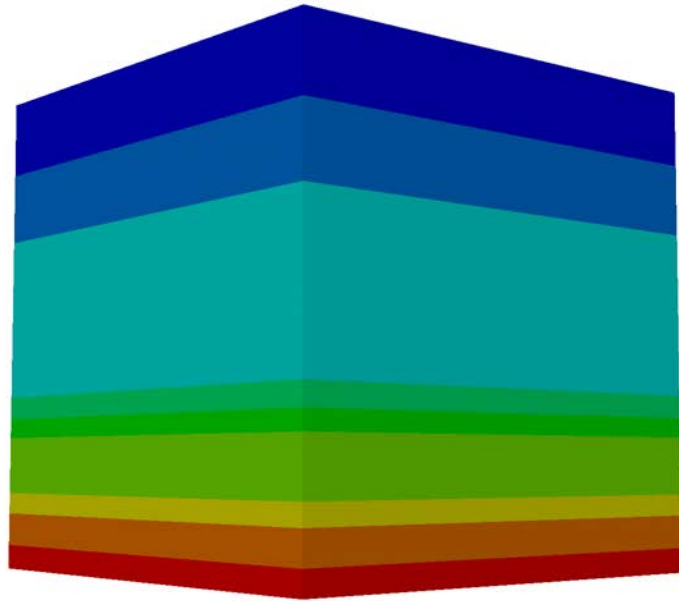
# Generalized site-scale conceptual model, Southwest New Mexico

