

# GeoThermalCloud:

## Cloud Fusion of Big Data and Multi-Physics Models using Machine Learning for Discovery, Exploration, and Development of Hidden Geothermal Resources

May 2024

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U.S. DEPARTMENT  
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Pacific Northwest National Laboratory  
Richland, Washington 99354

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# Executive Summary

The primary goals of this project are exploring hidden geothermal resources in the U.S.A. and designing profitable enhanced geothermal systems (EGS). Many processes and parameters control geothermal exploration and energy production from geothermal fields. Diverse datasets (e.g., geology, geochemistry, geophysics, satellite, airborne geophysics) are available to help characterize subsurface geothermal conditions. Sparse and multi-scale characteristics of these datasets prohibit properly leveraging these datasets for geothermal exploration and profitable EGS design. Recent advancements in machine learning (ML) promise to resolve these issues. The tremendous challenges and risks of geothermal exploration and production bring the demand for novel ML methods and tools that can (1) analyze large field datasets, (2) assimilate model simulations (large inputs and outputs), (3) process sparse datasets, (4) perform transfer learning (between sites with different exploratory levels), (5) extract hidden geothermal signatures in the field and simulation data, (6) label geothermal resources and processes, (7) identify high-value data acquisition targets, and (8) guide geothermal exploration and production by selecting optimal exploration, production, and drilling strategies.

To address these necessities, ML-based geothermal resources exploration and enhanced geothermal systems (EGS) design tools have been developed. The exploration tool is called **GeoThermalCloud** and EGS design tool is called **GeoDT-ML**. **GeoThermalCloud** (<https://github.com/SmartTensors/GeoThermalCloud.jl>) utilizes a LANL unsupervised ML platform called SmartTensors (<https://tensors.lanl.gov/>) to automate data analyses and interpretations by extracting hidden signatures to identify geothermal prospects. Also, it enables the identification of critical measurements needed to identify geothermal resource signatures. Alternatively,

**GeoDT-ML** (<https://github.com/SmartTensors/GeoThermalCloud.jl/tree/master/EGS>) is an ML-based alternative to GeoDT (<https://github.com/GeoDesignTool/GeoDT.git>), a fast, simplified multi-physics solver to evaluate EGS project designs in uncertain geologic systems. **GeoDT-ML** leverages recent advances in deep learning and high-performance computing. It is a faster and simpler version of GeoDT. To make this project a success, we used capabilities of LANL, PNNL, Google, Stanford, and Julia Computing.

We analyzed eight datasets of the U.S.A. using **GeoThermalCloud** and demonstrated potential highly prospective geothermal resources and identified key factors defining highly prospective sites. The **first** data set includes 44 locations in southwest New Mexico and 18 geological, hydrogeological, geophysical, geothermal, geochemical attributes. We defined low- and medium-temperature hydrothermal systems and discovered a new highly prospective site. The **second** data set analyzed 18 shallow water chemistry attributes at 14,342 locations in the Great Basin. It demarcated modestly, moderately, and highly prospective sites including key attributes for each type of prospectivity. The **third** data set analyzed Utah FORGE data including satellite (InSAR), geophysical (gravity, seismic), geochemical, and geothermal attributes. Here, we performed prospectivity analysis to identify future drilling locations using geological, geochemical, and geophysical attributes. Maps of temperature at depth and heat flow are constructed based on the available data. Prospectivity maps were generated, and drilling locations were proposed for future geothermal field exploration. The **fourth** data set analyzed 21 attributes at 120 locations in Tularosa Basin, New Mexico; data comes from past play fairway analyses in this region. ML analyses identified geothermal signatures associated with modestly, moderately, and highly

hydrothermal systems. We also defined dominant attributes and spatial distribution of the geothermal signatures. The **fifth, sixth, seventh, and eighth** datasets include Tohatchi Springs, New Mexico, Hawaii, Brady site, Nevada, and EGS Collab, respectively.

Moreover, we coupled ***GeothermalCloud*** and magnetotellurics data to pinpoint drilling locations for developing geothermal projects in the Tularosa Basin, New Mexico. ***GeothermalCloud*** found potential prospective locations for geothermal resources near White Sands Missile Range and McGregor Range at Fort Bliss. Magnetotellurics data determined the potential depth (~1800m) of geothermal prospects at McGregor Range based on apparent resistivity structures/layers in the subsurface. The McGregor Range consists of three resistivity layers and two resistivity structures. Magnetotellurics data also helps identify that the western portion of the McGregor Range has thick and low-resistivity earth materials. The low resistivity to the west is most likely for a fault system. Assuming temperature is consistent with a geothermal reservoir, the west-central part of the McGregor Range has the highest geothermal potential because of the increase in porosity and associated permeability attributed to the interpreted fault system.

Also, we devised a coupling strategy between a process model and ***GeothermalCloud*** to characterize hydrogeological conditions and geothermal conditions, respectively. The process model characterizes hydrogeological and geothermal conditions on highly prospective geothermal sites provided by ***GeothermalCloud***. We developed a physics-informed neural network (PINN) version of the Burns equation that can be easily coupled with ***GeothermalCloud***.

Furthermore, we performed an optimal design decision maximizing the economic value of an EGS power plant. This study optimized the range of well spacing between injection and production wells maximizing net present value in dollars (NPV). For this task, we used the GeoDT to simulate the Utah FORGE EGS development cycle from the initial well design to the end of production.

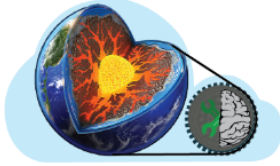
Next, we accomplished another crucial task, which is predicting permeability of geothermal reservoirs. Predicting permeability of geothermal reservoirs is a non-trivial task because of huge computational runtime of simulation and lack of measurements. To avoid these limitations, we used easy-to-measure chemical concentrations in the subsurface as measurement data and convolutional neural network based ML model of a high-fidelity model. Next, we predicted permeability using Markov chain Monte Carlo simulation. We found that Markov chain Monte Carlo simulation predicts permeability with a high certainty if the prediction zone in the simulation area has chemical concentration data.

Finally, we analyzed the DOE funded INGENIOUS and GeoDAWN projects data. For discovering hidden geothermal systems in the Great Basin, the INGENIOUS project accumulated old data, collected new data, and released them in 2022. The dataset includes a total of 24 geological, geophysical, and geochemical attributes. Data resolution and scale significantly vary prohibiting an appropriate usage. To avoid such limitations, we brought all data in the same resolution and scale by applying the inverse distance weighting interpolation technique for predicting data in unsampled locations. Subsequently, we analyzed LiDAR data of the GeoDAWN project. We received data in tiles format. The DOE's overarching goal is to use ML on LiDAR data for finding favorable geological structures (e.g., step up faults in Brady, Nevada). To serve the purpose, we need to label favorable geologic structures that correspond to LiDAR data. We wrote an algorithm to label the LiDAR data with the favorable geologic structures.

# GeoThermalCloud: A Machine Learning Framework for Geothermal Resources Exploration

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GeoThermalCloud



<https://github.com/SmartTensors/GeoThermalCloud.jl>

## Chapter 1: GeoThermalCloud and Its Usage

### GeoThermalCloud

#### Introduction

The project is motivated by the challenges, risks, and costs associated with geothermal exploration and production<sup>1</sup>. Many processes and parameters impacting geothermal conditions are poorly understood. Diverse datasets are available to help characterize subsurface geothermal conditions (public and proprietary; satellite, airborne surveys, vegetation/water sampling, geological, geophysical, etc.). Yet, it is unclear how to properly leverage these datasets for geothermal exploration due to an incomplete understanding of how physical processes impacting subsurface geothermal conditions are represented in these observations. Recent advancements in machine learning (ML) promise to resolve these issues<sup>1</sup>.

The tremendous challenges and risks of geothermal exploration and production bring the demand for novel ML methods and tools that can (1) analyze large field datasets, (2) assimilate model simulations (large inputs and outputs), (3) process sparse datasets, (4) perform transfer learning (between sites with different exploratory levels), (5) extract hidden geothermal signatures in the field and simulation data, (6) label geothermal resources and processes, (7) identify high-value data acquisition targets, and (8) guide geothermal exploration and production by selecting optimal exploration, production, and drilling strategies<sup>2</sup>. Our goals and work under Phases 1 and 2 (as proposed) of this project address all these needs.

Under Phase I&II, we have developed ***GeoThermalCloud*** and ***GeoDT-ML***. ***GeoThermalCloud*** is an unsupervised ML-based tool to discover and extract new (unknown/hidden) geothermal signatures in existing site, synthetic, and regional datasets. Our ML analyses also identified high-value data acquisition strategies that can reduce geothermal exploration/production costs and risks. Moreover, ***GeoThermalCloud*** categorized geothermal data, which is applied to generate geothermal data labels (e.g., geothermal resource types). ***GeoThermalCloud*** allows for the treatment of both public and proprietary datasets. This is an essential feature considering the high sensitivities associated with using proprietary data. Moreover, the ***GeoThermalCloud*** framework includes a series

of advanced pre-processing, post-processing, and visualization tools, which tremendously simplify its application for real-world problems. These tools make the ML results understandable and visible even for non-experts. Thus subject-matter expertise is not a critical requirement during the training phase of the *GeoThermalCloud* framework; however, their opinions are useful for verifying the outputs.

*GeoDT-ML* is an enhanced geothermal system (EGS) prospecting tool. It is an ML version of GeoDT<sup>3-6</sup>. GeoDT is a very fast modeling tool to run thousands of realization tweaking reservoir, drilling, and geothermal plant parameters. The main mechanism is to use *GeoThermalCloud* for geothermal resources exploration to find favorable geothermal locations and then use *GeoDT-ML* for exploring EGS prospectivity. Figs 1.1.1 and 1.1.2 demonstrate the schematics of *GeoThermalCloud* and *GeoDT-ML*, respectively.

We have used *GeoThermalCloud* on ten geothermal datasets. Eight datasets include site/real data, including a large and sparse dataset of the Great Basin, and two datasets are synthetic data. The analyses found critical information that could not be found using supervised ML or exploratory statistical analyses. Most of the data and analyses are available on GitHub as well. Obtained results can be reproduced and further expanded by adding additional data. Practitioners and researchers are welcome to utilize *GeoThermalCloud* to solve other geothermal problems. *GeoDT-ML* can be used for studying FORGE EGS prospectivity.

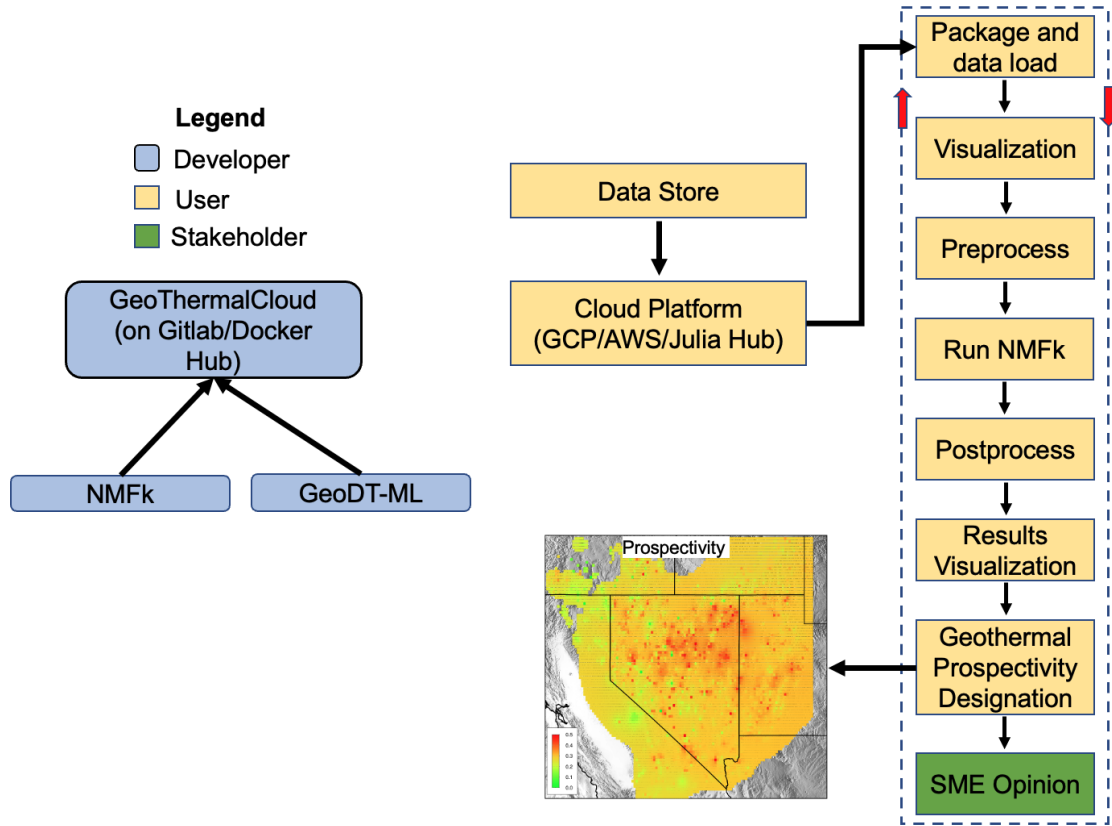
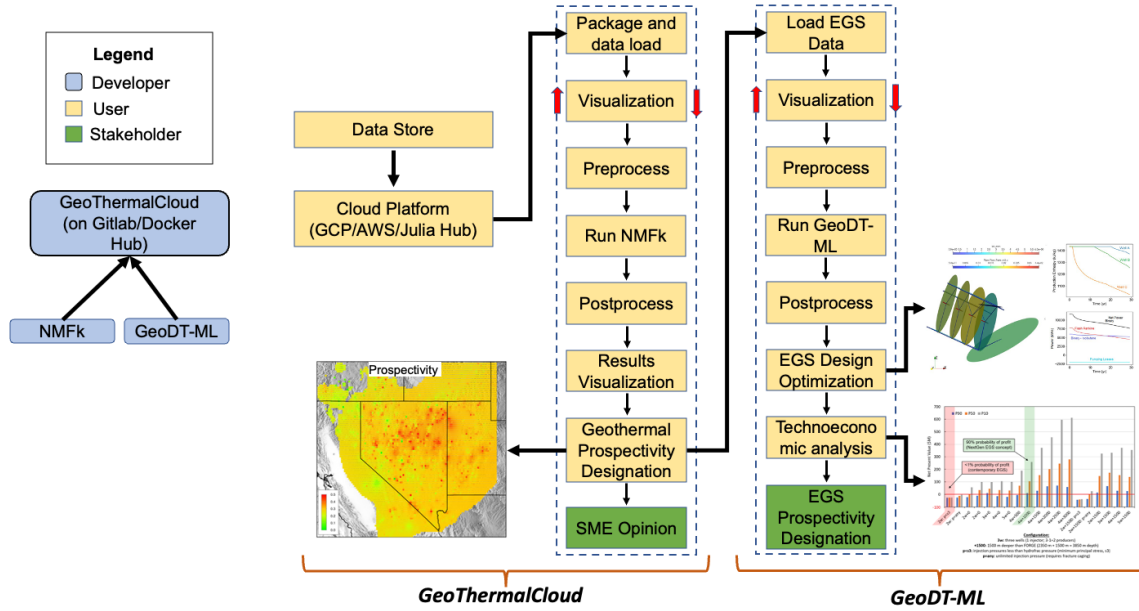


Fig.

1.1.1: Specific components of developers, users, and subject matter experts in the *GeoThermalCloud* platform.



**Fig. 1.1.2: Specific components of developers, users, and subject matter experts in the *GeoThermalCloud* and *GeoDT-ML* platforms.**

## Capabilities

GeoThermalCloud capabilities include (1) analyzing large field datasets, (2) assimilating model simulations (large inputs and outputs), (3) processing sparse datasets, (4) performing transfer learning (between sites with different exploratory levels), (5) extracting hidden geothermal signatures in the field and simulation data, (6) labeling geothermal resources and processes, (7) identifying high-value data acquisition targets, and (8) guiding geothermal exploration and production by selecting optimal exploration, production, and drilling strategies. The GeoThermalCloud is an open-source tool available at <https://github.com/SmartTensors/GeoThermalCloud.jl> (a part of our SmartTensors framework; <http://tensors.lanl.gov>, <https://github.com/SmartTensors>)<sup>2</sup> and its counterpart docker image is <https://hub.docker.com/r/bulbulahmmed/geothermalcloud-v1>.

## Methods

ML methods, in general, can be subdivided into three categories: supervised, physics-informed, and unsupervised. The supervised methods require attributes and corresponding labels of the analyzed data<sup>7</sup>. The labeling should be done by subject-matter experts who can identify, for example, locations with high-, intermediate-, and low-temperature geothermal prospectivity or specific geologic features such as fault offsets. The supervised methods are then applied to learn geothermal prospectivity based on the available data. However, the successful training of supervised methods requires large, continuous (without data gaps), non-noisy (with small measurement errors) training datasets that are typically not available for geothermal exploration. In essence, the supervised methods cannot discover something that is not already known and provided as labels in the training dataset. The supervised methods are highly efficient to process large datasets and find out how the processed data can be categorized. For example, they can be trained to recognize images of cats and dogs;



however, they will not recognize horses if they have not been trained already to identify them. Furthermore, the supervised ML methods are sensitive to noise in the analyzed data or the so-called “adversarial examples”<sup>8</sup> where small random noise, undetectable for the human eye, can fool the detection capabilities of these methods. All of these features make the application of supervised ML methods challenging for real-world science applications. Commonly used supervised methods include deep neural networks<sup>6,9</sup>, convolutional neural networks<sup>10</sup>, recurrent neural networks<sup>11</sup>, and random forest<sup>12</sup>.

Physics-informed ML (PIML) methods also learn from data as the supervised methods do, but they also include preconceived science knowledge through equations and models representing physics laws, constitutive relationships, and processes. Physics information can be (1) directly embedded in the ML framework<sup>13</sup> or (2) added as penalties in the ML loss minimization process<sup>14</sup>. However, the physics-informed neural networks (PINN) are problem specific and not general like the traditional supervised deep neural networks. Therefore, the construction PINN needs subject-matter expertise related to the analyzed problem. Still, PIML analyses have better efficiency, accuracy, and robustness compared to the traditional ML analyses. In contrast, the unsupervised ML techniques extract information from existing datasets without any prior labeling or subject-matter preprocessing. The unsupervised ML is applicable to discover unknown features and unmix mixed signals present in the processed data.

**GeoThermalCloud** utilizes our novel, open-source, LANL-developed, patented ML methods and computational tools. All these methods are distributed as **SmartTensors** (<http://tensors.lanl.gov>, <https://github.com/SmartTensors>). **SmartTensors** is a toolbox for unsupervised and physics-informed ML based on matrix/tensor factorization constrained by penalties enforcing robustness and interpretability (e.g., nonnegativity; physics and mathematical constraints; etc.). **SmartTensors** has already been successfully applied to analyze diverse datasets related to a wide range of problems, from COVID-19<sup>15</sup> to wildfires and text mining. Also, the **SmartTensors** framework can handle big data and has already been demonstrated to perform tens of TBs of data using DOE supercomputers.

The two most commonly used ML algorithms in **SmartTensors** are nonnegative matrix/tensor factorization methods coupled with customized  $k$ -means clustering (NMF $k$  and NTF $k$ ). They perform nonnegative matrix/tensor factorization coupled with customized  $k$ -means clustering<sup>1,16</sup>. NMF $k$  and NTF $k$  are capable of identifying (i) the optimal number of hidden signatures in data, (ii) the dominant set of attributes in data that correspond to identified hidden signatures, and (iii) locations associated with each hidden signature.

All datasets are formed by directly observable quantities, while the underlying processes or data signatures usually remain unseen, hidden, or latent<sup>16</sup>. These hidden signatures (or features/signals) can be either impossible to measure directly or are simply unknown. For example, let us assume that a series of microphones are placed in a noisy ballroom where many people are talking. The collected data records the mixtures of voices, sounds, and noises. The latent signatures are the individual voices that cannot be recorded separately but can be extracted from the collected data. Extracting latent signatures reduces the dimensionality of the data and defines low-dimensional subspaces<sup>17</sup> that represent the entire dataset. After the extraction, the obtained information is post-processed by subject-matter experts to identify the physical meaning or the origin of the extracted signatures.



Similarly, our unsupervised ML techniques have been applied here to extract latent signatures and hidden (mixed) physical processes embedded in large, diverse geothermal datasets. Hidden (latent) signatures provide a low-dimensional and compressed representation of the processed dataset. They can also be viewed as basis vectors providing optimal data projection. In the case of geothermal applications, these signatures typically represent information about a series of physical processes that occur in observable and/or simulated datasets. These signatures can be multi-dimensional capturing processes occurring in spatiotemporal space and captured by a set of diverse attributes. Geothermal attributes we have processed in this report include temperature, gradients, geothermometers, conductivity, permeability, fluxes, fracture densities, in-situ stresses, etc.

To discover hidden signatures and their optimal number in large geothermal datasets, NMF $k$  and NTF $k$  are at the forefront among various unsupervised ML methods such as nonnegative matrix factorization (NMF)<sup>17</sup>, principal component analysis (PCA)<sup>18</sup>, independent component analysis (ICA)<sup>19</sup>, singular value decomposition (SVD)<sup>20</sup>, nonnegative tensor factorization (NTF)<sup>21</sup>, and Gaussian process/mixture modeling<sup>22</sup>. In contrast, with traditional NMF<sup>17</sup>, NMF $k$  allows for automatic identification of the optimal number of signatures (features) present in the data<sup>1,2,23</sup>. The nonnegativity constraint makes the decomposed matrices easier to interpret than PCA, SVD, and ICA because the extracted signatures are additive. Moreover, NMF $k$  and NTF $k$  can handle huge (TBs), real, categorical, and missing data. Dealing with missing data is challenging or impossible for other supervised and unsupervised ML methods. Even more importantly, the missing data (some or all of it) can be reconstructed from available data using the obtained NMF $k$  and NTF $k$  results. Our ML methods also provide estimates of uncertainties associated with the estimated missing data. All of these features of our ML methods make them very suitable for geothermal ML analyses.