## North, South, East, and West BCs

- Zero energy flux
- No water flow
- Concentration: Zero flux

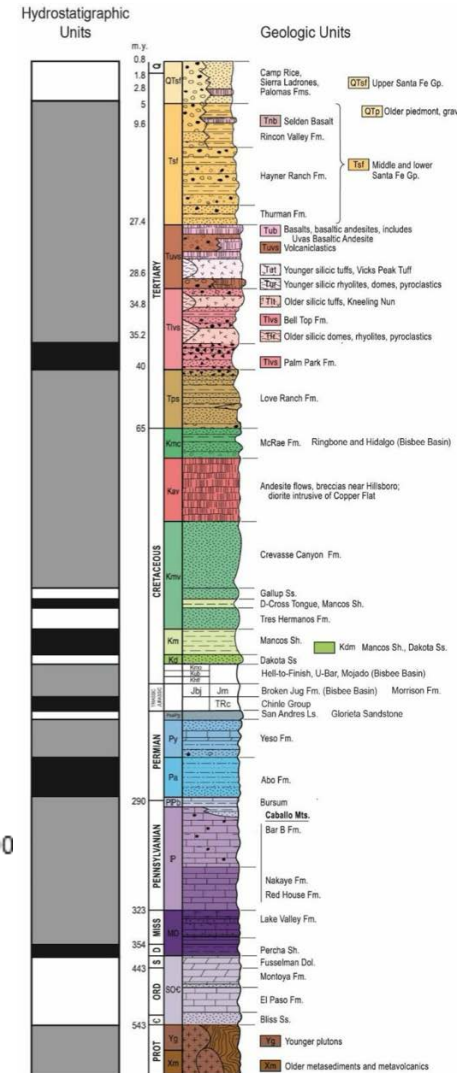
## Top surface BCs

- Temperature: Zero gradient
- Pressure: 1 MPa
- Concentration: Zero flux

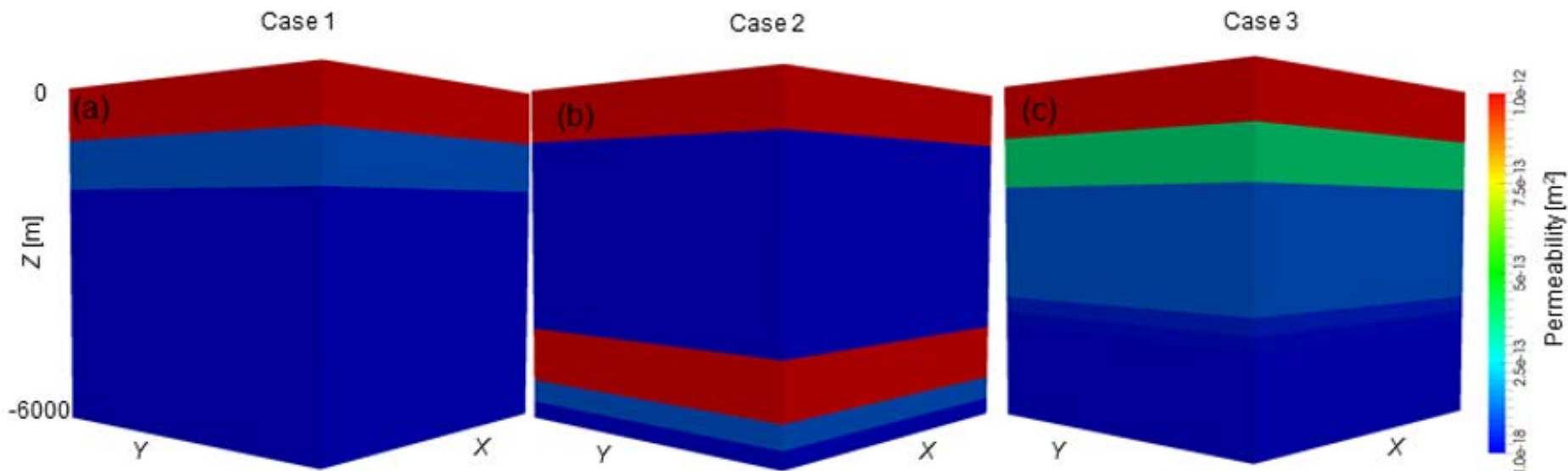


## Bottom surface BCs

- Energy flux:  $0.08 \text{ Wm}^{-2}$
- Pressure: 7 MPa
- Concentration: Zero



# Permeability for three different model realizations

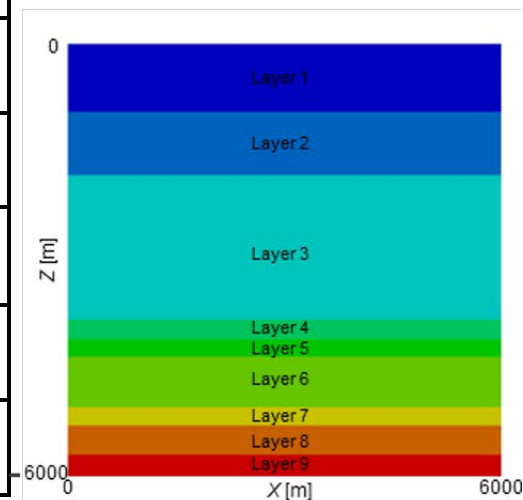


- **Case 1 (low-permeability case):** Permeabilities in the **bottom geological layers are lower** compared to Case 2 and Case 3.
- **Case 2 (high-permeability at depth case):** Permeability in **middle layers is very low** compared to Case 2 and Case 3; there is high- $k$  layer near the bottom.
- **Case 3 (permeability decay with depth):** Permeability **gradually decreases** with depth. There are no rapid changes in the permeability across the layers.

# PFLOTRAN site-scale model realization specifics

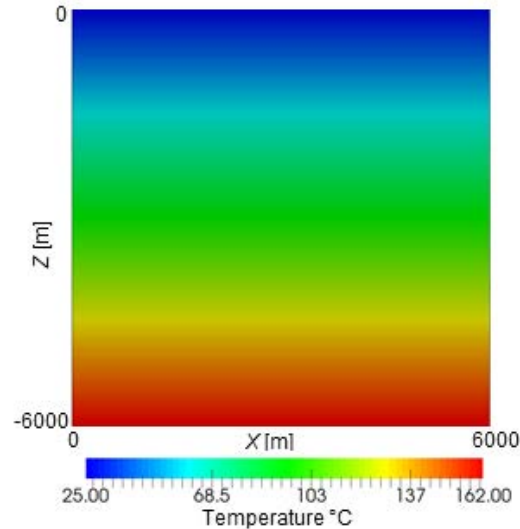
Layer	Major rock type (geologic time)	Total depth of layer [m]	Log( $k_x$ ) [ $m^2$ ]			Anisotropy [ $k_x/k_z$ ]	Effective Porosity
			Case 1	Case 2	Case 3		
Layer 1	Fluvial sediments (Upper Tertiary – Quaternary)	950	-12	-12	-12	100	0.3
Layer 2	Lava flow and ash flow (Lower Tertiary)	880	-13	-15	-12.5	1	0.15
Layer 3	Sandstone, shale, and conglomerate (Cretaceous)	2000	-14.5	-16	-13	1	0.25
Layer 4	Sandstone, shale, and conglomerate (Triassic–Jurassic)	270	-15	-17	-13.5	1	0.25
Layer 5	Mudstone, sandstone, and siltstone (Permian)	240	-15.5	-15	-14	1	0.25
Layer 6	Limestone, shale and dolomite (Pennsylvanian)	700	-16	-11	-14.5	1	0.2
Layer 7	Limestone and shale (Devonian–Mississippian)	260	-16.5	-12	-15	1	0.2
Layer 8	Limestone and dolomite (Cambrian–Silurian)	400	-17	-13	-15.5	1	0.2
Layer 9	Granite and metamorphic rocks (Precambrian).	300	-18	-15	-16	1	0.05