### Nonnegative matrix/tensor factorization

Detailed descriptions of our novel NMF $k$  and NTF $k$  algorithms are provided in our papers<sup>1,16</sup>. Here, we give just a high-level description of the NMF $k$  and NTF $k$  methodologies to support the discussion of geothermal analyses in this report. NMF $k$  performs matrix factorization of a data matrix,  $X_{m \times n}$ , where the  $m$  rows represent measurement locations, and the  $n$  columns are the values of the geothermal attributes. The goal of NMF $k$  is to find the optimal number of signatures  $k$  that describe the analyzed dataset. This is accomplished by matrix factorization, which can be represented as using:

$$X \cong W \times H \quad (1.1)$$

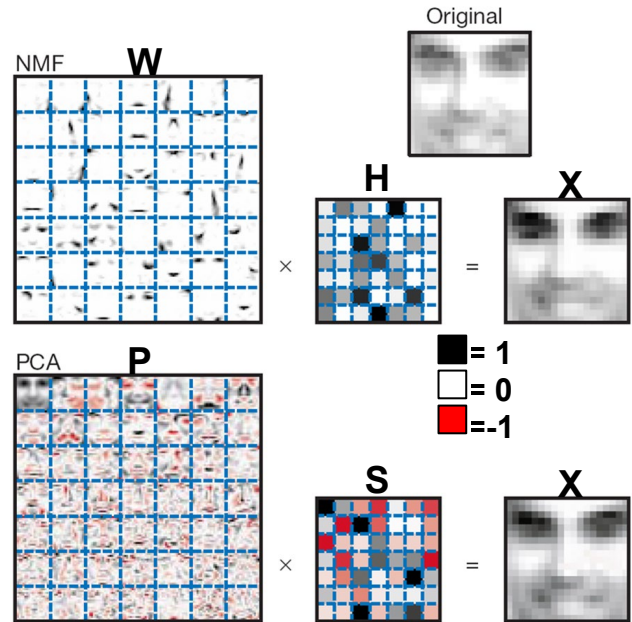
where  $W_{m \times k}$  is an “attribute” matrix characterizing the significance of attributes and  $H_{k \times n}$  a “location” matrix captures the importance of locations and their spatial association. It is important to note that all the elements of matrices  $W$  and  $H$  are unknown. The number of signatures  $k$  is also unknown. The matrix factorization in (1) provides an approximate representation of the data  $X$ . To solve for all the unknowns, NMF $k$  performs a series of matrix factorization with random initial guesses for  $W$  and  $H$  elements and for a range of values of  $k$ ; theoretically,  $k$  can range between 2 and  $\min(m, n)$ . For a given number of signatures  $k$ , Equation 1 is solved iteratively by minimizing the reconstruction error  $O(k)$ :

$$O(k) = ||X - W \times H||_F \quad (1.2)$$

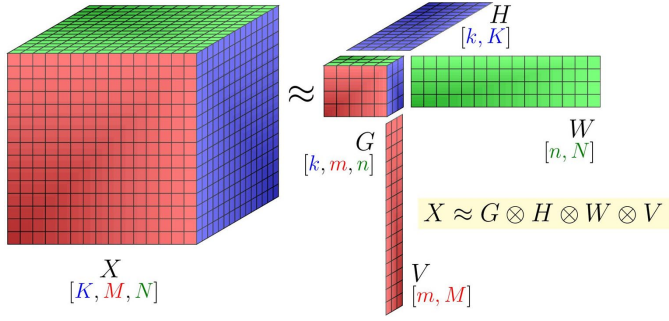
by constraining the  $W$  and  $H$  elements to be greater or equal to zero (nonnegative), and  $F$  defines the Frobenius norm<sup>24</sup>. Under the NMFk algorithm, NMF is executed numerous times (typically 1,000), which generates a series of solutions for  $W$  and  $H$  matrices for a given  $k$  value. The resulting multiple  $H$  solutions are clustered into  $k$  clusters using a customized  $k$ -means clustering<sup>1,16</sup>. The average silhouette width  $S(k)$  based on cosine norm is computed for all  $k$  clusters. This metric measures how well the random NMF solutions are clustered for a given value of  $k$ . The values of  $S(k)$  theoretically can vary from -1 to 1.

These operations are repeated for a series of  $k$  values. The optimal number of signatures,  $k$ , is estimated on how the reconstruction error  $O(k)$  and the average silhouette width  $S(k)$  vary with the increase of  $k$ . The reconstruction error decreases as  $k$  increases. The average silhouette width behavior is more complicated;  $S(k)$  generally declines as  $k$  increases from 1 to -1. However,  $S(k)$  values frequently spike up for specific  $k$  values, indicating that these  $k$  values are potentially optimal. In an ideal case, a given  $k$  value is considered optimal when adding another signature does not significantly improve the reconstruction of  $X$  (i.e., lower  $O(k)$ ) and does not lower  $S(k)$ . In practice, a solution with  $S(k)$  greater than 0.5 and the lowest  $O(k)$  value can be chosen as an optimal solution. The solutions with  $k$  values less than the optimal value and  $S(k)$  values  $> 0.5$  are acceptable; they provide underfitting representations of the data matrix  $X$ . All the solutions with  $k$  values greater than the optimal value are not acceptable; they provide overfitting representations of the data matrix  $X$ .

We listed the benefits of NMFk over similar unsupervised ML tools above. PCA is the closest similar tool to NMFk. PCA factorizes the data matrix  $X$  into score (S) and principal component (P) matrices. The factorization can be represented as:



**Fig. 1.1.3: ML of faces using NMF and PCA. Nonnegativity constraint provides additive, sparse and interpretable results where facies features such as eyes and noses are well defined. Interpretation of PCA results is challenging (after Lee & Seung, 1999).**



**g. 1.1.4: Example factorization of a data tensor  $X$  into**

$$X \cong SP \quad (1.3)$$

$S$  is a diagonal matrix. As in NMF, Equation 3 is solved iteratively by minimizing the following function:

$$L = \| |X - SP| \|_F \quad (1.4)$$

PCA searches for linear combinations in the data by projecting each data point onto an optimal set of principal components (PCs) to obtain a low-dimensional representation of data while preserving maximum data variation. PCs are ordered by the magnitude of data variance as captured by the  $S$  diagonal elements.

Even though NMF and PCA are mathematically similar, the ML results obtained by both methods are very different. For instance, both NMF and PCA can reconstruct human faces very well (Fig. 1.1.3). Both methods extracted 49 basic facial features (can also be called dictionaries, basis vectors, or eigenvectors; the matrices on the left) needed to reconstruct the entire training set of  $\sim 1,000$  faces (i.e., both methods performed data dimensionality reduction from  $\sim 1,000$  to 49). However, the nonnegativity constraints provide additive, sparse, and interpretable results where facial features such as eyes and noses are well defined (Fig. 1.1.3;  $W$  matrix; top left). NMF face reconstruction is obtained by adding a series of dominant features shown as black squares in the  $H$  matrix. In contrast, the interpretation of PCA results is challenging. The first face (upper left corner of matrix  $P$ ) is the average face of the training set, and the reconstruction of face  $X$  is obtained by adding and subtracting a series of facies features (in  $P$ ) based on the weights (in  $S$ ; red defines negative values or feature subtraction; black represents positive values or feature addition).

In addition to matrices, our ML methods can process multi-dimensional datasets, i.e., tensors. Most of the geothermal data are multi-dimensional. The data indices can be space coordinates and time for each spatiotemporal location, and there might be numerous observables coming from different data sources (streams). Similarly, geothermal model outputs are multi-dimensional. There is a limited number of ML methods that can process multi-dimensional datasets, and our novel nonnegative tensor factorization method coupled with k-means clustering (NTFk) is at the forefront. The factorization process converts a data tensor (labeled as  $X$  in Fig. 1.1.4) into a smaller core tensor (labeled as  $G$  in Fig. 1.1.4) and three matrix factors for each dimension (labeled as  $H$ ,  $W$ , and  $V$  in Fig. 1.1.4). Matrix factors represent signatures in different dimensions. In the example presented in Fig. 1.1.4,  $H$ ,  $W$  and  $V$  contain

5, 4, and 3 signatures, respectively.  $\mathbf{G}$  defines how these signatures occurring in different dimensions are mixed to reproduce the original data tensor. The tensor factorization is again achieved through solving a minimization problem and the estimation of the optimal number of signatures in each dimension is performed using customized  $k$ -means clustering<sup>21,25</sup>.

### Inverse Distance Weighting

We performed IDW interpolation to determine attributes at unknown locations using highly variable data. IDW is efficient, intuitive, and provides relatively accurate data for a large number of points. The output value of an unknown location is attributed to the sample points located near it. Sample points, within a specified radius, have a greater “weight” associated with them making points that are closer to one another are more alike than those that are far apart<sup>26,27</sup>. Since the weights of the sample points are proportional to the inverse of the distance raised to a power value  $p$ , as the distance from an unknown point increases, the weight decreases quickly<sup>26,27</sup>. The formula of IDW is given by:

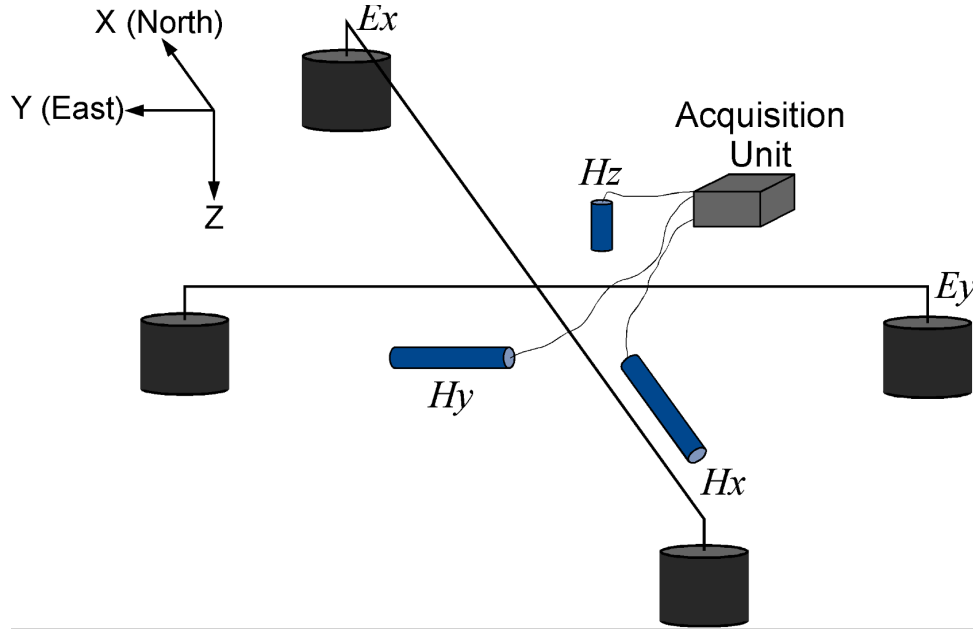
$$z_p = \frac{\sum_{i=1}^n \left( \frac{z_i}{d_i^p} \right)}{\sum_{i=1}^n \left( \frac{1}{d_i^p} \right)} \quad (1.5)$$

where  $z_p$  is the value of the unknown point,  $z_i$  is the value of the known point,  $d_i^p$  is the distance to the known point, and  $n$  is a fixed number of closest points.

### Magnetotellurics (MT)

MT is a passive geophysical technique used for measuring electrical resistivity structures in the subsurface<sup>28–31</sup>. Solar winds and lightning from thunderstorms cause natural variations in the earth’s magnetic field that penetrate the subsurface and induce an electrical current<sup>29</sup>. The electromagnetic fields (EM) from an MT survey are recorded at frequencies generally ranging from 0.001 kHz to 10 kHz<sup>32</sup>. The low-frequency response (<1 Hz) originates from solar winds, and the high-frequency response originates from worldwide lightning strikes<sup>29,32</sup>.

In MT data, a time series of the two components of the electric field ( $E_x$  and  $E_y$ ) and three components of the magnetic field ( $H_x$ ,  $H_y$ , and  $H_z$ ) are measured on the earth’s surface (Fig. 1.1.5). The ratio between the electric and magnetic field components ( $E/H$ ) is called the impedance tensor ( $Z$ ). As a proportion of the electric and magnetic fields are used to compute the impedance tensor. The impedance tensor,  $Z$ , is used to determine the apparent resistivity and phase<sup>29,32</sup>. The following equations use the components of  $Z$  to calculate apparent resistivity and phase. Both apparent resistivity and phase are commonly plotted as a function of frequency for MT data analysis to decipher subsurface structures.



**Fig. 1.1.5:** Schematic of the arrangement and setup of electrodes and coils in the field during MT data acquisition (modified from Grimm et al., 2021<sup>33</sup>).

### Burns' Analytical Equation

While NMFk is effective for defining potential geothermal resources and identifying their spatial location, for small site data, regional geothermal and hydrogeologic estimates are required for developing geothermal fields. Regional conditions dictate the sustainability of geothermal fields. For instance, information on the advective heat flow will provide insight into the sustainability of the heat source to the aquifer. To capture regional hydrogeological and geothermal conditions, Burns, et al., 2015 formulated a 1D analytical solution, which evaluates geothermal and hydrogeologic controls on regional groundwater temperature distribution  $T(s)$  (Burns, et al., 2015<sup>34</sup>; Eq. 39).

$$T(s) = [T_{LS}^0 + \Delta T_{geothermal} + \Delta T_{viscous}] + [T_0 - T_{LS}^0 - \Delta T_{geothermal} - \Delta T_{viscous}]e^{f_0 s} \quad (6)$$

where  $T(s)$  is temperature at space  $s$ ,  $T_{LS}^0$  is temperature at land surface at  $s = 0$ ,  $T_0$  is the temperature at  $s = 0$  where groundwater flows into domain,  $\Delta T_{geothermal}$  is the change in temperature across the vadose zone required to conduct the heat flow entering the aquifer at the basement,  $\Delta T_{viscous}$  is the change in temperature across the vadose zone to conduct the viscous heat generated, and  $f_0$  is a function of aquifer width and volumetric flux.

Input parameters in Burns equation include land surface temperature, groundwater flux, hydraulic head, vadose thermal conductivity, depth to water, and basal heat flux. The outputs include aquifer temperature, viscous heat flux, vadose heat flux, and advective heat flux that assist quantify components of heat flux that contribute to aquifer temperature. GeoThermalCloud includes both analytical solution and equivalent neural network based ML models.

## Performance Metrics

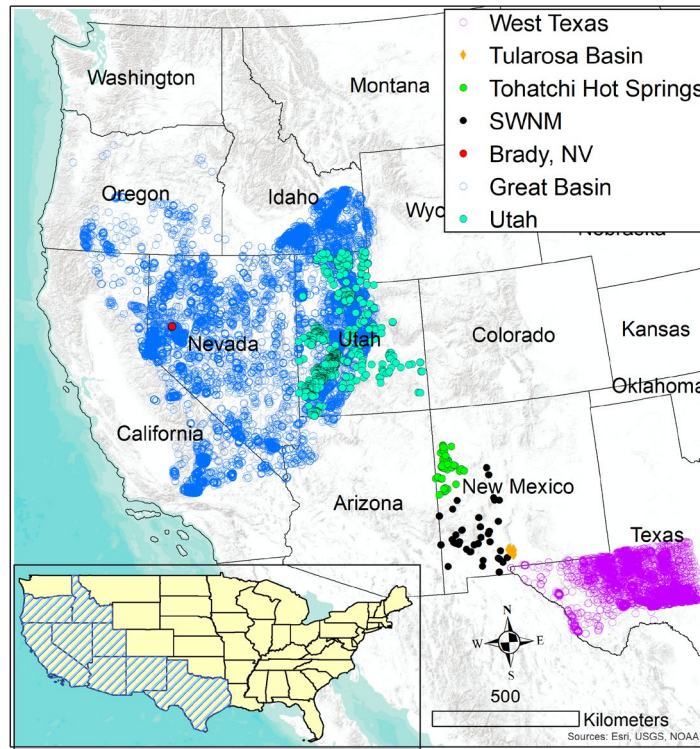
Besides reconstruction error and silhouette width, we also used  $R^2$  to determine the accuracy of prediction.

$$R^2 = 1 - \frac{\sum_{i=1}^n (\hat{y}_i - y_i)^2}{\sum_{i=1}^n (y_i - \bar{y})^2} \quad (1.7)$$

where  $n$ ,  $y_i$ ,  $\hat{y}_i$ , and  $\bar{y}$  represent the number of data points, actual data, predicted data, and mean of data, respectively.

## Case Studies

ML methods embedded in the **GeoThermalCloud** have been extensively tested and validated against various datasets (Fig. 1.1.6)<sup>2,35</sup>. Outputs of these applications have been published in presentations, conference papers, and peer-reviewed papers. The analyzed ML applications are



**Fig. 1.1.6: Locations of seven out of 8 analyzed site datasets by the GeoThermalCloud framework. The other site dataset is in Hawaii, not shown here.**

1. **Great Basin:** In this dataset, we analyzed 18 shallow water chemistry attributes at 14,342 locations. This work extracted hidden geothermal signatures associated with low-, medium-, and high-temperature hydrothermal systems, their dominant characterization attributes, and spatial distribution within the study area<sup>36</sup>. The analyses are based on the public data available on the Nevada Bureau of Mines and Geology website.



2. **Southwest New Mexico (SWNM):** Here, we analyzed 18 attributes at 44 locations and identified low- and medium-temperature hydrothermal systems; found dominant attributes and spatial distribution of extracted hidden hydrothermal signatures; demonstrated blind predictions of the regional physiographic provinces<sup>1</sup>.
3. **Brady site, Nevada:** We identified key geologic factors controlling geothermal production in the Brady geothermal field<sup>37</sup>.
4. **Tularosa Basin, New Mexico:** Analyzed 21 Play Fairway Analysis (PFA) attributes at 120 locations<sup>38</sup>; data comes from past PFA work in this region<sup>39</sup>. ML analyses identified geothermal signatures associated with low-, medium-, and high-temperature hydrothermal systems. Dominant attributes and spatial distribution of the geothermal signatures were also defined.
5. **Tohatchi Springs, New Mexico:** Explored 19 geothermal attributes at 43 locations in Tohatchi Springs, New Mexico<sup>40</sup>. Successfully defined geothermal signatures associated with low- and medium-temperature hydrothermal systems. Also, we found their dominant attributes and spatial distribution.
6. **Hawaii:** Analyzed four islands' data separately and jointly; ML identified low-, medium-, and high-temperature hydrothermal systems and their dominant characterization attributes<sup>41</sup>.
7. **Utah FORGE:** Performed prospectivity analysis to identify future drilling locations using geological, geochemical, and geophysical attributes<sup>42</sup>. Maps of temperature at depth and heat flow are constructed based on the available data. Processed data includes satellite (InSAR), geophysical (gravity, seismic), geochemical, and geothermal attributes. Prospectivity maps were generated, and drilling locations were proposed for future geothermal field exploration.
8. **EGS Collab:** Field experiment data processed to extract dominant temporal patterns observed in 49 data streams; erroneous measurement attributes and periods automatically identified; interrelated data streams automatically identified. This work has not been published yet.

## How to Use It?

**GeoThermalCloud** can be used in three ways (i) on Julia, (ii) on Python, and (iii) on a Cloud platform (e.g. JuliaHub, Google Cloud Platform, Amazon Web Services, Azure Cloud Services through Docker). Julia's installation is explained at <https://github.com/SmartTensors/GeoThermalCloud.jl> and also given below.

```
import                                     Pkg
Pkg.add("GeoThermalCloud")
import                                     GeoThermalCloud

GeoThermalCloud.SWNM() # performs analyses of southwest New Mexico
GeoThermalCloud.GreatBasin() # performs analyses of the Great Basin region
GeoThermalCloud.Brady() # performs analyses of the Brady site, Nevada.
```

The Python installation process is described below:

```

$                                     python3
import                               julia
julia.install()
from                                julia      import      Base
from                                julia      import      Main
Main.eval("import Pkg; Pkg.build(\"GeoThermalCloud\")")

```

Docker container development is still in progress. We will provide an update on how to use GeoThermalCloud when it is ready for use.

## Conclusions

**GeoThermalCloud** is an open-source cloud-based ML framework for geothermal exploration that can simultaneously handle both public and proprietary datasets. Also, it consists of a series of advanced pre-processing, post-processing, and visualization tools that tremendously simplify its application for real-world problems. These tools make the ML results understandable and visible even for non-experts; therefore, ML and subject-matter expertise are not critical requirements to use our ML framework. **GeoThermalCloud** utilizes a series of novel LANL-developed patented ML tools called *SmartTensors* (<https://github.com/SmartTensors>). *SmartTensors* has already been applied to solve a wide range of real-world problems, from COVID-19 to wildfires (<http://tenosrs.lanl.gov>), and it has won two 2021 R&D 100 awards, including a bronze award for market disruptor tools. Now, it has two components (i) GeoThermalCloud and (ii) GeoDT-ML.

**GeoThermalCloud** is developed to process and analyze diverse small and large datasets. Also, it can handle sparse datasets with missing values. It analyzes and finds actionable information to enable decision-makers to make sound decisions for geothermal exploration, development, and production. It finds such actionable information by finding mapping functions between all input parameters. We analyzed eight diverse site datasets and found critical information that would not be possible by visual inspection or any other statistical tools. Overall, **GeoThermalCloud** can (1) analyze large field datasets, (2) assimilate model simulations (large inputs and outputs), (3) process sparse datasets, (4) perform transfer learning (between sites with different exploratory levels), (5) extract hidden geothermal signatures in the field and simulation data, (6) label geothermal resources and processes, (7) identify high-value data acquisition targets, and (8) guide geothermal exploration and production by selecting optimal exploration, production, and drilling strategies.

## GeoDT-ML

### Introduction

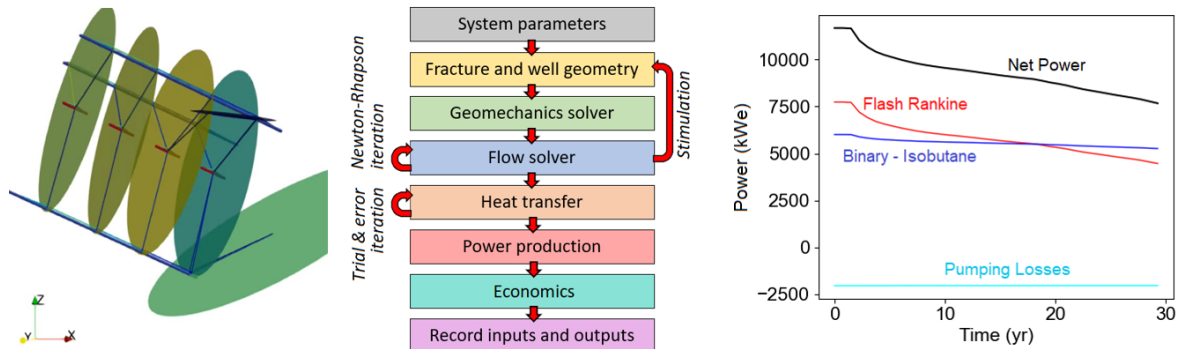
**GeoDT-ML** is an ML-based version of GeoDT, which is a fast, simplified multi-physics solver to evaluate EGS designs in uncertain geologic systems<sup>3,4,6</sup>. It is numerically efficient enough to model thousands of realizations in a few hours using a desktop computer. The underlying assumptions of this model are empirically based on laboratory and field data to partially account for complex coupled processes obviating running expensive numerical simulations. The intent of this model is to run it with full uncertainty, as informed by a broad spectrum of relevant prior laboratory and field measurements, and to reduce the uncertainty



only when suitable information is available. When a promising EGS design is identified, it can be investigated in greater detail and at higher fidelity using other more powerful, but more expensive, numerical modeling codes.