**Representative values from Freeze & Cherry, 1979; Pepin et al., 2015**



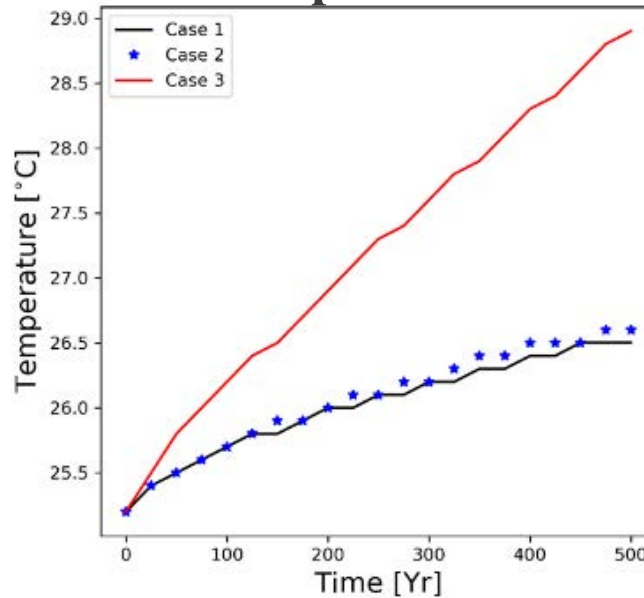
# Preliminary modeling result on evolution of temperature

## Initial temperature profile



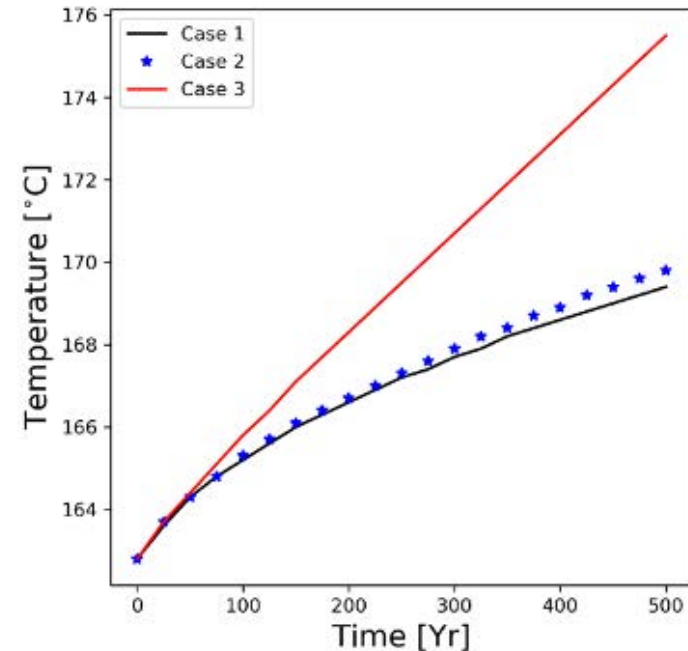
Assuming  
uniform  
geothermal  
gradient of  
 $23^{\circ}\text{C}/\text{km}$

## Temperature evolution at top surface



- Case 1 (low-permeability case)
- Case 2 (high-permeability at depth case)
- Case 3 (permeability gradually decreases with depth)