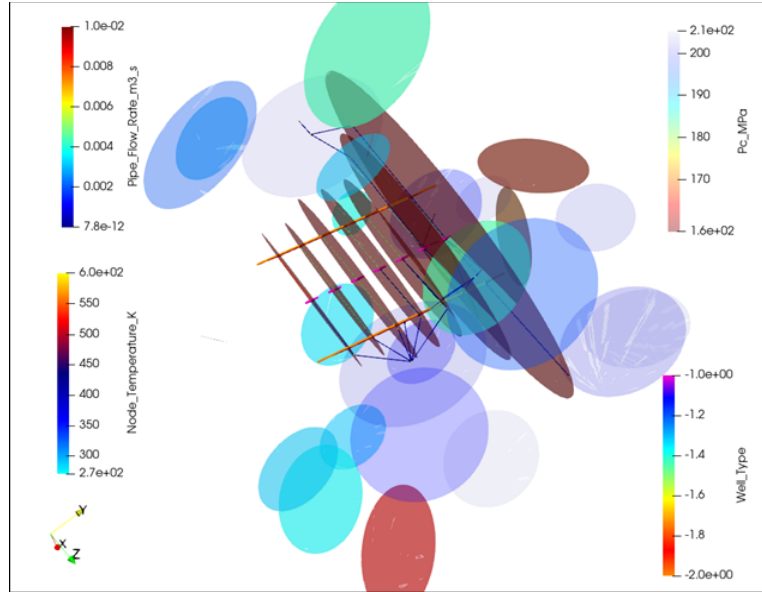
The primary features of **GeoDT-ML** include (Fig. 1.2.1):

1. Pressure and flow rate prediction for 3D networks of intersecting wells and fractures modeled as pipes and nodes.
2. Hydraulic stimulation prediction with shear and tensile mechanisms where fracture apertures depend on effective stress.
3. Transient heat production predictions that depend on fluid enthalpy, rock conductivity, and stored energy change over time.
4. Electrical power generation using the combined single-flash Rankine and isobutane binary cycle.
5. Net present value prediction based on geothermal cost estimation tools, electricity sales, and a simple earthquake cost model.

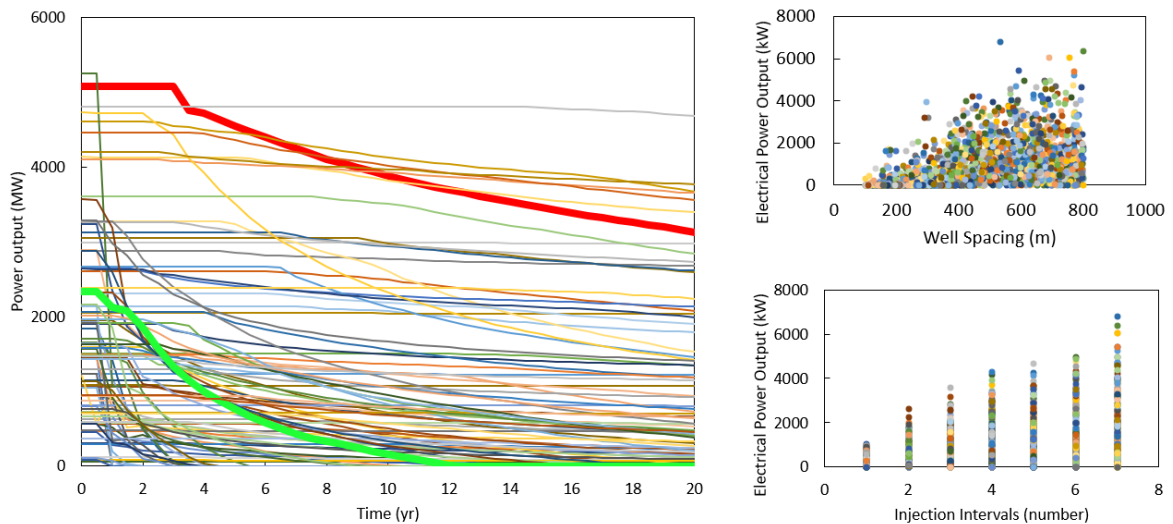


**Fig. 1.2.1: GeoDT or *GeoDT-ML* stochastically predicts reservoir parameters, flow networks, hydraulic stimulation, heat production, power production, injection-induced seismicity potential, and ultimately net present value by fast and simplified methods. Most models complete in ~15 seconds using a common desktop computer with a single processor thread.**

Multiple datasets have been generated using GeoDT for EGS Collab and Utah FORGE site. One was used for the PIVOT 2022 Datathon to simulate the whole geothermal development cycle from the initial well design to the end of production. This dataset includes the Utah FORGE site characteristics and its measured uncertainties. The database includes 44,492 unique realizations, each with at least 30 years of production. Based on site characteristics, fractures are stochastically created (Fig. 1.2.2). Next, simulations are performed to compute power outputs for each situation (Fig. 1.2.3).



**Fig. 1.2.2: Stochastically generated fracture and well scenario with injection into one well across seven isolated intervals and production from two bounding wells. The parallel hydraulic fractures propagated from each injection interval are shown in red, the color indicating that these fractures require relatively low pressure for activation ( $P_c$ ).**



**Fig. 1.2.3: Geothermal power production simulations based on the Utah FORGE parameters. In the time series plot, a high-performing case is highlighted in red, and a poor performer is highlighted in green. There is also a clear link between the well spacing and power output in addition to the number of injection intervals (i.e., isolated zones) and power output (plots on the right).**

## GeoDT-ML Workflow

In this section, we describe the workflow scripts for GTC for EGS techno-economic analysis. The python scripts for the workflow development are available at [https://github.com/SmartTensors/GeoThermalCloud.jl/tree/master/EGS/GeoDT\\_ML\\_v1/Python\\_Scripts](https://github.com/SmartTensors/GeoThermalCloud.jl/tree/master/EGS/GeoDT_ML_v1/Python_Scripts). Equivalent Jupyter Notebooks and Google Colab notebooks will be made available in future at this GTC GitHub location.

## Data Processing and Curation

The GeoDT code (<https://github.com/GeoDesignTool/GeoDT.git>) is used to generate the training database<sup>3,4</sup>. The data for DL modeling is available at [https://github.com/SmartTensors/GeoThermalCloud.jl/tree/master/EGS/GeoDT\\_ML\\_v1/Data](https://github.com/SmartTensors/GeoThermalCloud.jl/tree/master/EGS/GeoDT_ML_v1/Data). In our study, a total of 4078 realizations are generated. The python scripts – *get\_inp\_out.py* and *get\_preprocessed\_data.py* are used to process the raw data and curate it using various pre-processing methods such as StandardScaler, MinMaxScaler, MaxAbsScaler, RobustScaler, PowerTransformer (Yeo-Johnson), QuantileTransformer (uniform output), and QuantileTransformer<sup>43</sup>. The python script – *get\_train\_val\_test\_splits.py* allow us to split the curated data into 80% training, 10% validation, and 10% testing. When the DL model identifies a promising EGS design, it can then be further investigated in greater detail. For example, we can use high-fidelity process models and simulation codes such as PFLOTRAN<sup>44</sup> to explore promising EGS scenarios. This currently study does not include the use of high-fidelity codes, but these python scripts can be leverage and modified to perform such DL analysis with minimal effort.

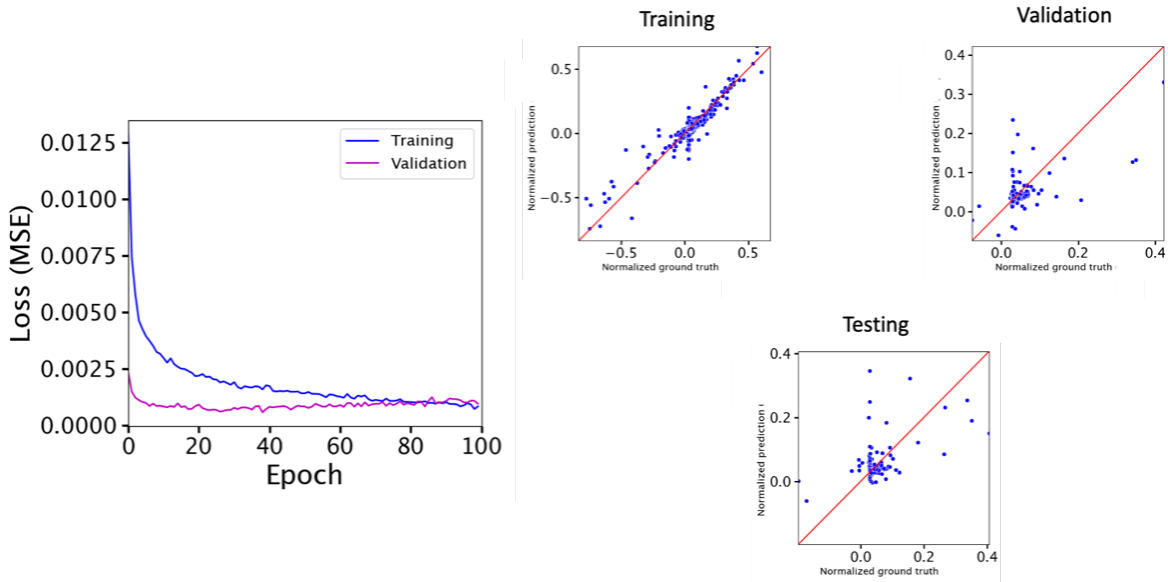
## Local and Global Sensitivity Analysis

The data worth analysis is performed using the *get\_ftest\_mi\_npv.py* and *get\_ftest\_mi\_npv\_others.py* scripts. These python scripts allow us to perform local and global data worth analysis. Sensitivity analysis is performed using two different approaches, F-test and mutual information<sup>45–47</sup>. F-test is a univariate linear regression tests returning F-statistic and p-values. It provides insights on the linear dependency of a given EGS design parameter with respect to economics (e.g., undiscounted cashflow), thereby allowing us to identify potentially predictive design parameters for DL model training for undiscounted cashflow. On the other hand, mutual information provides insights on non-linear dependency between EGS design parameters and undiscounted cashflow. The MI between an EGS design parameter and undiscounted cashflow is a non-negative value and is equal to zero if and only if two variables are independent, and higher values mean higher non-linear dependency.

## DL Model Training and Hyperparameter Tuning

This curated data is given as input to deep neural networks, which are trained on multiple cores available on high-performance computing machines (HPC). This AI training at scale is performed in parallel, allowing us to train and tune various deep neural networks in

minimal time. We combine python and AI modules such as mpi4py, multiprocessing, parallel hdf5, and TensorFlow to achieve this training at scale. The performance of the trained DL models is compared using the validation loss, and a tuned model is then selected. This hyperparameter tuning is computationally intensive and requires a lot of HPC resources. Python scripts such as *get\_dir\_hp\_dnn\_\*.py* and *get\_dnn\_results\_\*.py* are available to achieve this. They provide specifics on how to run on MacOSX, Linuc, and HPC resources. In our case, we trained these models on a HPC resource at PNNL using 20,000 CPU cores. Fig. 1.2.4 shows a plot of one such DL model training and inference.



**Fig. 1.2.4.** Training loss and one-to-one plots for training, validation, and test datasets of a preliminary DL model. More than 20,000 DL models are trained on HPC resources to estimate the EGS economics. This trained deep neural network model has three hidden layers, with neurons = [1000, 500, 250] in each of these layers. Leaky ReLU is used as an activation function with alpha value = 0.1. The dropout value, which allows for minimizing over-fitting during the training process, is assigned a value of 0.1. The total number of epochs for training is equal to 100. Batch size, which is the number of training samples that a DL model sees for each iteration in an epoch is equal to 64. The resulting DNN has approximately 750K trainable weights.

## Conclusions

**GeoDT-ML** is an ML-based version of GeoDT, a fast, simplified multi-physics solver to evaluate EGS designs in uncertain geologic systems. It is numerically efficient enough to model thousands of realizations in a few hours using a desktop computer. It is designed to find prospective enhanced geothermal systems in hot, dry rocks. In this study, we developed and provided preliminary DL workflow scripts to estimate EGS economics from design parameters. The database for DL model training is developed using GeoDT, a multi-physics

solver. Sensitivity analysis using F-test and mutual information is performed on this database to gain insights into the GeoDT parameters. The DL model training requires HPC resources as training and hyperparameter tuning is computationally expensive. To overcome this challenge, we will also provide notebooks and pre-trained ML models in the GitHub for the geothermal community. Advanced hyperparameter tuning scripts using open-source softwares such as DeepHyper and Keras-Tuner will also be made available at <https://github.com/SmartTensors/GeoThermalCloud.jl/tree/master/EGS>.

## How to Use it?

The following are the steps to use the GeoDT-ML through GTC:

1. Create a virtual python environment (e.g., myenv)
  - `conda create --name myenv`
  - Install the following additional packages in the virtual environment: `tensorflow`, `keras-tuner`, `mpi4py`, `h5py`
2. Git clone <https://github.com/SmartTensors/GeoThermalCloud.jl.git>
3. `cd` to `EGS/GeoDT_ML_v1/Python_Scripts`
4. On terminal run – `python <file_name.py>`

These above instructions will be available through the readme markdown file on GTC. As the scripts utilize HPC resources for training ML models, a user can use their own HPC systems to run these scripts in parallel. These parallel scripts are not available through Jupyter Notebooks or Google Colab notebooks. Such instructions will be made available at GTC GitHub repository.

## Outreach Activities

### Publications in journals and magazines

AI pinpoints renewable energy in ***Albuquerque Journal***, 2020.

Unearthing clean energy in LANL magazine 1663.

<https://discover.lanl.gov/publications/1663/september-2022/unearthing-clean-energy/>

### YouTube Videos

New GeoThermalCloud:

GeoThermalCloud:

<https://www.youtube.com/watch?v=ryFxdyQgCJg&list=PLpVcrIWNIP22LfyIu5MSZ7WHp7q0MNjsj&index=11>

SmartTensors

Platform:

<https://www.youtube.com/watch?v=ni3EgQVypbQ&list=PLpVcrIWNIP22LfyIu5MSZ7WHp7q0MNjsj&index=17>.

NMFk optimization process:

<https://www.youtube.com/watch?v=6NAvJmY3Ae8&list=PLpVcrIWNIP22LfyIu5MSZ7WHp7q0MNjsj&index=36>

Unsupervised ML workshop GSA:

<https://www.youtube.com/watch?v=8a6Gw29RHcM&list=PLpVcrIWNIP22LfyIu5MSZ7WHp7q0MNjsj&index=12>

## Demo Problems

SWNM

Brady

Great Basin

Utah FORGE

Tularosa

Maruti: GeoDT-ML

## Chapter 2: What after NMFk: Pin pointing drilling site coupling NMFk and magnetotellurics data in the Tularosa Basin

### Introduction

The United States Energy Information Administration projects a 50% increase in global energy consumption between 2018 and 2050<sup>48</sup>. Geothermal energy is a non-intermittent renewable resource, which has the potential to contribute to the growing global energy demand while mitigating carbon emissions attributed to the burning of hydrocarbons. Specifically, in the United States, geothermal electric power capacity has the potential to increase from 2.3 GWe in 2019 to 60 GWe by 2050<sup>49,50</sup>. Geothermal energy is generated from the decay of naturally occurring radioactive elements and stored deep in the subsurface. Even though there is essentially an inexhaustible geothermal energy supply in the subsurface, much of the heat is unevenly distributed, seldomly concentrated, and too deep to be economically exploited<sup>51</sup>. However, there are locations where thermal energy is accessible by drilling that are the targets for geothermal exploration.

Productive geothermal systems have three major characteristics: high heat flow, temperature, and permeability. Geothermal resources are confined to regions of high heat flow and temperature due to magmatism and/or crustal thinning<sup>52</sup>. Specifically, extensional settings exhibit intermediate to high heat flow that can be the target of geothermal exploration, and temperatures of 125–225°C can produce geothermal energy<sup>52,53</sup>. However, finding the optimal location for the development of such resources and the potential depth of drilling is challenging because of high drilling and development costs. Typically, play fairway analysis (PFA), a heavily used tool in the hydrocarbon industry, is used for finding spatial locations

of geothermal resources. Next, an MT survey or exploration drilling is performed to identify the optimal drilling depth. PFA separately computes the importance of each attribute in a geothermal dataset and estimates a composite score by combining scores for all attributes. The composite score is used for defining spatial locations of geothermal resources. Such a study has a significant human bias. Here, we propose an ML based alternative PFA approach that simultaneously analyzes all attributes in a dataset without human intervention to find spatial locations of geothermal resources. Finally, we integrate MT data in the workflow to identify the most prospective drilling depth. Note that no such study in the literature combines ML-based PFA and MT data.

Integrating ML and geophysical techniques assesses heat flow, temperature, and permeability for geothermal exploration and development. Here, we use unsupervised ML called non-negative matrix factorization with k-means clustering (NMFk). This approach clusters/groups data related to heat flow, temperature, and permeability to establish groups with geothermal resource significance in both attribute and spatial domains<sup>16,54</sup>.

NMFk has been successful in various geothermal applications in identifying the location of potential geothermal resources<sup>35</sup> and geologic factors associated with geothermal production<sup>37</sup>. MT is a passive geophysical technique used for measuring electrical resistivity structures in the subsurface and is commonly used to characterize geothermal resources<sup>28–31,55</sup>. Generally, high-potential geothermal systems are characterized by low resistivity because of high salinity of geothermal fluids. Geothermal systems commonly include faults and fractures filled with highly conductive high-salinity fluids. In addition, clay products from mineral alteration in a geothermal system also have low electrical resistivity. The correlation between low resistivity measurements and geothermal resources makes MT surveys ideal for geothermal resource development.

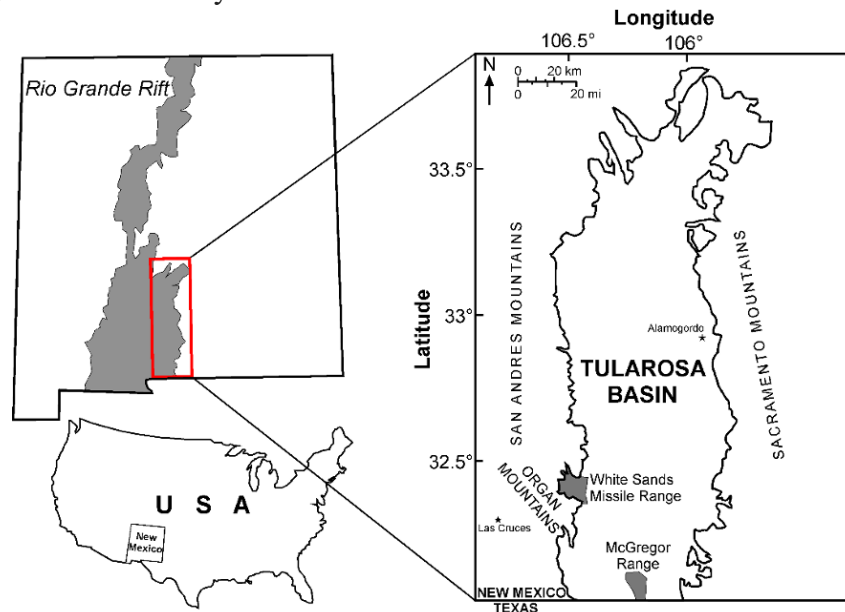
This study aims to demonstrate how NMFk analysis identifies the most prospective locations for geothermal resource development, and MT inversion aids in the subsurface characterization of those resources. Play fairway analysis (PFA) performed by Ruby Mountain Inc. and the Energy and Geoscience Institute at the University of Utah identifies two highly prospective geothermal locations within the Tularosa Basin, New Mexico: White Sands Missile Range and the McGregor Range at Fort Bliss. Due to data limitations, heat flow, temperature, and permeability data from White Sands Missile Range is used to demonstrate the ability of NMFk to further characterize a predetermined high-potential geothermal location, whereas McGregor Range is used to demonstrating the ability of MT data to identify geothermal prospects in the subsurface. Finally, we demonstrate how NMFk and MT may be integrated to provide a 3D assessment of high-potential geothermal resources, facilitating fast and economic geothermal play development.

## Geologic background

The Tularosa Basin is located on the eastern flank of the Late Paleogene Rio Grande rift<sup>56,57</sup>. The Rio Grande Rift occurs as a north-trending, intermontane graben within south-central New Mexico and is bounded to the east by the Sacramento Mountains and to the west by the Organ and San Andreas Mountains (Fig. 2.1). Faults associated with the Rio Grande Rift have several thousand feet of displacement and separate the basin from the surrounding uplifted mountains<sup>56</sup>. Paleogene rifting induces high heat flow within southwestern New Mexico and therefore, makes the southern portion of the Tularosa Basin favorable for geothermal exploration<sup>39</sup>. In the southern part of the basin, temperatures recorded from

wellbores range from 170°C to 200°C<sup>58</sup> and clay mineral analysis indicates temperatures as high as 225°C<sup>59,60</sup>.

The Tularosa Basin is filled with strata of Paleozoic to Tertiary age<sup>58,60–62</sup> (Fig. 2.2). Bedrock consists primarily of Paleozoic carbonates, including Ordovician and Silurian dolomite, Devonian and Mississippian interbedded chert-rich shales and limestones, and Pennsylvanian limestone with thinly bedded shales. Tertiary felsic intrusions commonly crosscut the Paleozoic bedrock, and Quaternary graben fill overlies the bedrock and is composed of gravel, sand, silt, and clay derived from prograding alluvial fans originating from the edge of the rift valley.



**Fig. 2.1:** Location of the White Sands Missile Range and McGregor Range study areas within the Tularosa Basin of southern New Mexico. The Tularosa Basin is an intermontane graben located on the eastern flank of the Rio Grande Rift.

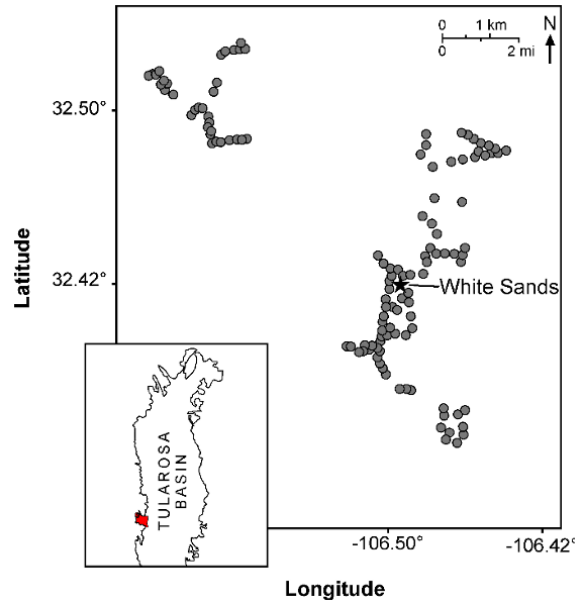


	Stratigraphic Unit	Generalized Lithological Description
CENOZOIC	Quaternary	Alluvial basin fill
	Tertiary	Felsic sills and dikes
PALEOZOIC	Pennsylvanian	Black lime mudstones and wackestones; cherty limestones interbedded with grey shale
	Mississippian	Limestone interbedded with black shale
	Devonian	Black shale
	Silurian	Cherty dolomite
	Ordovician	Dolomite

**Fig. 2.2:** Generalized stratigraphic succession of the Tularosa Basin sedimentary and igneous fill.

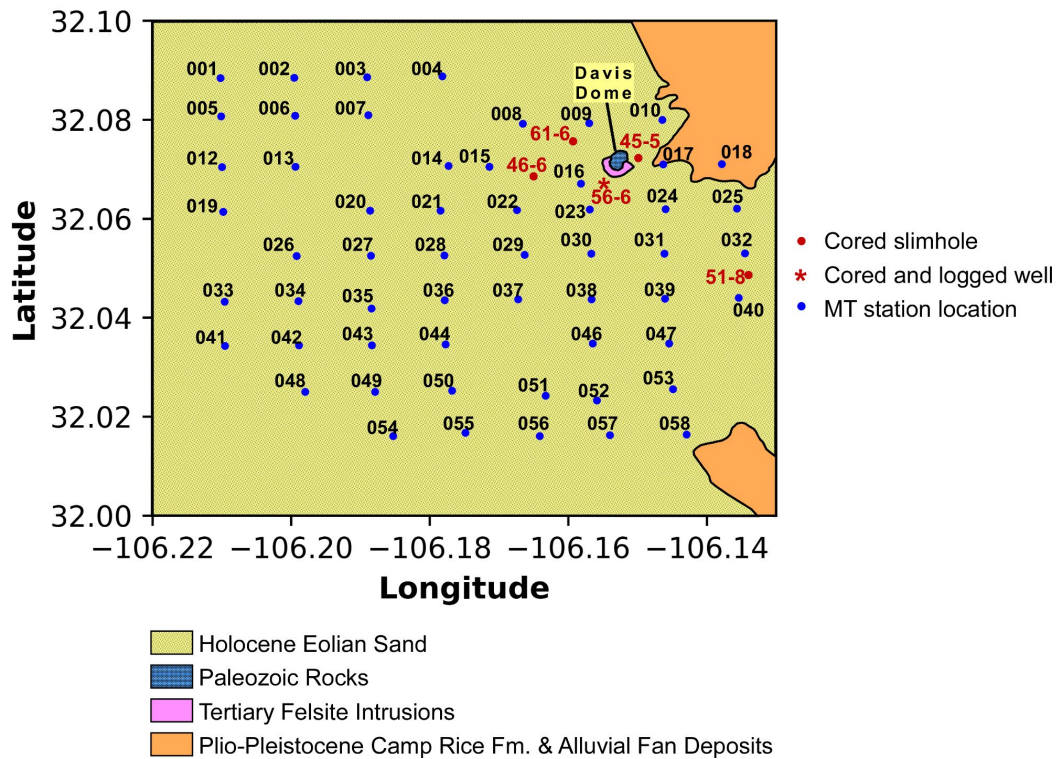
## Data

The dataset has 10 attributes at 120 locations (Fig. 2.3). With an observational dataset, obtaining values for 10 attributes at each location is difficult. In this study, the only attribute available at all 120 locations is temperature@2m, and the remaining attributes had missing values for some locations. To address the missing values, we apply the nearest neighbor interpolation techniques<sup>63</sup> based on distance (not points) to heat flow, gravity, NaK-Giggenbach geothermometer, K-Mg geothermometer, NaK-Fournier geothermometer, silica geothermometer, and Li<sup>+</sup> concentration. The distance is calculated using a variogram analysis. Note, we also use block mean<sup>64</sup>, kriging<sup>65</sup>, and inverse distance weighting<sup>26</sup> interpolation techniques. However, the nearest neighbor method provides the best results for the dataset used in this study. R<sup>2</sup> score (Eq. 1.7) based on interpolated and actual values is used to evaluate four interpolation techniques. ArcMap is used to interpolate fault distance and fault density values. Specifically, the near coverage tool was used to find the distance from the location to the nearest fault, and the kernel density function was used to calculate fault density.



**Fig. 2.3:** Locations (120 total) near White Sands is selected as input data for NMF $k$ . At each site, 11 geothermal attributes are collected and used as input into the NMF $k$  model.

A 56-station MT survey was conducted at the McGregor Range by Quantec Geoscience and the inversion modeling was completed by the Energy and Geoscience Institute at the University of Utah (Fig. 2.4)<sup>39</sup>.



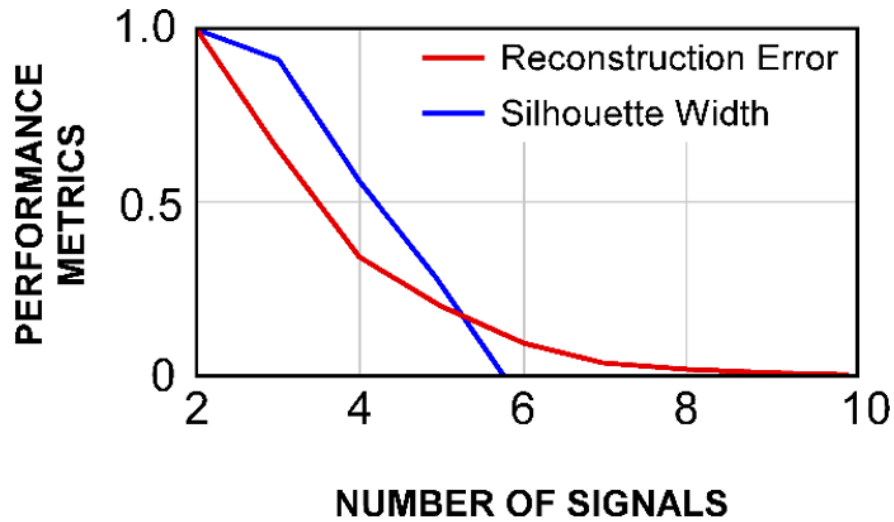
**Fig. 2.4:** Geologic map of the McGregor Range with MT station locations (blue) and slimhole core locations (red). McGregor is largely covered by Recent eolian sands, although

Paleozoic and Tertiary outcrops occur in the northeast portion of the study area at Davis Dome.

## Results

### Geothermal characterization of NMFk signatures

We applied NMFk on the dataset and it determines the optimal solution for by evaluating reconstruction quality and average silhouette width (Fig. 2.5). Optimal solutions have low and high values. Generally, low and  $>0.25$  are acceptable solutions<sup>1,66</sup>. NMFk is run for 2 to 10 signatures, and the  $k=4$  solution is found to be the optimal solution because of its low and high values. The solution with  $k<4$  is an underfitting representation of data, whereas  $k>4$  is an overfitting representation of data.

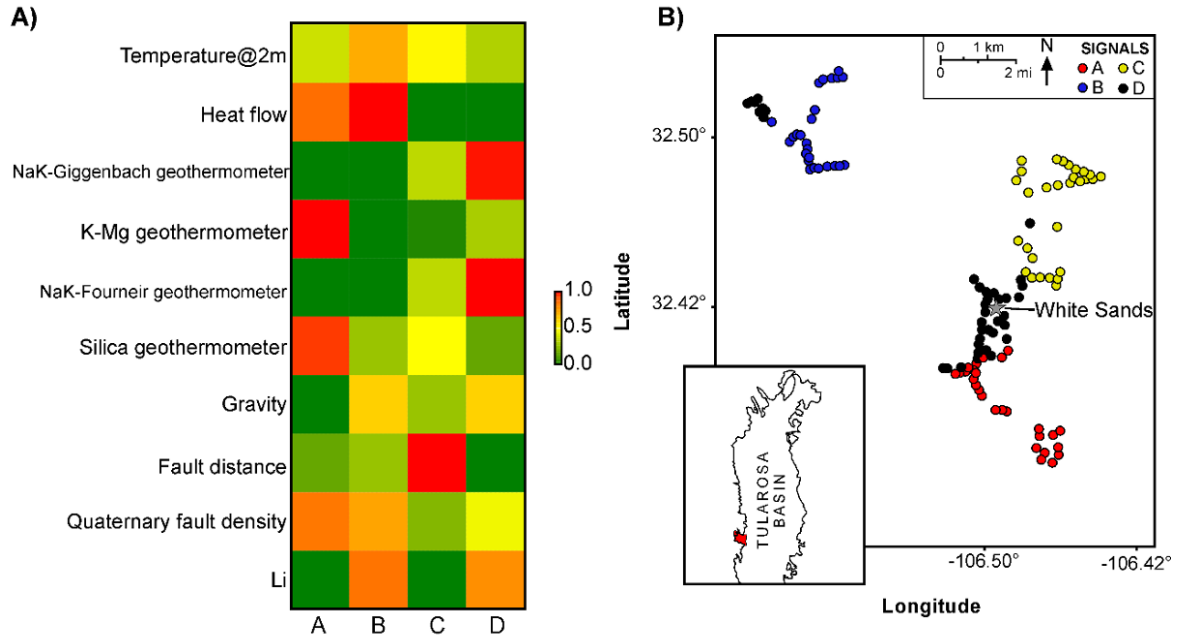


**Fig. 2.5:** NMFk reconstruction error (red curve) and silhouette width (blue curve) for different numbers of clusters  $k$ . The optimal  $k$  value has low reconstruction error and higher silhouette values. In this study, the optimal number of signatures is 4.

Each column of the attribute matrix,  $H_{nxk}$ , is known as a signature and captures certain characteristics in the dataset (Fig. 2.6A). The characteristics are defined by the contribution/weight of each attribute in a signature. The warm colors represent a high weight between the signatures and attributes and the cool colors represent a relatively low weight (Fig. 2.6A). Furthermore, for the geothermal attributes the warm colors correlate to high values and the cool colors correlate to lower values. The spatial distribution of each signature is plotted with a different color on Fig. 2.6B.

The dominant attributes of signature A are heat flow, K-Mg geothermometer, silica geothermometer and quaternary fault density indicating high heat flow, subsurface temperature, and permeability. Like signature A, signature B is characterized by high heat flow, temperature@2m, and  $\text{Li}^+$  concentration. Furthermore, the high  $\text{Li}^+$  concentration indicates that signature B is characterized by high vertical permeability. No geothermometer had a significant contribution to signature B. Fault distance is the major attribute in signature C. This indicates locations assigned as C have lower potential vertical permeability because they are relatively far from faults that act as conduits for fluid flow. Signature C is

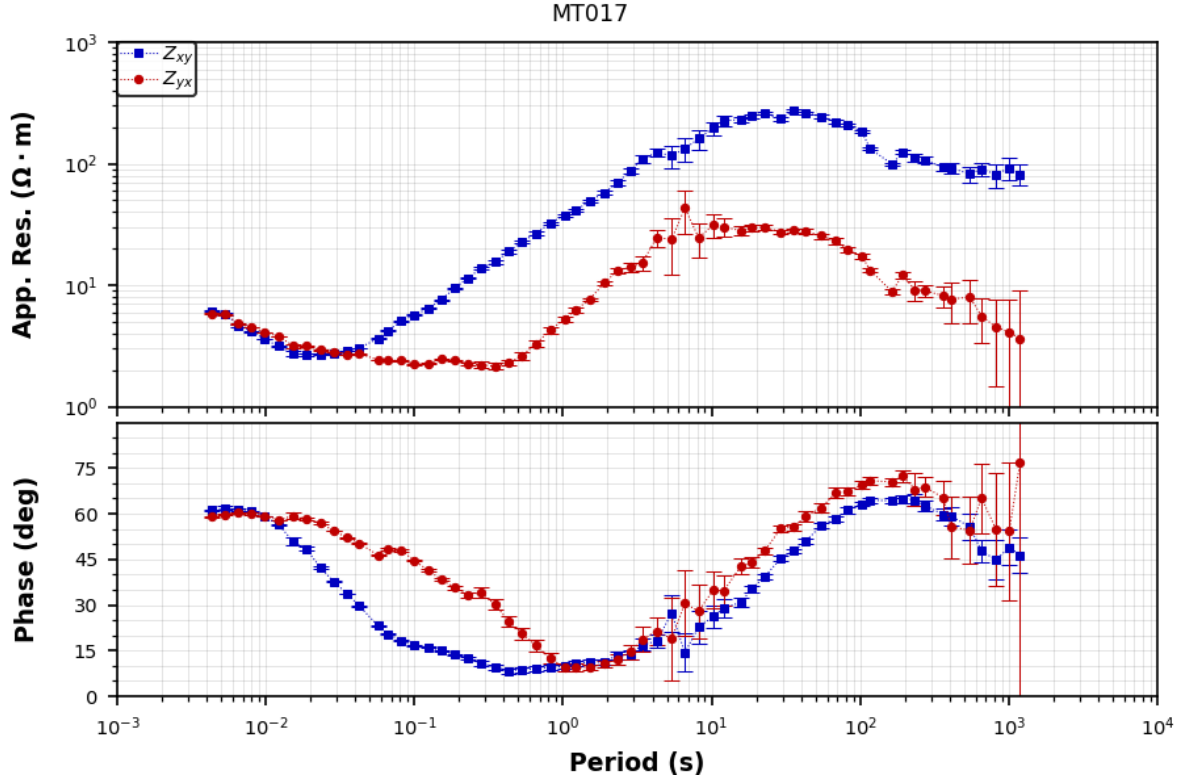
characterized by lower heat flow and temperature relative to the other signatures. The dominant attributes for signature D are the Na-K Giggenbach geothermometer and NaK-Fourneir geothermometer indicating high subsurface temperatures. Moderate weights for quaternary fault density and Li concentrations in signature D indicate relatively high permeability. Heat flow and temperature@2m have a relatively low contribution to signature D.



**Fig. 2.6:** Results from the NMFk model. A) Heatmap identifying the dominant geothermal attributes in each signature. The warmer the color the more dominant the attribute for a particular signature. B) Spatial distribution of signatures for the 120 locations at White Sands.

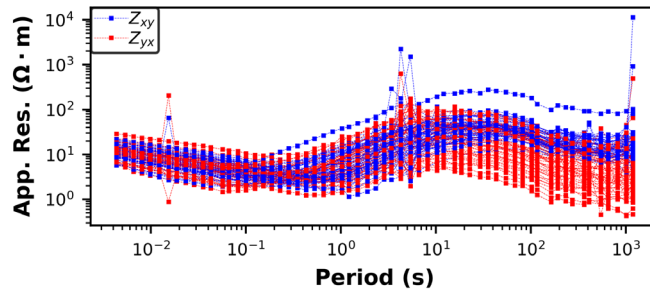
## Subsurface characterization of potential geothermal locations

Apparent resistivity and phase curves display resistivity trends using the period as a proxy for depth (longer periods correspond to increased depth). Congruent MT apparent resistivity curves of  $Z_{xy}$  and  $Z_{yx}$  indicate a 1D resistivity structure, whereas separation indicates more complicated 2D or 3D resistivity structure<sup>29</sup>. For example, MT apparent resistivity curves for station 017 located in the northeast section of the survey show separation between the two curves at shorter periods, i.e., shallower depths (Fig. 2.7). This corresponds to geological structures related to Davis Dome, a small intra-bolson horst near station 017<sup>60</sup>.



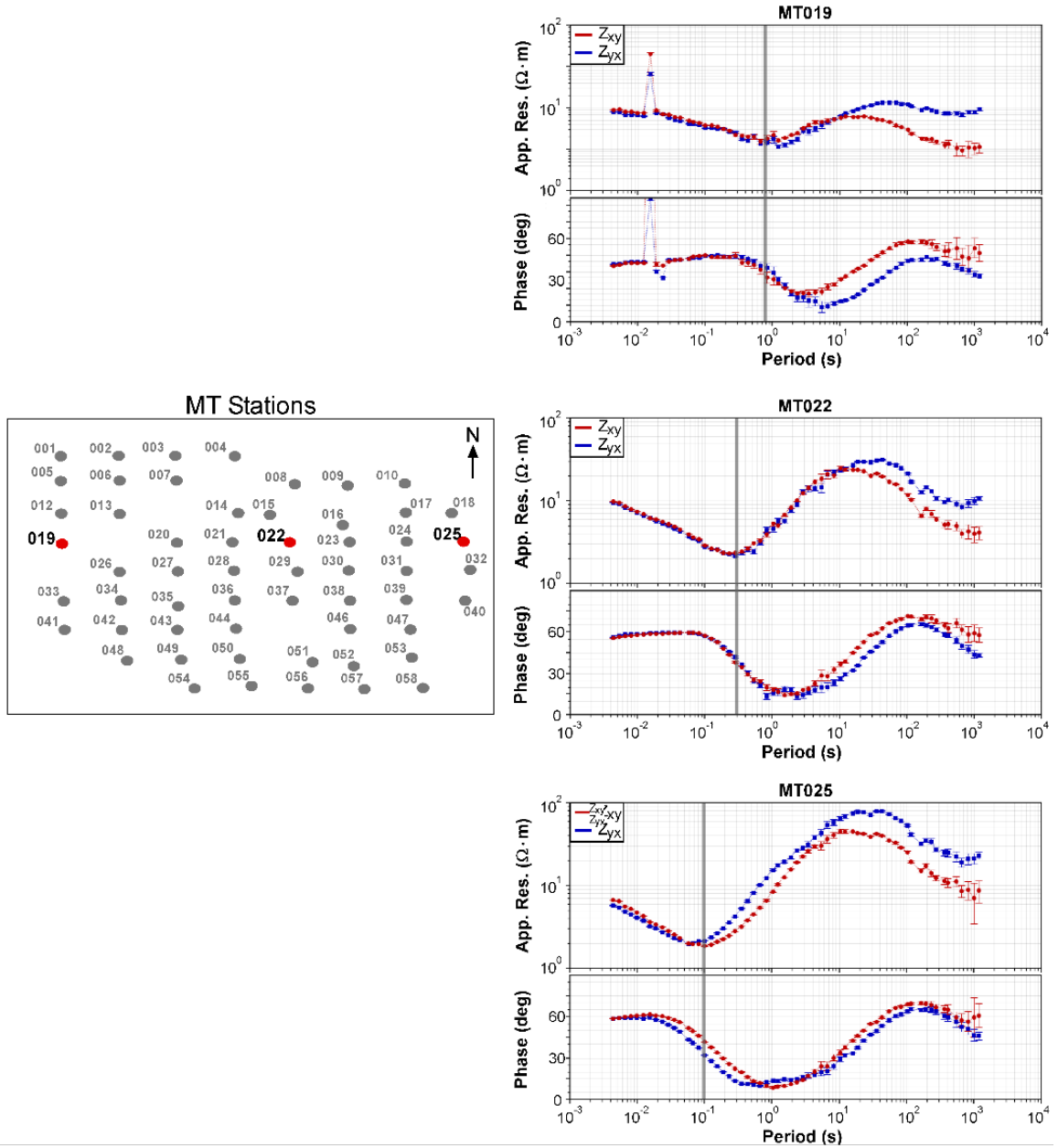
**Fig. 2.7:** Apparent resistivity curves for station MT017. The period is a proxy for depth, i.e., longer periods are deeper depths. Separation of  $Z_{xy}$  and  $Z_{yx}$  curves at 0.05 s indicate 2D or 3D resistivity structures.

MT apparent resistivity and phase curves of  $Z_{xy}$  and  $Z_{yx}$  from all 56 MT sites are shown in Fig. 2.8. The apparent resistivity values show a cyclic trend from shorter to longer periods (shallower to deeper depths). At shallower depths, the apparent resistivity gradually decreases. Between 1 s and 100 s the apparent resistivity increases. At deeper depths, longer than 100s, the apparent resistivity decreases. Furthermore, at longer periods, the  $Z_{xy}$  and  $Z_{yx}$  curves diverge indicating complex, 3D resistivity structure at deeper depths. The depth of the low apparent resistivity varies from east to west. For MT stations 019, 022, and 025 the troughs for apparent resistivity occur at 1 s, 0.3 s, and 0.1 s, respectively (Fig. 2.9). The longer period to the west indicates that the low resistivity unit occurs deeper in the west than in the east.



**Fig. 2.8:** Apparent resistivity curves from all 56 MT stations. From shorter to longer periods the general apparent resistivity trend is lower at shorter periods, increases at medium periods,

and then decreases at longer periods for a low-high-low trend. Furthermore, at longer periods, the  $Z_{xy}$  and  $Z_{yx}$  curves separate indicating 2D or 3D structure at deeper depths.



**Fig. 2.9:** Apparent resistivity curves for MT stations 019, 022, and 025. The curves show a change in the low resistivity unit depth from west to east. The low apparent resistivity trough of the  $Z_{xy}$  and  $Z_{yx}$  curves for MT019 occurs at 1s. The trough of the  $Z_{xy}$  and  $Z_{yx}$  curves for MT022 occurs at 0.3 s. The trough of the  $Z_{xy}$  and  $Z_{yx}$  curves for MT025 occurs at 0.1 s.