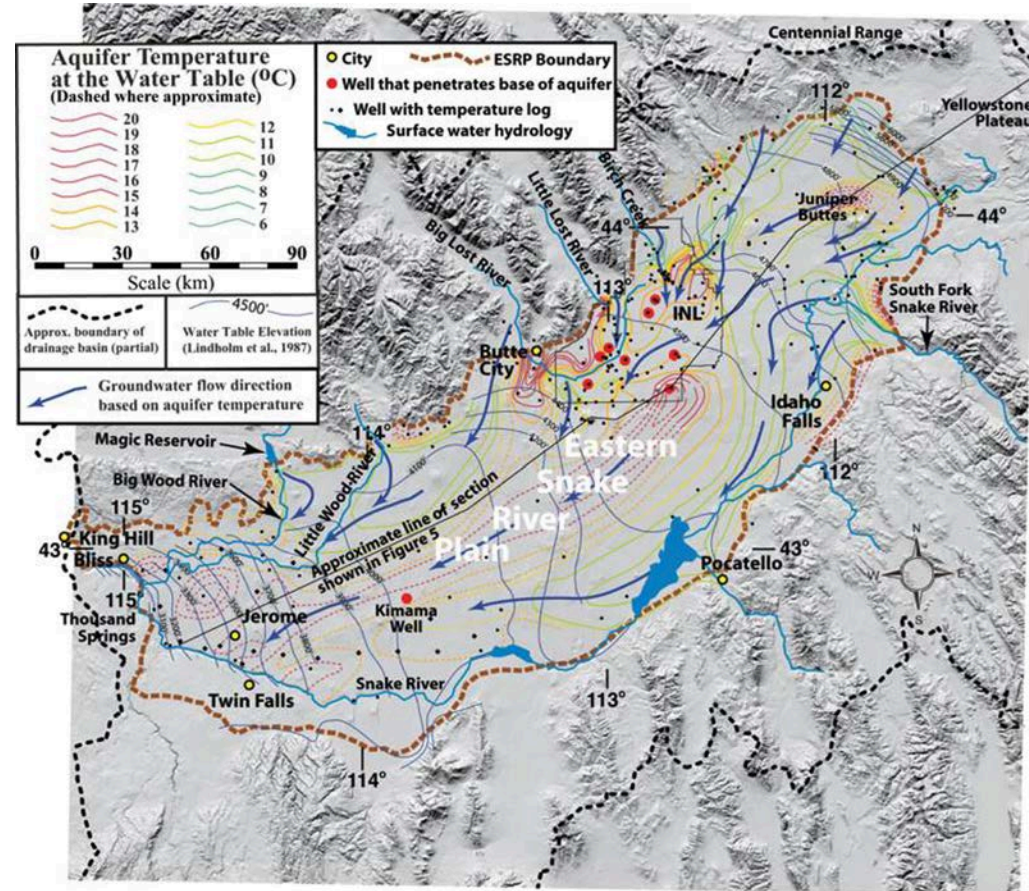
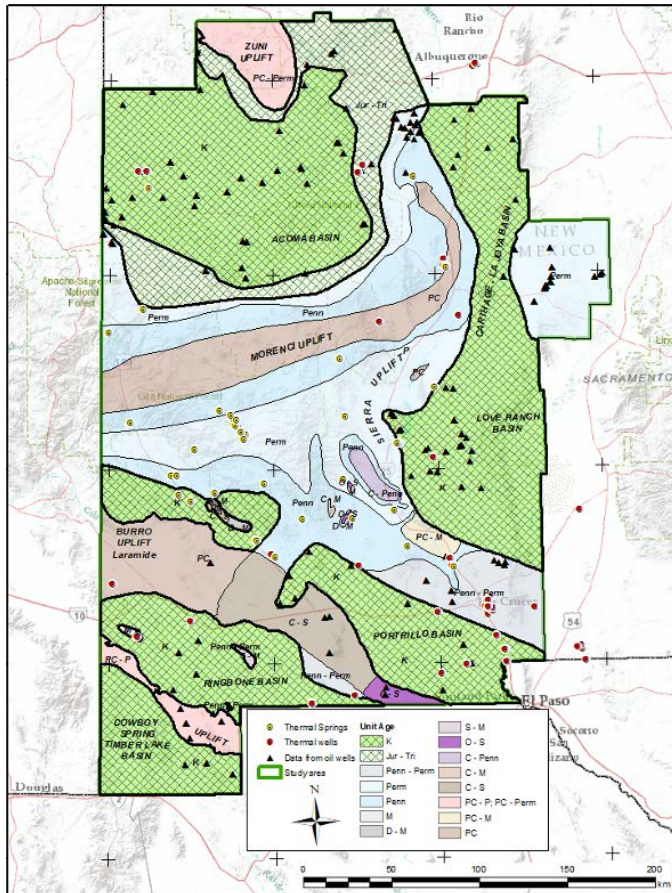
## Temperature evolution at bottom surface



# Conclusions

- **We presented a preliminary conceptual and numerical model to simulate coupled thermal-hydrologic-chemical processes**
- **We performed high-fidelity numerical simulations for different types of geological settings (impacting the vertical permeability profile)**
- **Enhanced permeability in the geological layers provides a means for improved energy transfer from the rock to fluid**
- **This preliminary modeling work showed that manipulating permeability to reasonable values is key to improving energy extraction from a site-scale reservoir**
- **The developed models will be applied to assimilate existing observational data to infer reservoir flow properties and their uncertainties**
- **These models will be also applied to estimate the risk associated with geothermal exploration.**

# Path forward: Improving conceptual models and machine learning analysis



- **ML-based data assimilation:** Site-scale and regional-scale models of Southwest New Mexico

- **Machine learning models** for evaluating geothermal heat flow in East Snake River Plan (ESRP), Basin and Range Province

# Summary: Machine learning (ML) model development for EGS and geothermal exploration