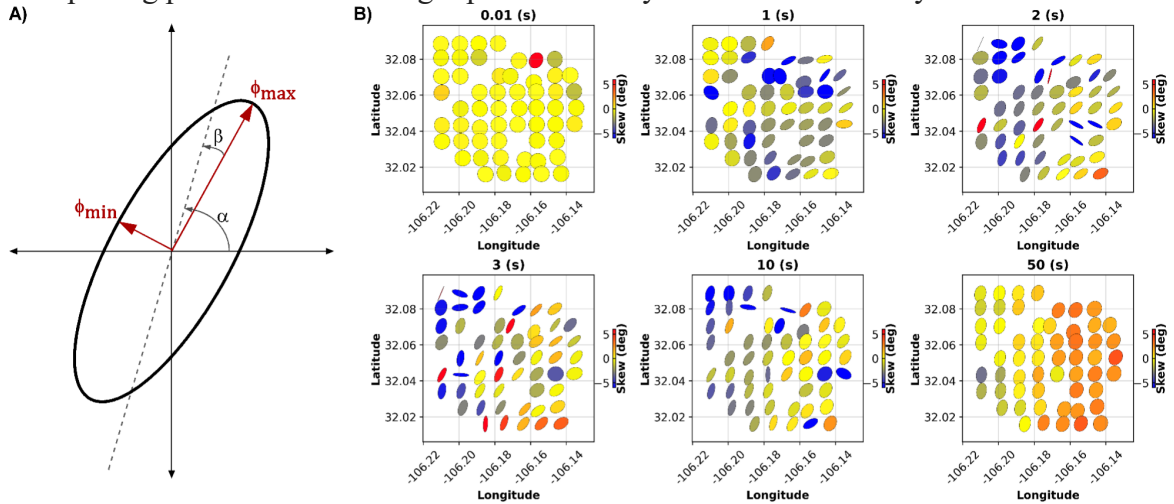
The dimensionality of the resistivity structure is determined by phase tensors. One-dimensional resistivity structures indicate a natural change in resistivity with depth due to compaction<sup>32,67</sup>. Phase tensors are useful in identifying lateral variations (2D and 3D resistivity structures) in the underlying regional resistivity<sup>32</sup>. Lateral variations in resistivity



result from changes in porosity due to fault- and/or fracture-related diagenesis, and/or changes in lithology.

The phase tensor is commonly plotted as an ellipse with a minimum and maximum principal axis and skew angle,  $\beta$  (a measure of asymmetry) (Fig. 2.10A). In Fig. 2.10B, ellipses are colored based on the skew angle. Yellow colors indicate a skew angle of 0 and the red and blue colors indicate larger skew angles ( $\pm 5^\circ$ ). The larger the skew angle, the more asymmetric the phase tensor indicating higher dimension resistivity structures. For 1D resistivity structures, the minimum and maximum principal axes are the same ( $f_{max} = f_{min}$ ) resulting in the phase tensor characterized by a yellow, circular shape. The phase tensor of a 2D resistivity structure is characterized by an elliptical shape and skew angle close to zero ( $\pm 3^\circ$ ). For 3D resistivity structures, the phase tensor is asymmetric; hence, the phase tensor is characterized by blue or red. Furthermore, a rapid direction change in the phase tensor's principal axes between sites indicates a 3D resistivity structure<sup>68</sup>.

In general, across the study area, the shorter periods are characterized by 1D resistivity structures and then higher dimension 2D and 3D resistivity structures with depth (Fig. 2.10B). This observation is consistent with the separation in apparent resistivity curves at longer periods (Fig. 2.7). Specifically, at 0.01s and 0.1s the phase tensors are characterized by 1D structures as indicated by the yellow circles. An exception to this observation is the northeastern corner of the study area where the shape of the tensors is more elliptical, and the skew angle is higher indicating lateral variation in the resistivity structure. This increase in dimensionality is consistent with shallow structural features and northwest-trending faults associated with Davis Dome<sup>61</sup>. The shape of the ellipses and the red, blue, and orange colors at periods greater than 1s indicate 2D or 3D resistivity structures. Specifically, the abrupt changes in the ellipse's shape at 10s suggest possible faulting. Caution must be taken when interpreting phase tensors at longer periods as they are more affected by attenuation.



**Fig. 2.10:** A) Graphical representation of the phase tensor. B) Phase tensor maps at 0.1, 0.01, 1, 10, 50 and 100s indicate the spatial distribution of resistivity structures with depth.

## Discussion

The geothermal resource potential of signature

Temperature, heat flow, and permeability are the main geothermal attributes driving geothermal success<sup>52</sup>. The locations associated with signature A have high geothermal resource potential because of the characteristically high heat flow, high K-Mg and silica geothermometers, and medium to high quaternary fault density. Therefore, signature A has a high likelihood of possessing higher temperature, heat flow, and permeability compared to the other signatures. The locations associated with signature D have moderate geothermal potential because of the combination of high NaK-Giggenbach and NaK-Fourneir geothermometers values and low temperature@2m and heat flow. The locations associated with signature B have moderate geothermal potential because of high temperature@2m, heat flow, quaternary fault density, and Li<sup>+</sup> concentrations; however, low values for the geothermometers suggest subsurface temperatures may not be suitable for a geothermal resource. The locations associated with signature C have the lowest geothermal resource potential because no geothermal attributes have a major contribution to the signature.

### MT inversion interpretation

Once a spatial location is determined through NMF $k$ , MT can be a valuable tool to aid in the subsurface characterization of a potential geothermal resource by analyzing resistivity trends. Resistivity values are found through numerical inversion of MT data. Generally, geothermal fluid demonstrates low resistivity because of the presence of high concentration elemental composition or total dissolved solids. The resistivity values of the McGregor geothermal system potentially indicate three resistivity layers and two resistivity structures (Fig. 2.11). Layer 1 (L1) is characterized by the lowest resistivity (<8  $\Omega$ m) and is confined generally to the upper 500 m of the study interval. L1 is thickest to the west and thins to about 300 m in the east (Fig. 2.11). L1 is thinnest in the northeast corner near Davis Dome. This regional low resistivity cap is most likely attributed to basin-fill deposits. O'Donnell, Jr., et al. (2001)<sup>61</sup> performed a seismic reflection survey over the same study area and observed a wedge-shaped feature above the bedrock attributed to alluvial fan deposits shed from the surrounding mountains. The observed thickening of L1 to the west in the MT data is consistent with the wedge-shaped feature observed in the seismic survey (Fig. 2.11).

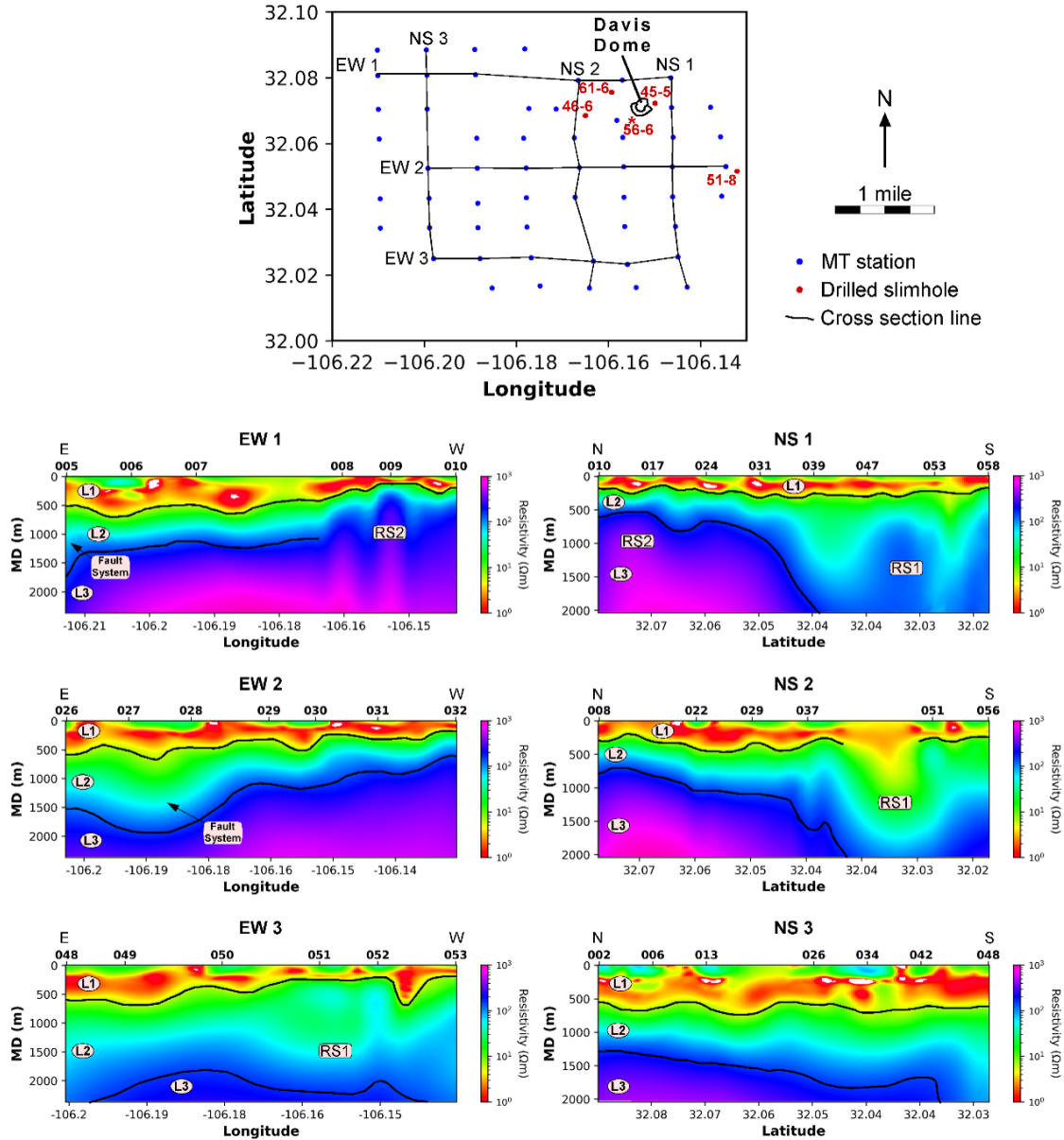
Layer 2 (L2) is a low resistivity (10 – 100  $\Omega$ m) layer with the top 200 – 600 m beneath the surface. In general, L2 is shallower to the east (~300 m) and deeper to the west (~ 600 m). Wells drilled in the northeast portion of the study area suggest that the top of L2 corresponds to Paleozoic (Pennsylvanian limestone) bedrock<sup>58,60</sup>. Finger & Jacobson (1997)<sup>58</sup> observed and measured fracture permeability in cores in nearly all Paleozoic units. Phase tensor analysis in the western part of the study area indicates a 2D resistivity structure that suggests the presence of a possible fault system (Fig. 2.10B). The thicker and lower resistivity L2 in the west may be attributed to an increase in fractures and/or faults that act as storage or conduits for geothermal fluids decreasing resistivity, i.e., L2 in the west is influenced by higher fractured and/or faulted units.

A low resistivity structure (RS1) is present below MT stations 039, 047, 051, 052, and 053 in the southeast section of the study area (Fig. 2.11). The structure has similar resistivity as L2 but extends to 2000 m. The lower resistivity of RS1 is interpreted to be related to a deformation observed in surrounding wells. A thrust fault and overturned beds are observed in cores from well 51-8 located to the northeast of cross-section EW3 suggesting deformation in the area (Fig. 2.11). Units related to this structure are pervasively fractured and may



provide a conduit for fluid flow and associated lower resistivity in RS1 as observed in Fig. 2.11.

Layer 3 (L3) is characterized by the highest resistivity values ( $>100 \Omega\text{m}$ ) and the top is located about 250 – 2000 m beneath the surface (Fig. 2.11). L3 follows a similar east-west thickening trend as observed within L2. In the east, the top of L3 is shallower ( $\sim 500$  m) and in the west, the top of L3 is deeper ( $\sim 1800$  m).



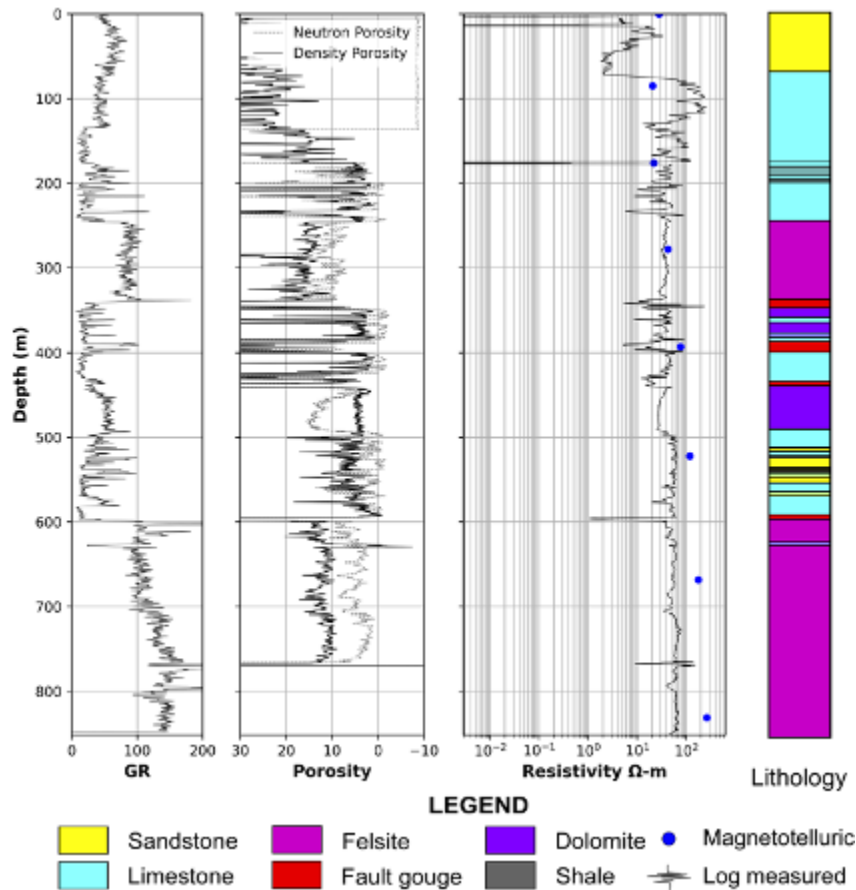
**Fig. 2.11:** Three north-south and east-west MT cross sections with interpreted resistivity layers and structures. The low resistivity to the west is interpreted as a fault system. The faults, fractures, and possible dissolution because of geothermal fluids increase porosity thus decreasing resistivity. Assuming temperature is consistent with a geothermal reservoir, the west-central part of the McGregor Range has the highest geothermal potential because of the increase in porosity and associated permeability attributed to the interpreted fault system.

A high resistivity structure (RS2) is present in the northeast portion of the study area and has similar resistivity values to L3 (Fig. 2.11). The spatial distribution of resistivity and cored wells in the area (45-5, 46-6, and 61-6) suggest RS2 coincides with structures related to Davis Dome, an intrusive igneous laccolith (Fig. 2.11). Cored wells encounter felsic sills, a felsic laccolith, and Mississippian limestone and shale at relatively shallow depths between 360 m and 530 m<sup>58,61</sup>. The thin L2 layer above RS2 is most likely fractured Paleozoic strata and high resistivity RS2 is most likely a low permeability felsic body associated with the Davis Dome intrusion. These interpretations are consistent with a structural high from a laccolith intrusion observed in reflection seismic data velocity, and gravity models from O'Donnell Jr. et al., 2001<sup>61</sup>.

The west-central section of L2 is interpreted as a possible fault system with the highest geothermal potential. Geothermal reservoirs tend to have resistivity values between 10 – 60  $\Omega$ m similar to those observed in L2<sup>30,68</sup>. The location where L2 is the thickest coincides with north-northwest trending, anomalously high thermal gradients (up to 140°C/km). The anomaly may be due to geothermal waters rising along a common fault zone or fractured bedrock adjacent to the fault zone<sup>69</sup>, which is consistent with the highly faulted and/or fractured units observed in L2 to the west (Fig. 2.11). Furthermore, the westward thickening of L2 suggests the possibility for a corresponding increase in reservoir transmissivity and an increase in well productivity<sup>70</sup>.

## Limitations of MT

MT data is limited by its hectometer-scale vertical resolution. Resistivity is measured in well 56-6 using wireline logs with a vertical resolution of 0.6<sup>71</sup>. Compared to inverted MT resistivity, the well logs provide more detailed variations in resistivity (Fig. 2.12). For example, from 90 – 220 m, well-log resistivity is characterized by high variability due to thinly interbedded limestones and shales that are not detected in the MT resistivity. Only general interpretations of fluid saturation and porosity can be made with MT data because of the low vertical resolution.



**Fig. 2.12:** Comparison of wireline logs, resistivity logs, and MT resistivity of well 56-5. The resistivity from well logs provides more detailed variations in resistivity that are not detected from lower resolution, inverted MT resistivity data. Lithologies are based on petrophysical interpretations from accompanying gamma ray (GR), neutron and density porosity, photoelectric effect (PE), deep resistivity logs, and core cutting descriptions.

Lithologic interpretations from MT inversions are difficult since resistivity is primarily influenced by the salinity of pore-filling fluid and secondarily by porosity<sup>59</sup>. Because all rock matrices are potentially saturated with similar saline water, porosity controls resistivity variations. In general, lithification increases with depth and is associated with a decrease in porosity and permeability consistent with the observed increase in MT resistivity from L1 to L3 (Fig. 2.11)<sup>67</sup>. Correlations between the four cored wells in the northeast portion of the study area indicate that L1 coincides with Quaternary basin fill that is under-compacted and highly porous and permeable, and therefore, characterized by low resistivity. Older strata associated with L2 and L3 are highly compacted and cemented and characterized by lower porosity and permeability and higher resistivity. The transition from L2 to L3 is controlled by porosity rather than lithology. For example, as seen in EW2, L2 thickness increases to the west suggesting an increase in porosity. The phase tensors in the west show 2D resistivity structures with increasing depth suggestive of a possible fault system (Fig. 2.11). Secondary pore networks derived from fluid-rock interactions induced by the high permeability fault system are interpreted to be filled with high salinity, and low resistivity fluids. Also, cored wells 61-6, 45-5, 46-6, 56-6, and 51-5 indicate that L2 and L3 coincide with Paleozoic

bedrock composed primarily of resistive carbonates. The resolution limitations of MT resistivity measurements mean that small-scale changes in carbonate lithologies are not detected and suggests that differences between L2 and L3 are not related to lithology (Fig. 2.12).

## Conclusions

1) NMF $k$  is a useful ML tool to assess prospective geothermal regions by evaluating variability in geothermal, geological, geophysical, and geochemical attributes. In the southwestern portion of the Tularosa Basin at White Sands Missile Range, four signatures (A-D) were established through NMF $k$  for their geothermal resource potential. Signature A is interpreted to have the highest geothermal potential due to a combination of high heat flow, reservoir temperatures, and comparatively high porosity and permeability. Signatures B and D have moderate potential because of their relatively low heat flow and temperature. Signature C has the lowest geothermal resource potential because no geothermal attributes have a major contribution to the signature.

2) MT inversions detect subsurface geothermal prospects based on resistivity. MT provides insight into relative porosity and associated permeability that is related to the subsurface resistivity trends detected in the MT inversion. From an MT survey from McGregor Range, three resistivity layers (L1, L2 and L3) and 2 resistivity structures (RS1 and RS2) are identified. The layers are inferred to be related to a combination of depth-related compaction and lithification effects and the resistivity structures are related to Davis Dome, laccolith, and faulting. A fault system is interpreted in the western portion of the study area as indicated by the thickening of L2. Because low resistivity is a defining characteristic of geothermal prospects, the western portion of the McGregor MT survey has the highest geothermal potential.

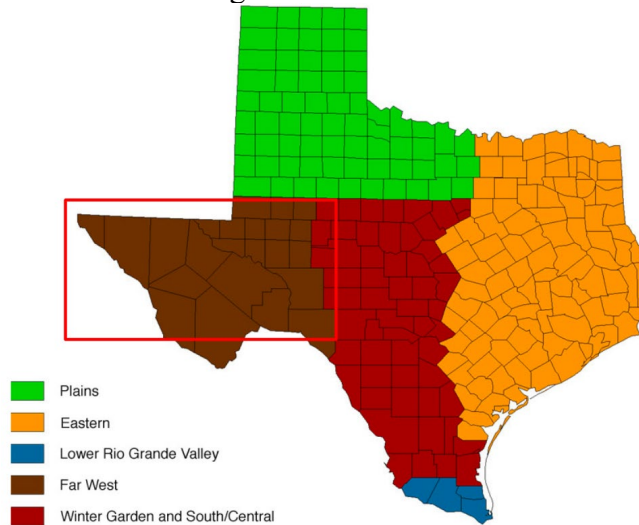
The low vertical resolution of MT data, in contrast with high-resolution borehole resistivity measurements, makes it difficult to relate lithological variability and associated rock attributes with MT inversions. MT is limited in that the interpreted resistivity layers only provide insight into relative porosity and do not correlate with lithological or stratigraphic units. Only large-scale characterization of porosity and associated permeability can be made when interpreting MT inversions. Therefore, the MT survey may be used as a preliminary study before drilling a well, which will provide more detailed information for developing a geothermal field.

# Chapter 3: Characterization of Potential Geothermal Energy Utilization in West Texas

## Introduction

The total U.S. energy consumption is  $\sim 13.68 \times 10^9$  GJ<sup>48</sup>, and a majority of which comes from fossil fuels that emit carbon into the atmosphere. To reduce CO<sub>2</sub> emissions, carbon-free energy sources such as wind, solar, and geothermal are becoming more prevalent. Geothermal energy is poised to become an important continuous source of heat and energy. Currently, geothermal energy makes up <1% of U.S. electricity generation but can increase dramatically as the U.S. has  $\sim 2 \times 10^{14}$  GJ of extractable geothermal energy<sup>48</sup>.

Large areas of land in the U.S. with a high geothermal gradient may possess hot water resources. Most importantly, a large portion of oil and gas fields have high thermal gradient that can be converted into geothermal energy. As geothermal energy use becomes more prevalent, it is important to easily determine the proper setting and attributes for utilizing this energy to displace the greatest amount of fossil fuels. Therefore, the main purpose of this work is to estimate geothermal prospectivities and commercial feasibility in western Texas (Fig. 3.1) using publicly available oil and gas field data.



**Fig. 3.1:** The map of Texas including their basin configuration. Study area is in west Texas bounded by the red rectangle.

Western Texas because it not only has a high number of existing and orphaned oil fields/wells but also has a medium geothermal gradient and easy-to-drill sedimentary formations. These existing or abandoned oil wells are a great opportunity for geothermal energy as their interconnected piping infrastructure and drilled wells can be repurposed for geothermal energy production, reducing a large portion of the costs associated with geothermal development. Medium geothermal gradient and soft sedimentary formations favor drilling new wells if necessary. Additionally, geothermal resources in the form of water and other heated fluids can be found along with oil and gas.

We mainly used three geothermal attributes including thermal conductivity, heat flow, geothermal gradient, and bottom hole temperatures (BHT). Next, preprocessing was

performed to remove spurious data. Next, we interpolated using the inverse distance weighting (IDW) technique to estimate values at unknown locations based on known locations. Next, we delineated the proper utilization of this geothermal energy for electricity production, spas & balneology, and greenhouse farming based on their temperatures at 1, 2, 3, and 4 km depths.

Three variables used in this study contained about 48% outliers. For instance, the maximum and minimum values for the temperature gradient far exceeded the appropriate range of the geothermal gradient throughout the U.S. Whereas the average geothermal gradient range in western Texas is contoured between 15 – 40°C/km, the provided data ranged between 0 - 1386°C/km [2]. We removed these outliers from the data by creating a new dataset that only included values that were greater than or equal to 15°C/km or less than or equal to 40°C/km. Additional outliers existed within the heat flow data set, so we instead opted to use the following formula to calculate new data for the heat flow throughout the West Texas region:

$$q = K_T \nabla T \quad (3.1)$$

where  $q$  is the heat flow (W/m<sup>2</sup>),  $K_T$  is the geothermal conductivity (W/mC), and  $\nabla T$  is the temperature gradient (C/m). To obtain accurate heat flow data, we located the thermal conductivity points either in the same location or closest to those in the new geothermal gradient dataset. To do so, we conducted a nearest neighbor calculation using a binary search tree or K-D tree to determine the shortest Euclidean distance between points based on the longitude and latitude data. The data provided by this calculation allowed us to extract only the points in thermal conductivity data that geospatially coincided with the new geothermal gradient dataset. Next, we performed the IDW described in the method section of Chapter 1.

## Utilization Scheme

Each industry has a unique temperature requirement to continue their business. For spas, a comfortable inlet water temperature is around 40 °C with 50 °C[[insert source here](#)]. While current spas can use water temperatures above 50 °C, this water requires additional cooling to achieve a safe temperature. Following Germany’s example, the maximum allowed inlet water temperature was 60 °C [[insert source here](#)].

The temperature required for heating systems in greenhouses ranges from 40 – 100 °C, as greenhouses can use various heating systems [[insert source here](#)]. These greenhouses can utilize this geothermal energy through finned pipes, fan coil units, soil heating, plastic tubing, cascading, bare pipes, unit heaters, or a combination [[insert source here](#)]. The heating method used in these greenhouses will determine the inlet temperature for the water.

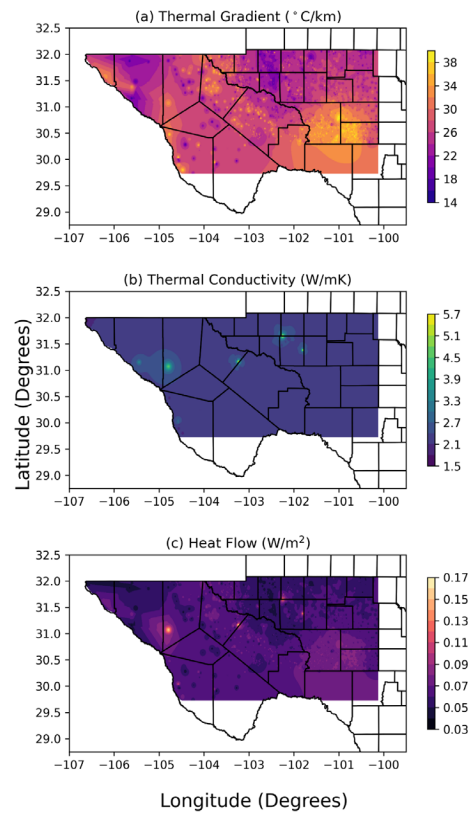
There are three major types of geothermal power plants in the market (cite) namely dry steam, flash steam, and binary (Table 3.1). A dry steam power plant primarily uses steam extracted directly from the geothermal reservoir. Flash steam is the most common type of power generation plants in operation today that use fluids at temperatures greater than 150 °C. This fluid is rapidly vaporized to produce vapor in order to spin a turbine. The power plant with the greatest potential for geothermal utilization however is the binary cycle power plant. This plant differs from the previous plants in that it uses the water acquired from the geothermal resource to heat a secondary fluid through a heat exchanger. The benefit here is that binary cycle power plants can use low-enthalpy fluids with temperatures ranging from 95 - 150°C.

**Table 3.1: A list of geothermal power plant types, corresponding fluid types and temperature ranges.**

Geothermal power plant type	Fluid type	Temperature range (°C)
Dry steam	Steam	>150
Flash steam	Liquid	>150
Binary	Liquid	95-150

## Results and Discussion

We received numerous attributes from the Bureau of Economic Geology, UT Austin. Among those attributes, only bottomhole temperature, geothermal gradient, thermal conductivity, and heat flow possess good quality data (Fig. 3.2). Continuous interpolated contour at 1 km depth of each attribute is shown in Fig. 3.2a-c.



**Fig. 3.2: Continuous contours of geothermal gradient (a), thermal conductivity (b), and heat flow (c) in the study area at 1km.**

Thermal gradient is the change in temperature per unit depth and is vital in determining temperatures at specified depths. The geothermal gradient in the study area had much greater variation in values than the other attributes and averaged  $27.5^{\circ}\text{C}/\text{km}$  with a maximum of  $39.5^{\circ}\text{C}/\text{km}$  and a minimum of  $15.3^{\circ}\text{C}/\text{km}$  (Fig. 3.2a). The average of  $27.5^{\circ}\text{C}/\text{km}$  is only 5.3%

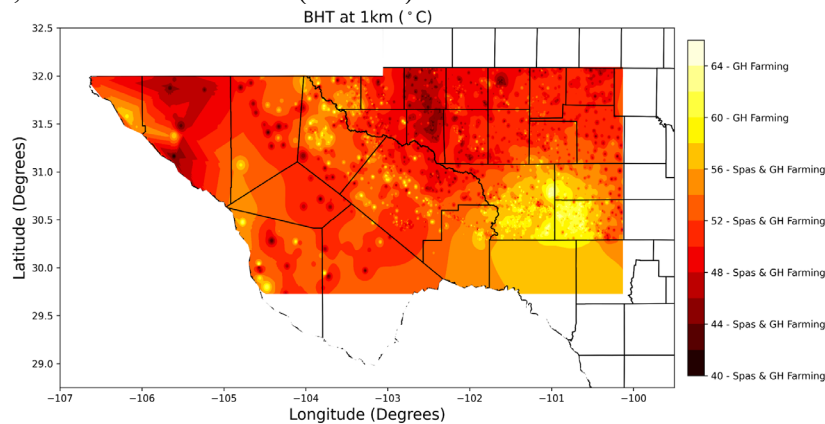


below the average gradient for the continental U.S. However, when compared to western states, the West Texas geothermal gradient was 21.14% below the 34°C/km value [5].

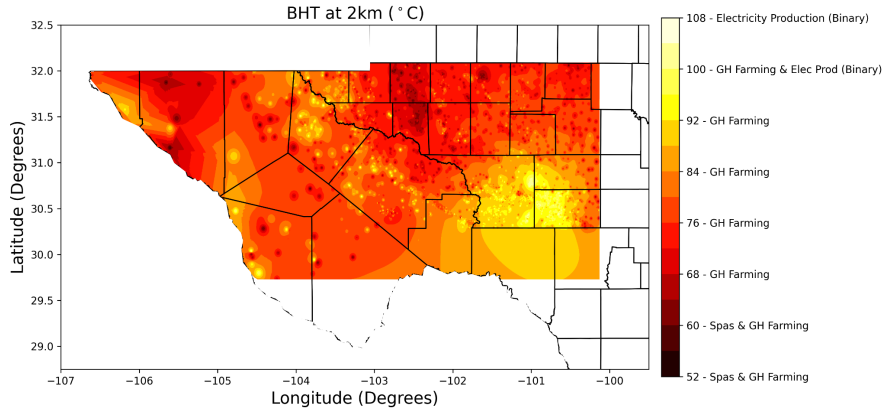
The thermal conductivity throughout the majority of the West Texas region lies at approximately 2.5 W/mK with spikes in conductivity up to 5.44 W/mK towards the western edge and throughout the center of the region (Fig. 3.2b). Thermal conductivity describes a material's ability to transfer heat through conduction. For a geothermal resource, thermal conductivity is critical to understand as it directly controls the steady state temperature field [3]. Additionally, it can have a large impact on required bore hole depth to meet the heating demands of a utility when utilizing a ground-source heat pump or ground coupled heat exchanger.

Heat flow in a geothermal context is, “the movement of heat/energy from the interior of the Earth to the surface” [4]. A larger heat flow is typically indicative of good geothermal heat production. Additionally, heat flow determines vertical conductive heat flow losses as geothermal fluids rise to the surface either naturally or through piping. Throughout the West Texas Region heat flow averages around 0.0637 W/m<sup>2</sup>, with a few spikes up to 0.1635 W/m<sup>2</sup> (Fig. 3.2c).

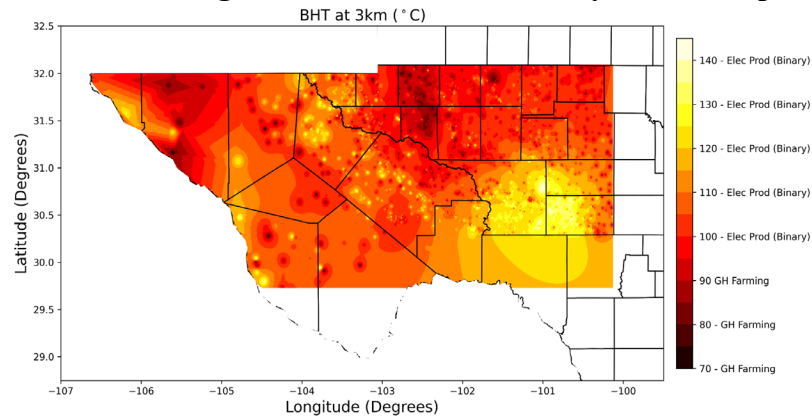
To determine the bore hole temperatures at depths between 1 km and 4 km with 1 km incremental depth, the geothermal gradient dataset was multiplied by the chosen depth and added to the standard surface temperature of 25°C. Utilities were then added to their corresponding temperature ranges on the plots to highlight the potential forms of utilization and their pervasiveness throughout the region (Figs. 3.3–3.6). Bottom hole temperature rises following geothermal gradients, ranging from a minimum of 40°C at 1 km to a maximum of 178°C at 4 km, hence the utilization (Table 2).



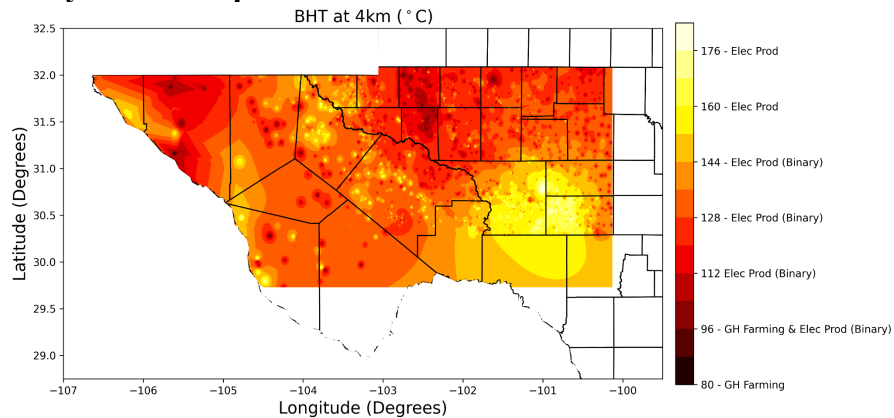
**Fig. 3.3: Spas could be a favorable utility at 1 km depth.**



**Fig. 3.4: Green house farming could be a favorable utility at 2 km depth.**



**Fig. 3.5: Electricity production through binary geothermal power plant could be a favorable utility at 3 km depth.**



**Fig. 3.6: Electricity production through binary & steam flash geothermal power plant could be a favorable utility at 4 km depth.**

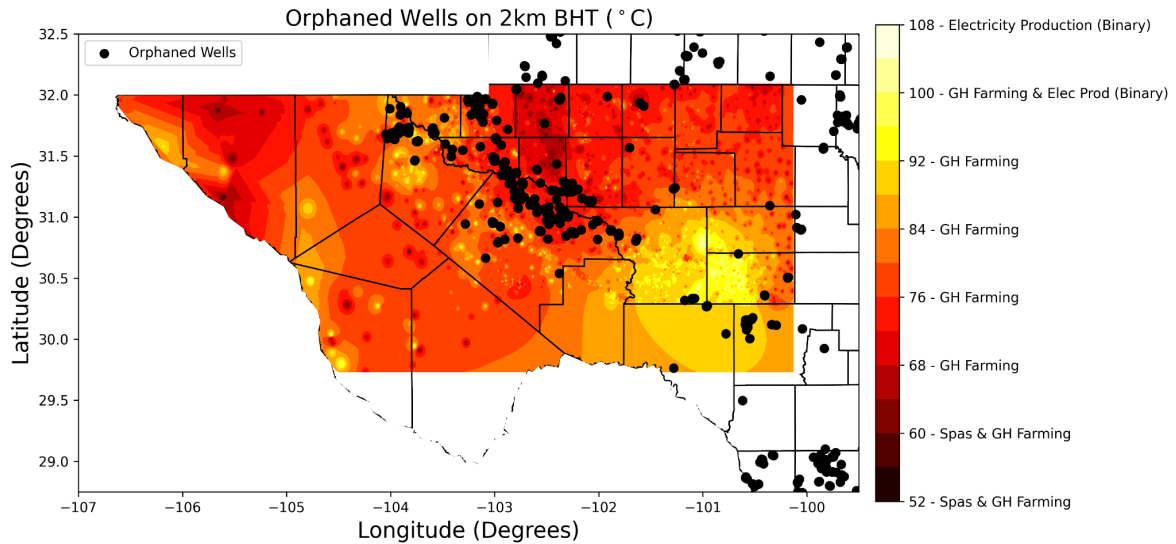
**Table 3.2. Summary of potential utilities for 1 - 4 km depth.**

Utility	1km	2km	3km	4km

Spas & GH Farming	98.94%	0.10%	N/A	N/A
GH Farming	1.06%	98.84%	6.8%	0.10%
GH Farming & Elec Prod (Binary)	N/A	0.93%	10.97%	0.21%
Elec Prod (Binary)	N/A	0.12%	82.24%	85.37%
Elec Production	N/A	N/A	N/A	14.32%

It is important to note that Table 3.2 is reflective of only the data points created from the interpolated datasets and not the actual geospatial locations. As displayed above, at 1km spas and greenhouse farming could potentially be the dominant utility encompassing 98.94% of the West Texas geothermal resources. However, beyond a 1 km, the temperature becomes too high to support safe and efficient geothermal spas, so spas are essentially infeasible. At 2 km the greenhouse farming utility dominates 98.84% of the potential available utilities. Since the average depth of crude oil and natural gas wells is approximately 2 km [6], geothermal greenhouse farming operations become the most potentially viable utilities if they are able to take advantage of the existing infrastructure. Additionally, 2 km is where it can be seen that some binary electricity production can begin to occur. At 3 and 4 km, binary electricity production becomes the dominant utility with some potential for greenhouse farming. Flash steam power plant is only feasible at or beyond 4 km. While BHT at 4 km is still considered “reasonable”, it is quite costly to drill that deep. If electric utility companies are willing to spend higher upfront costs, there is a large potential for the expansion of flash steam cycle energy production.

We also plotted orphan wells on top of the BHT map at 2km (Fig. 3.7). Many of the wells are located on top of geothermal resources that could be used for greenhouse farming with some located on resources that could be used to produce electricity from a binary cycle power plant (Fig. 3.7). These orphan wells might be a good avenue to reduce upfront cost to set up utility facilities.



**Fig 3.7: Orphan wells could be used to extract hot fluid; however, a detail study is required on whether they can sustain thousands of barrel fluid withdrawal in a day.**

## Conclusions

West Texas has a huge potential for certain geothermal utilization facilities ranging between spas to electricity production that varies with depth. For instance, at 1 km depth, geothermal spas could be a favorable utility while greenhouse farming can be expected to make great use of not only the geothermal resources, but the existing oil and gas infrastructure at 2 km depth. At 3 & 4 km, binary cycle power plants would predominantly use the geothermal resource to produce clean and continuous electricity. At 4 km depth, steam-flash power plant could be used to generate electricity although spatially sporadically. Orphan wells can be used to reduce cost; however, thorough study is required if they can sustain 1000s barrel fluid extraction in a day.

## Chapter 4: Machine learning and a process model to better characterize hidden geothermal resources

### Introduction

Geothermal is a growing renewable energy resource that can be utilized 24 hours a day without shutting off a geothermal power plant. However, in the U.S.  $\sim 3.7$  GJ/year ( $<1\%$ ) of electricity generation is from geothermal resources<sup>48</sup> although it has  $\sim 2 \times 10^{14}$  GJ/year tappable energy<sup>50,72</sup>. This potential energy resource is largely unexplored because many geothermal reservoirs are hidden or blind (no apparent surface exposures), which often leads to expensive and risky exploration<sup>73,74</sup>. Typically, play fairway analysis (PFA), adapted from the oil & gas industry, is performed for geothermal discovery, exploration, and development. PFA integrates available geologic, geophysical, and geochemical attributes indicative of

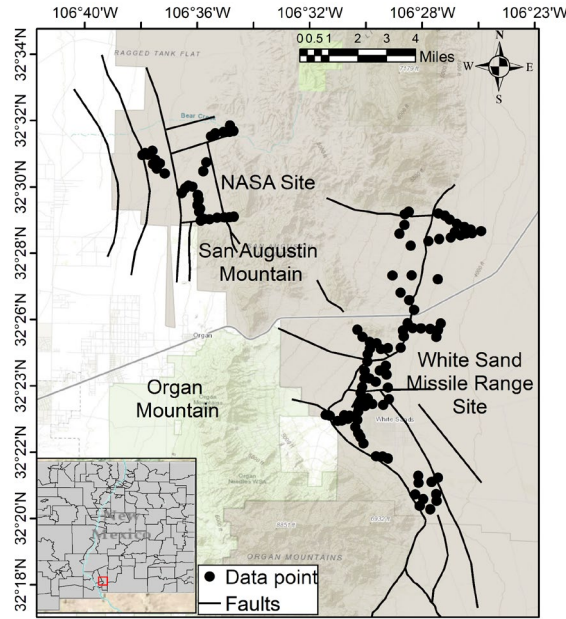
geothermal activity and estimates the importance of these attributes for the characterization of the geothermal resource<sup>75–80</sup>. PFA separately quantifies the relative importance of each attribute instead of simultaneous usage of all attributes. Here, we used a tool called GeoThermalCloud, which simultaneously analyzes available attributes, finds geothermal prospectivities, and discovers key parameters defining geothermal prospectivities<sup>1,37</sup>.

GeoThermalCloud (GTC) utilizes different machine learning (ML) methods. GTC can (1) analyze large field datasets, (2) assimilate model simulations (large inputs and outputs), (3) process sparse datasets, (4) perform transfer learning (between sites with different exploratory levels), (5) extract hidden geothermal signatures in the field and simulation data, (6) label geothermal resources and processes, (7) identify high-value data acquisition targets, and (8) guide geothermal exploration and production by selecting optimal exploration, production, and drilling strategies. Although GTC can implement different ML methods, its core component is an unsupervised machine learning (ML) called non-negative matrix factorization with customized  $k$ -means clustering (NMF $k$ )<sup>1,16,25,54</sup>. Here, we applied NMF $k$  to the Tularosa Basin PFA dataset collected by the Department of Energy (DOE).

The Tularosa Basin is located in the Basin and Range province, which exhibits high favorability of occurrence for geothermal resources due to high heat flow related to the Rio Grande rift. A few geothermal facilities have been developed within the Basin and Range province<sup>81,82</sup>. Recently, it has been the subject of geothermal studies due to its high geothermal potential coupled with the U.S. Army's interest in using the geothermal resource as an energy source for White Sands Missile Test Range and McGregor Range<sup>58,60,61</sup>.

Geologically, the Tularosa Basin is located on the eastern flank of the Rio Grande rift zone as a north trending, intermontane graben located in south central New Mexico. It is bounded to the east by the uplifted Sacramento Mountains and to the west by the uplifted Organ and San Andreas Mountains. Faults related to the Rio Grande rift with several thousand feet of displacement separate the basin from the surrounding, uplifted mountains. Stratigraphically, the Tularosa Basin consists of Paleozoic limestones and shales to Tertiary age rocks<sup>58,60–62</sup>. Rifting during the Paleogene resulted in characteristically high heat flow in south-central New Mexico<sup>83,84</sup>. High heat flow makes the southern part of the Tularosa Basin favorable for geothermal exploration.

Recently, the DOE has collected data to develop geothermal fields in the Tularosa Basin. The data include geological, geophysical, geothermal, and geochemical attributes. Also, a comprehensive PFA study was conducted by Ruby Mountain Inc.<sup>39,84</sup>, and they demonstrated prospective geothermal locations. In this study, we curated data from the DOE Geothermal Data Repository and then used them as input parameters for GTC. Results from GTC provide insights into the relationship between attributes and prospective geothermal locations which we then compared to the PFA study by Ruby Mountain Inc.. Lastly, we discussed how NMF $k$  and Burns' equation<sup>34</sup> can be coupled to obtain a better understanding about prospective geothermal sites.



**Fig. 4.1: Data locations and Quaternary faults in the study area.**

## Data

In this study, we used a total of 10 attributes: temperature at 2m depth (*temperature @2m*), *heatflow*, *NaK-Giggenbach geothermometer*, *K-Mg geothermometer*, *NaK-Fourneir geothermometer*, *silica geothermometer*, *gravity*, *fault distance*, *quaternary fault density*, and *Li concentration*. All these attributes are critical for geothermal resources discovery and exploration. *Temperature @2m* has been used to explore geothermal fields at Dead Horse Wells, the Hawthorne Army Depot, and Emerson Passin in Nevada<sup>85</sup>. *Heatflow* defines how heat flows to the geothermal reservoir from the deep subsurface. Geothermometers (*NaK-Giggenbach geothermometer*, *K-Mg geothermometer*, *NaK-Fourneir geothermometer*, and *silica geothermometer*) are used to estimate potential reservoir temperature and geochemical processes in the reservoir. These geothermometers help estimate potential reservoir temperature leading to less number of exploratory well drilling. Gravity may represent secondary mineralization and help characterize geologic structure<sup>86</sup>. Faults can act as conduits of (1) groundwater flow water from depth to the ground surface as well as (2) groundwater recharge. We have two fault attributes: fault distance and quaternary fault density. Fault distance represents distance from fault to the data point. Fault density (quaternary) is the number of faults per square meter of an area. Finally, *Li concentration* is a geochemical element that represents deep fluid circulation. All these attributes were used at 120 locations (Fig. 4.1)

However, all attributes are dispersely located and are not available at 120 locations except *temperature @2m*. We applied different interpolation techniques to sample all attributes at the specified 120 locations. For *heatflow*, *NaK-Giggenbach geothermometer*, *K-Mg geothermometer*, *NaK-Fourneir geothermometer*, *silica geothermometer*, *gravity*, and *Li concentration* interpolation was used by making the study area as a grid. Interpolation was performed based on block mean, kriging, and inverse distance weighting. Next,  $R^2$  score was

computed based on interpolated values and real values. We found all methods provide equivalent  $R^2$  scores. Block mean was selected as the optimal interpolation method because it takes least time to execute. The interpolated values were used in the nearest neighbor algorithm to sample 120 values at 120 locations. The nearest neighbor algorithm finds mean value based on either radius or number of points around a point. Here, we use radius to find the mean value. The radius was calculated based on variogram study in the data.

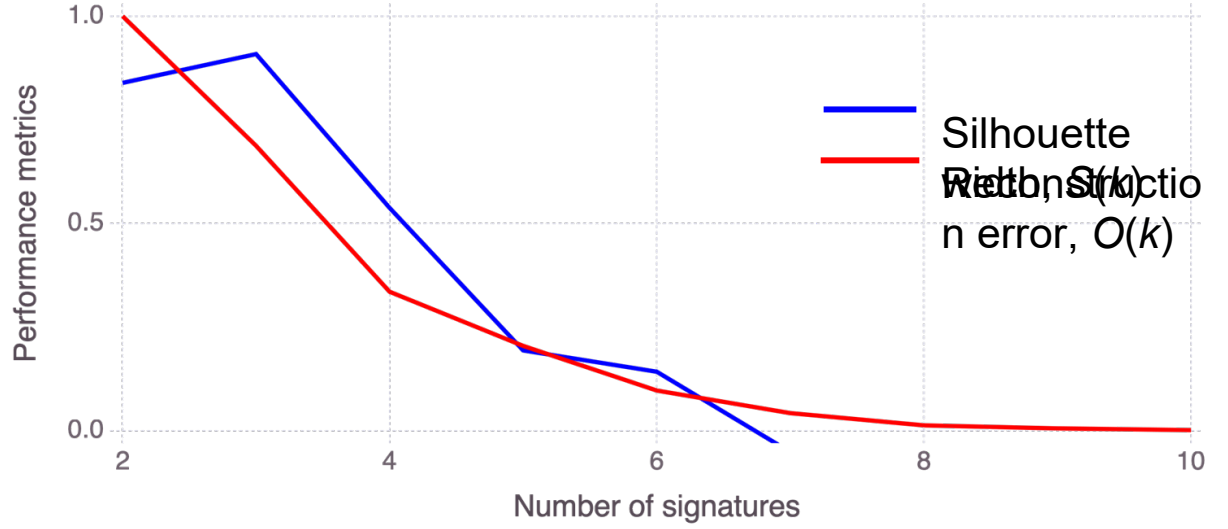
Fault distance and fault density were estimated using different approaches. For estimating fault distance, we generated a normal raster on ArcMap. The raster was converted to points. Next, a near coverage tool on ArcMap was used to compute the distance of each point from nearest faults. For estimating fault density, we also generated normal raster followed by converting points. Next, the near coverage tool was used to find the distance from point to nearest faults. Finally, the kernel density function was used to calculate fault density. Unit of fault density is  $m/m^2$ .

For developing a neural network based ML model, we generated data based on Eastern Snake River Plain by varying input parameter ranges based on variance and mean of data using Eqn. 6. Next, we form a 1D deep neural network with three layers. Each layer has 256, 128, and 64 layers, respectively. We used relu as the activation function. We trained the model for 500 epochs with a learning rate of 0.001. Using a data matrix instead of generating files is the main benefit of utilizing the neural network model. Also, point based prediction is feasible with the neural network based model that is not possible with Burns' equation.

## Results

Fig. 4.2 shows the reconstruction quality  $O(k)$  and average silhouette width  $S(k)$  for different number of geothermal signatures,  $k$ .  $O(k)$  values exponentially decrease with the increase of the number of signatures. However, that is not generally true for  $S(k)$ . Although optimal solutions have low  $O(k)$  and high  $S(k)$  values, their optimal values are not theoretically established. Generally, low  $O(k)$  and  $S(k) > 0.25$  can be considered to be acceptable. Here, the solutions for  $k=2, 3, 4, 5$ , and  $6$  were accepted, while the  $k=8$  to  $10$  solutions were rejected by the algorithm. This conclusion is based on the high  $S(k)$  values ( $> 0.25$ ) and the  $O(k)$  decline curve (Fig. 4.2). The  $k=4$  solution is found to be optimal because of its low  $O(k)$  and high  $S(k)$  values. The solution with  $k < 4$  is an underfitting representation of data while  $k > 3$  is an overfitting representation of data. In the following paragraphs, we will describe each signature of the  $k=4$  solution (Fig. 4.3(a&b)).

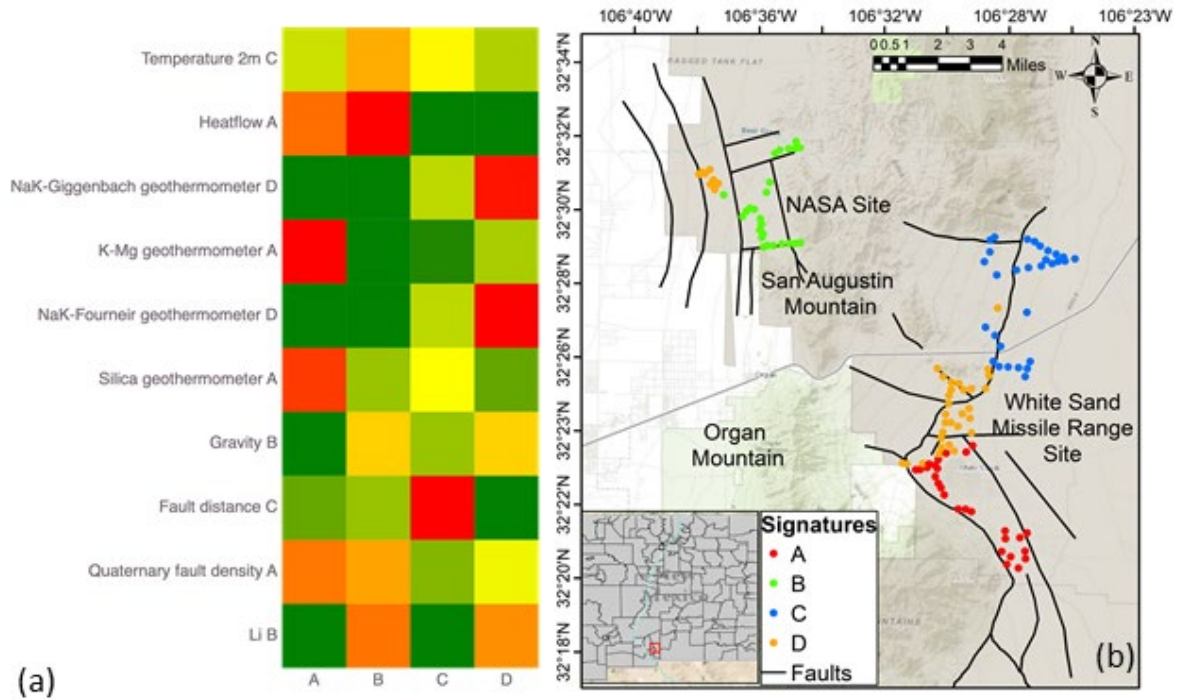




**Fig. 4.2: NMF $k$  results for normalized reconstruction quality/fit  $O(k)$  in red color and solution robustness (based on the average silhouette  $S(k)$  width of the clusters) in blue color for different numbers of signals  $k$ .**

Fig. 3(a) shows a heatmap of signatures found by GeoThermalCloud. Each signature captures certain characteristics in the dataset. Colors in each signature represent the contribution of each attribute. Green, yellow, and brown-red colors represent minor, moderate, and major contributions, respectively. Note, minor and major contributions also means low and high attribute values in the actual dataset.

The dominant attributes of Signature A are *heat flow*, *K-Mg geothermometer*, *silica geothermometer*, and *quaternary fault density* (Fig. 3a). Heat flow is one of main geothermal attributes while *K-Mg* and *silica geothermometers* potentially represent high reservoir temperature. Low contribution from *NaK-Giggenbach* and *NaK-Fourneir geothermometers* suggests that geochemical processes in the reservoir are not controlled by Na enriched minerals. High contribution of *quaternary fault density* may indicate elevated secondary permeability. The contribution of *Temperature @2m* is medium that is consistent with high *heat flow*. Another critical component of this signature is low contribution from *fault distance*. Low *fault distance* means fault is close to the locations associated with this signature that may lead to elevated secondary permeability. All these factors are good indicators for high geothermal prospects; therefore, the locations associated with Signature A have a high chance of having geothermal resources (Fig. 3b).



**Fig. 4.3: Geothermal signature heatmap (a) and their spatial distribution (b). Each signature captures certain characteristics in the data. Here, Signatures A and B represent highly prospective geothermal signatures. Green, golden, and red colors in (a) represent low, medium, and high contributions, respectively.**

The dominant attributes of Signature B are *Temperature @2m* and *heat flow*, *quaternary fault density*, and *Li concentration* (Fig. 3a). *Temperature @2m* and *heat flow* are two main geothermal attributes. The high contribution of *quaternary fault density* may indicate elevated secondary permeability. The high contribution from *Li* suggests a potential fluid circulation from the deep subsurface that is a good indicator of potential geothermal resources. The contribution from *fault distance* is also low. Low *fault distance* means faults are close to the locations associated with this signature. All these factors are good indicators for high geothermal prospects; therefore, the locations associated with Signature B have a high chance of potential geothermal resources (Fig. 3b). However, no geothermometers had major contributions on this signature except close to medium contribution from *silica geothermometer* suggesting the geothermal potential is not as high as Signature A. a careful approach should be taken prior to making any decision about geothermal resource development.

No geothermal attributes had a major contribution on Signature C; therefore, we conclude that the locations associated with it have a low chance of possessing geothermal resources. In Signature D the dominant attributes are *NaK-Giggenbach* and *NaK-Fourneir geothermometers*. These attributes suggest that the reservoir has a high temperature. The medium and high contribution of *Quaternary fault density* and *Li concentration* suggest elevated secondary permeability and deep fluid circulation. However, *temperature @2m* and *heat flow* had low contribution. All these factors suggest that the locations associated with Signature D (Fig. 3b) may or may not have high prospectivity. However, Signature D has

some positive characteristics for exploring geothermal resources and because of its proximity to Signature A (high prospective signature), there is some potential for sustainable geothermal resources in the locations associated with Signature A. Note, the prospective geothermal locations are consistent with the Ruby Mountain's PFA prospective locations.

NMFk results help us discover potential geothermal resources and their spatial locations. Regional hydrogeological and geothermal conditions would facilitate a better understanding on whether we can develop a long-term geothermal facility here. To obtain such results, we can apply Eq. (3) to compute aquifer temperature, viscous heat flux, vadose heat flux, and advective heat flux. Among these four attributes, viscous heat flux and advective heat flux could be used to estimate the potential time to heat up the geothermal reservoir temperature during energy production and injection; hence, the viability and sustainability of geothermal reservoirs. We coupled the Burns' equation with NMFk and GeoThermalCloud has the capability to perform such tasks. However, we could not demonstrate a study because of lack of data. We will conduct and demonstrate such a study if we receive a good dataset in the future.

## Conclusions

Tularosa basin has potential geothermal resources, which can be used to support several federal facilities in the area. To find geothermal prospects, we studied 10 attributes at 120 locations. Attributes include *temperature @2m*, *heatflow*, *NaK-Giggenbach geothermometer*, *K-Mg geothermometer*, *NaK-Fournier geothermometer*, *silica geothermometer*, *gravity*, *fault distance*, *quaternary fault density*, and *Li concentration*. The dataset was used as input parameters to GTC. GTC finds four signatures (A, B, C, and D), two of which are geothermal signatures. The locations associated with Signatures A and B have high geothermal resource prospectivities that are spatially consistent with the Ruby Mountain's PFA study. We also found that the locations associated with Signature D are not as prospective as Signatures A and B, but they might assist a sustainable geothermal reservoir in the area around the locations of Signature A. The key attributes defining the geothermal resources are *heat flow*, *K-Mg geothermometer*, *silica geothermometer*, *quaternary fault density*, *temperature @2m*, *fault density*, and *Li concentration*. Finally, we discussed how we can couple an existing analytical equation to GTC computing the viability and sustainability of geothermal reservoirs.

# Chapter 5: A FORGE Datathon Case Study to Optimize Well Spacing and Flow Rate for Power Generation

## Introduction

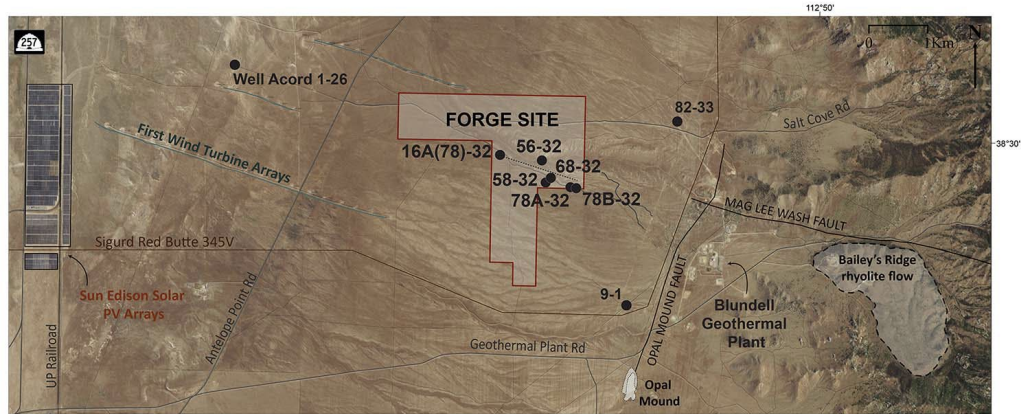
Enhanced geothermal systems (EGS) present a significant and long-term opportunity for widespread power production and direct heat<sup>74,87</sup>. But high exploration costs combined with uncertainties associated with subsurface characteristics (such as permeability, reservoir

temperature, fault connectivity, geochemistry, and *in situ* stress distribution) have impeded the geothermal market growth<sup>74,87</sup>. Moreover, building a profitable EGS is a major challenge. Profitable EGS fields will depend on many design parameters<sup>3,4</sup>. We will focus on the parameters of reservoir depth, project lifespan, injection temperature, well spacing, well length, well azimuth, well depth, well skew (i.e., non-parallel wells), well count, well toe (i.e., decreasing well spacing from heel to toe), well proportion (i.e., the ratio of injection well length to production well length), well phase (i.e., the placement of the production well above, beside, or below the injection well), well intervals (i.e., the number of isolated perforation clusters), production well pressure drawdown, stimulation flow rate, stimulation volume, and circulation flow rate. Finding optimal values for these design parameters is a computationally expensive task to say the least.

To tackle this challenge, PIVOT (a conference supported by the U.S. Department of Energy) organized a first-ever Geo Datathon event in 2022<sup>88</sup>. The primary goal of this Datathon was to identify production well placement. Participants in this event used different machine-learning methods to solve a geothermal engineering problem on a simulated dataset of the Utah FORGE site (Fig. 5.1). Data for the Datathon was generated by geothermal design tool (GeoDT) to investigate the power production potential of an EGS system. In this event, six teams (*Team Naturals*, *Benjamin Cassidy*, *Pebbles*, *GeoT360*, *S-Team*, and *GeotherML*) completed the competition. *Team Naturals* of Stanford University, *Benjamin Cassidy* of Hammer and Tongs Polymer Development, and *Pebbles* of the Colorado School of Mine were awarded champion, 1st runner up, and 2nd runner up, respectively.

Despite a short time for the competition and a challenging task, each team made a great contribution to identifying suitable locations for the production well. *Team Naturals* included metrics for risk by considering averages and standard deviations in power production. Also, they clearly demonstrated that net power production was not the best value to optimize. *Benjamin Cassidy* applied a unique set of approaches to the ML challenge to optimize well placement from more than one perspective. Crucially, these competitors also revealed several problems that needed to be solved to get the best answer to optimizing the well spacing: (1) identifying a suitable objective function (e.g., net present value), (2) finding a robust optimization method for the complex dataset, and (3) accounting for uncertainty and risk tolerance.

Here, the primary purpose of our study is to find optimal well spacing ( $w\_spacing$ ) and per-interval circulation flow rate ( $Q_{inj}$ ) for the same dataset. First, we define a new objective function, which yields reduced parameters for comparing realizations, e.g., average power or net present value (NPV) in dollar amount. We chose NPV because it provides the best estimate of monetary value. Second, we developed a binning-based optimization approach. Third, we identified optimized  $w\_spacing$  and  $Q_{inj}$  with an assessment of uncertainty.



**Fig. 5.1: Utah FORGE site with the injection well 16A(78)-32 and five monitoring wells (taken from Moore et al. 2021<sup>89</sup>).**

## Net Present Value (NPV) Estimation

Our new economic module in GeoDT yields estimated NPV in circa 2019 U.S. dollar amounts for a hot dry rock EGS geothermal project<sup>90</sup>. Such a reduced value is critical for optimizing geothermal design parameters. This module considers capital costs, maintenance costs, pumping costs, and power sales. Following the theme of fast-simplified physics, this module uses simplified methods to estimate costs where the underlying goal is to give a conservative view of the economic potential of a project. The cost terms that we employ in this study are summarized in Table 5.1. True costs for an EGS site depend on many factors beyond what our simple model includes. Ultimately, we use this cost model as an objective function to better contrast increasing power production with increasing capital costs and other financial risks.

**Table 5.1: Constants used to estimate NPV.**

Parameter	Unit	Value	Reference
Electricity sales per kilowatt-hour	USD/kWh	0.1372	EIA, 2022
Drilling cost per length	USD/m	2763	Lowry et al., 201
Drill pad cost	kUSD	590	Lowry et al., 201
Power plant cost	USD	2026	GETEM
Exploration cost per depth	USD/m	2683	GETEM
Operating cost per kilowatt-hour	USD/kWh	0.0365	GETEM

Outputs from GeoDT that pair with these cost factors include the net power output ( $P_{out}$ ) for each model timestep and timestep parameters (TimeSteps and LifeSpan). The net power production term ( $P_{out}$ ) for the Datathon only included the flash steam cycle for power

generation. In this study, we add a simplified estimate for isobutane binary-cycle power generation and an improved estimate of injection well pumping losses that accounts for open-loop fluid losses (<https://github.com/GeoDesignTool/GeoDT>). Each power term includes the effect of inefficiencies, with this study using a conservative 85% efficiency (GenEfficiency). Discrete fracture networks with open-flow boundaries formed the basis of all the GeoDT models.

## Data Description

The 16 most critical controllable design parameters (Table 2) can be divided into four categories: reservoir/site, power cycle, well, and stimulation. Of these, only 10 design parameters were varied to a meaningful degree because the first well at the site, well 16A(78)-32, has already been drilled at a diameter of 0.11 m to a depth of 2350 m with a highly-deviated lateral length of 1114 in the direction of 1.833 radians Azimuth at a dip of 0.483 rad below the horizon. This azimuthal direction is near-parallel to the in-situ minimum horizontal stress direction. Reservoir depth is the only controllable reservoir parameter, but it is not a variable in this study because of the preceding reasons. Injection temperature was the only power cycle parameter that was varied because this study focuses on subsurface EGS design optimization, not power systems engineering. While GeoDT is capable of modeling hydraulic stimulation separately from circulation, in this study the circulation stage is treated as a continuous stimulation stage for the lifespan of the EGS, so we did not parameterize these two stages independently. In other words, GeoDT predicts hydraulic fracturing and shearing at the same rate of injection as what is used for long-term circulation and heat mining. Our focus for design optimization will be set on well spacing ( $w\_spacing$ ) and per-interval circulation rate ( $Q_{inj}$ ) because these two terms were predicted to be first-order controls for power production.

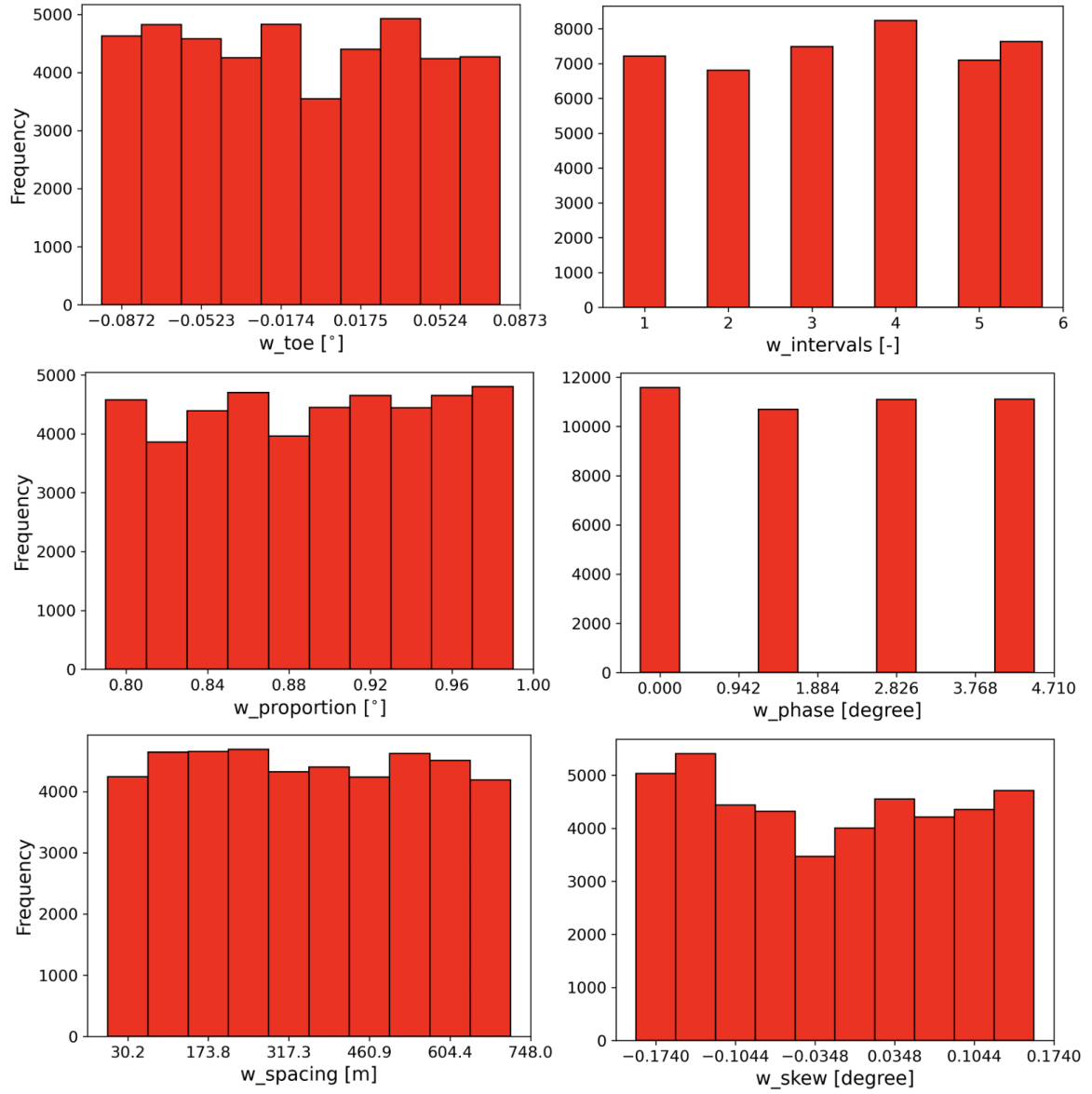
**Table 5.2: EGS project design parameters and corresponding units, minimum and maximum values, and their statistical distributions. Parameters in green color cells were optimized in this study.**

Category	Variable	Parameter	Unit	Min Value	Nominal value	Max Value	Distribution
Site	ResDepth	Nominal reservoir depth	m	2340		2360	
Power cycle	LifeSpan	Project lifespan	yr		30		-
Power cycle	Tinj	Injection temperature	C	85		99	-
Well	$w\_spacing$	Well spacing	m	50		1000	Uniform
Well	$w\_length$	Well length	m		1114		Lognormal
Well	$w\_azimuth$	Well azimuth	deg		1.833		Uniform
Well	$w\_dip$	Well dip	deg		0.438		Uniform

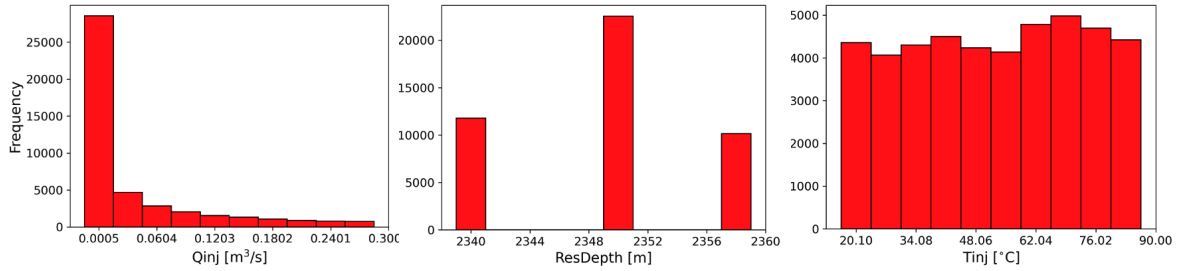
Well	w_skew	Well skew	deg	-10		10	Uniform
Well	w_count	Well count	well s	1		4	Uniform
Well	w_toe	Well toe	deg	-5		5	Uniform
Well	w_proportion	Well proportion	deg	0.8		1.1	Uniform
Well	w_phase	Well phase	deg		0, 90, 180, 270		Uniform
Well	w_intervals	Well intervals	zone s	1		6	Uniform
Well	dPp	Production well pressure rise	MPa	-10		2	Uniform
Well	perf	Perforation count	perfs		1		Uniform
Stimulation	Q <sub>inj</sub>	Circulation flow rate	m <sup>3</sup> /s	0.001		0.1	Exponential

Using statistical distributions for all the known and unknown site, fracture network, and design parameters, 44,492 realizations were generated for the Datathon (PIVOT, 2022). All the well parameters were generated using uniform distributions. The minimum and maximum values of the distribution are listed in Table 5.2, and histograms of six example parameters are shown in Fig. 5.2. The lifespan of the field was considered only 30 years, and injection temperatures varied from 85-99°C (Fig. 5.3). The injection rates per-interval ( $Q_{inj}$ ), which also serve as the stimulation rates, were generated using exponential distribution because this offers improved resolution for realizations with low flow rates, relative to the maximum simulated flow rate. When the optimal flow rate is not known, the exponential distribution helps explore a larger probability space in order to more clearly identify the optimal flow rates.





**Fig. 5.2: Distribution of design parameters for well.**

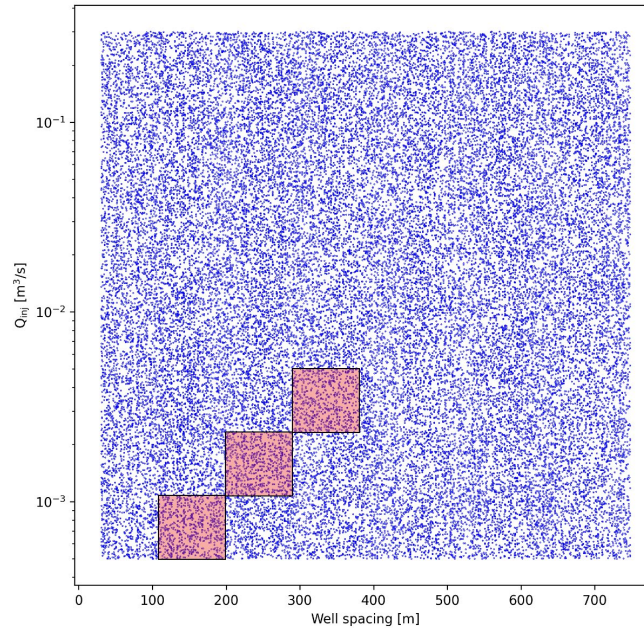


**Fig. 5.3: Distribution of injected flow rate ( $Q_{inj}$ ), reservoir depth ( $ResDepth$ ), and temperature of injected fluid ( $T_{inj}$ ).**

## Methods

In any optimization technique, identifying a suitable objection function is a crucial first step. Here, our goal is to maximize the NPV value of a geothermal project because NPV provides a common framework to measure the relative benefit and cost of each design decision. This contrasts with optimizing power production where the most productive scenarios can be unreasonably expensive with respect to drilling and pumping costs. The traditional parameter estimation study fits a physical model to data, finding optimal parameters. Such a study finds a single optimal value for each parameter and then the Markov chain Monte Carlo (MCMC) method or its variant is performed to generate distributions of parameters to provide uncertainty of the value in its distribution. However, MCMC cannot provide uncertainty based on the most likely scenarios for peak NPVs, an important attribute to investors.

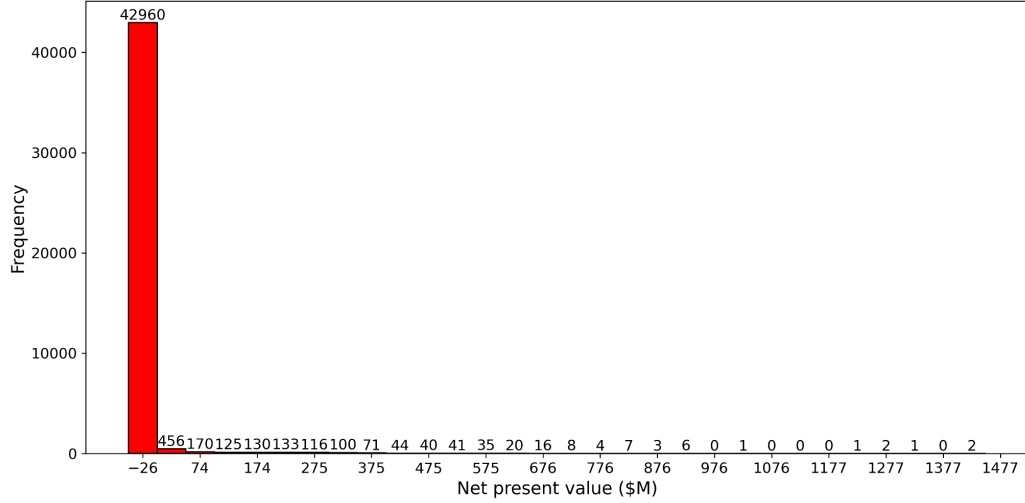
Investors would like to see what is the most likely chance of a profitable geothermal project based on NPVs; for instance, what are the 10<sup>th</sup>, 50<sup>th</sup>, and 90<sup>th</sup> percentile of NPVs for a given set of design parameters? Therefore, we chose binning-based optimization in this study (Fig. 5.4). In this technique, we define a bin volume based on discrete splitting of the design parameter values of injection rate and well spacing. Then, we compute NPVs of each realization in the corresponding volume. Finally, we compute the 10<sup>th</sup>, 50<sup>th</sup>, and 90<sup>th</sup> percentile of NPVs and their corresponding design parameters. Here, percentile values of NPV demonstrate the profitability of geothermal fields while the design parameter ranges provide the range within which the NPV would be profitable. For this study,  $w\_spacing$  and  $Q_{inj}$  were evenly split into 9 and 4 intervals, giving a total of 36 bins for our realizations. Nine intervals provided the finest discretization that yielded suitably large populations of data within each bin for achieving statistical significance.



**Fig. 5.4: Binning based optimization technique where blue dots represent each realization and red color rectangle shows example binned areas.**

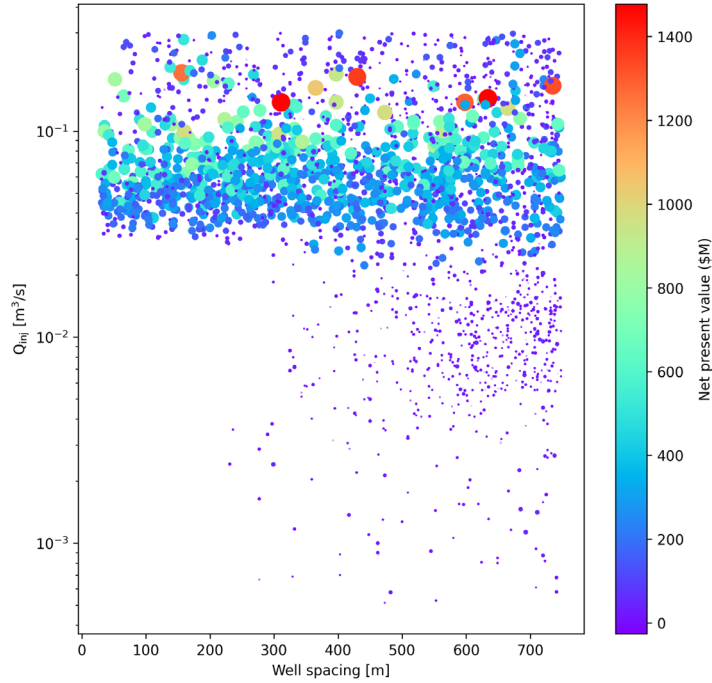
## Results

The model's NPV values are widely distributed, ranging from negative to hundreds of millions USD (Fig. 5.5). We plotted the frequency distribution plot of NPVs using 30 bins. The most common outcome was negative NPV due to the relatively cold 200°C temperature at the current depth of FORGE, when treated as an EGS. Out of 44,492, 42,960 (96.55%) realizations fall into this non-profitable category. Only 3.45% or 1,532 realizations fall into the profitable category. The profitable NPVs range from 0 to ~1500 million USD. The most likely profitable range was 25 to 676 million USD.



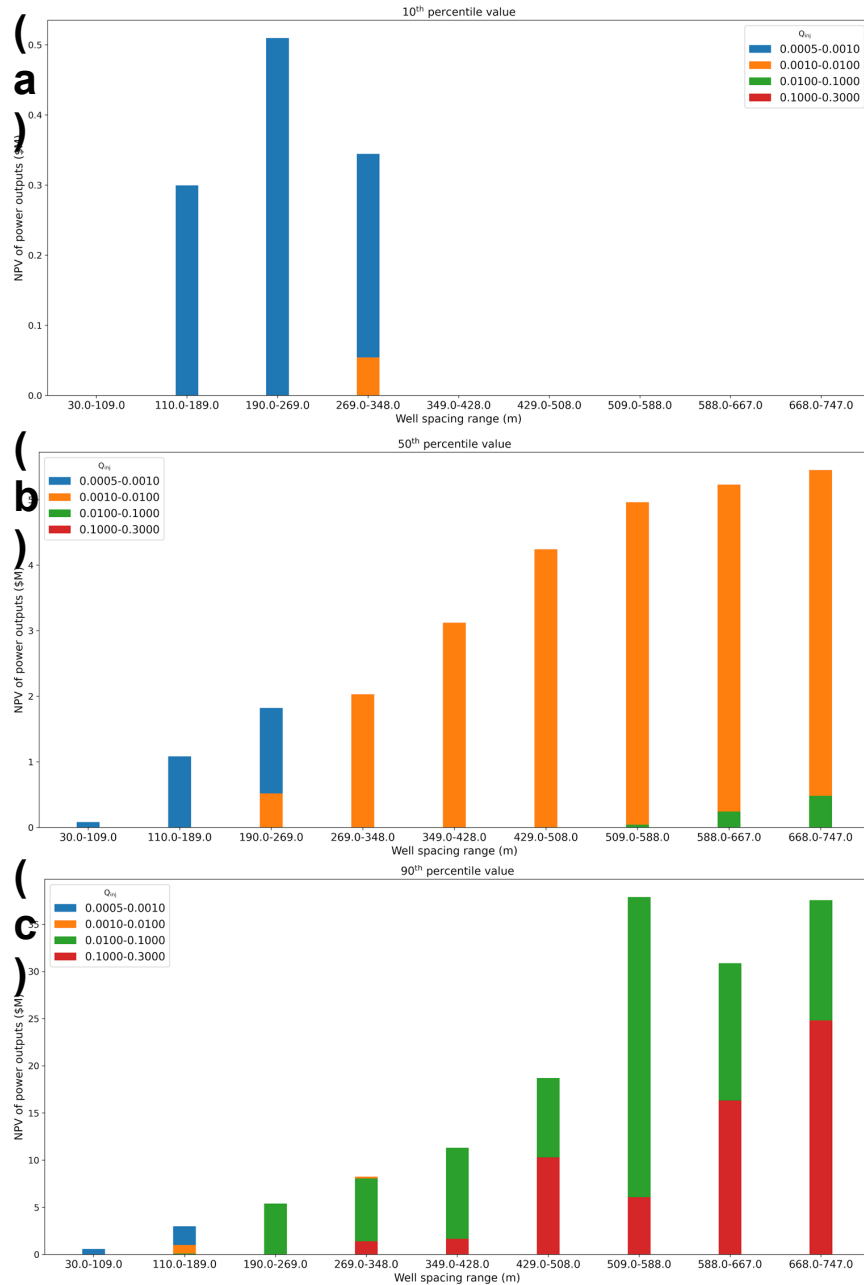
**Fig. 5.5: Histogram of NPVs where negative and positive values represent non-profitable and profitable geothermal fields, respectively. The number on top of each bar represents the total count of NPV for the corresponding bar. All drilling costs and pumping losses are included in this model.**

All NPVs are plotted against  $Q_{inj}$  and  $w_{spacing}$  in Fig. 5.6. Here, only positive or profitable NPVs are present, while negative values are absent. It is clearly shown that geothermal fields are non-profitable or marginally profitable for  $Q_{inj} < 0.01 \text{ m}^3/\text{s}$ . High and extreme  $Q_{inj}$  at rates above  $0.2 \text{ m}^3/\text{s}$  do not make a geothermal project profitable either. Therefore optimization of  $Q_{inj}$  is critical for achieving economic EGS, which confirms our apriori expectation but now better quantifies this trend. A similar optimization trend is less visible for  $w_{spacing}$  because profitable to non-profitable geothermal fields are present across the full  $w_{spacing}$  range. Therefore, we applied a binning-based optimization technique to find optimal  $w_{spacing}$  and  $Q_{inj}$ .



**Fig. 5.6: Positive (profitable) NPVs against  $Q_{inj}$  and  $w\_spacing$  where color and size represent NPVs. Warm and larger size circles represent higher NPVs or vice versa. Most of the realizations are not in this plot because of their negative USD values.**

The 10<sup>th</sup> percentile values show that profitable geothermal fields most likely occur between 110 to 348 m  $w\_spacing$  and 0.0005 to 0.001 m³/s  $Q_{inj}$  (Fig. 5.7a). Here, the closer space provides more profit because of the presence of fluid. The highest profit within the 10<sup>th</sup> percentile reached up to 0.5 million USD. The 50<sup>th</sup> percentile values demonstrate that profitable geothermal fields are feasible between 190 to 747 m  $w\_spacing$  and 0.001 - 0.01 m³/s  $Q_{inj}$  (Fig. 5.7b). The highest profit within the 50th percentile reached up to 5.5 million USD.



**Fig. 5.7: 10<sup>th</sup> (a), 50<sup>th</sup> (b), and 90<sup>th</sup> (c) percentile values of NPV in USD for different  $Q_{inj}$  and  $w\_spacing$  ranges.**

The 90<sup>th</sup> percentile values show more interesting characteristics across the ranges for both  $Q_{inj}$  and  $w\_spacing$  (Fig. 5.7c). Although all  $Q_{inj}$  seem profitable, the prominent  $Q_{inj}$  is 0.01 to 0.1 m<sup>3</sup>/s. The next most profitable  $Q_{inj}$  range is 0.1 to 0.3 m<sup>3</sup>/s. The  $w\_spacing$  range between 190 to 747 m is profitable. Among these ranges, the most profitable range is between 509 to 588 m. The next most profitable  $w\_spacing$  range is between 668 to 747 m. The highest profit within the 90<sup>th</sup> percentile can reach up to ~36 million USD. For both 50<sup>th</sup> and 90<sup>th</sup> percentile cases, low  $w\_spacing$  provides less profit, and high  $w\_spacing$  provides higher profits. This phenomenon contradicts the idea that close spacing will benefit from

having a better flow rate. Here, the total fluid volume generated more heat, thereby, more profits. So, it is clear that a total hot fluid volume is preferred to the flow rate in estimating NPV. In other words, more  $w\_spacing$  provides more volume facilitating more fluid extraction.

## Conclusions

We analyzed GeoDatathon data based on the Utah FORGE site parameters. The dataset has a total of 16 design parameters that control geothermal energy production, hence, its NPVs in USD. The primary goal of this study is to find the optimal design values for well spacing ( $w\_spacing$ ) and per-interval injection rate ( $Q_{inj}$ ) for developing profitable geothermal fields with specified uncertainties. We used a binning-based optimization technique to compute NPVs. We subdivided the whole realizations into 36 bins based on nine ranges for both  $w\_spacing$  and  $Q_{inj}$ . Following, NPV was calculated for all realizations in each bin. Next, we computed 10<sup>th</sup>, 50<sup>th</sup>, and 90<sup>th</sup> percentile scores of NPV in all bins. Based on the analysis, we came to the following conclusions:

1. The 10<sup>th</sup> percentile values demonstrate that profitable geothermal fields are feasible between 110 to 348 m  $w\_spacing$  and 0.0005 to 0.001 m<sup>3</sup>/s  $Q_{inj}$ . The maximum profit can reach up to 0.5 million USD.
2. The 50<sup>th</sup> percentile values demonstrate that profitable geothermal fields are possible between 190 to 747 m  $w\_spacing$  and 0.001 - 0.01 m<sup>3</sup>/s  $Q_{inj}$ . Low  $w\_spacing$  provides less profit, and high  $w\_spacing$  provides high profits. The maximum profit can reach up to 5.5 million USD.

The 90<sup>th</sup> percentile values are better to consider than the 10<sup>th</sup> and 50<sup>th</sup> percentile values because of (1) higher certainty and wide ranges of  $w\_spacing$  and  $Q_{inj}$ . The most profitable  $Q_{inj}$  is between 0.01 to 0.3 m<sup>3</sup>/s. The  $w\_spacing$  range between 190 to 747 m is profitable. Among these ranges, the most profitable range is between 509 to 588 m. The next most profitable  $w\_spacing$  range is between 668 to 747 m. The maximum profit can reach up to 35 million USD.

## Chapter 6: Coupling Thermo-hydro-chemical Modeling and Markov Chain Monte Carlo Method for Permeability and Porosity Estimation in a Geothermal Reservoir

### Introduction

Accurate geothermal reservoir characterization and maintenance help design a profitable geothermal power plant<sup>3,91</sup>. Specifically, accurate estimation of permeability and porosity is crucial for understanding the fluid flow mechanism and resources estimation of a geothermal field. For instance, higher permeability and porosity values could provide over-optimistic

resources estimation and resources extraction mechanism or vice versa. However, the detailed permeability and porosity field of geothermal fields remain unknown because of sparse core measurements. Crucially, there is no workflow for determining permeability and porosity values with quantified certainties from sparse measurements. The primary goal of this study is to demonstrate a workflow, which estimates the permeability and porosity distribution in a geothermal site from sparse core measurements.

There are several studies predicted permeability of geothermal reservoirs using either numerical simulation or lab experiments<sup>92–98</sup>. One notable study was performed by Jafari and Babadagli<sup>95</sup> on estimating correlation coefficient of fractures by investigating the fractal and statistical parameters of fractures. The major limitation of this study is that they did not use critical geothermal measurements e.g., groundwater temperature and tracer concentration to constrain the model. Catinat et al.<sup>96</sup> used nuclear magnetic resonance measurements to establish a relationship between porosity and permeability. This approach is reliable with two limitations (1) data are sparse and (2) fail to provide a good relation if one considers the total porosity. Weibel et al.<sup>93</sup> developed a relationship between porosity and permeability in low enthalpy geothermal reservoirs by investigating the effect of diagenesis on sandstone permeability. However, they did not verify the relationship with groundwater temperature and tracer concentration. Jiang et al.<sup>97</sup> estimated heterogeneous permeability distributions in an enhanced geothermal synthetic reservoir by combining an autoencoder neural network and a Bayesian inversion algorithm based on Markov chain Monte Carlo (MCMC) sampling. They used single-well injection withdrawal as measurement data that are not readily available. Suzuki et al.<sup>98</sup> developed a supervised machine-learning-based model based on random forest for estimating permeability distributions for a geothermal field using temperature and pressure distribution as measurements.

The preceding studies did not estimate permeability or porosity constraining the model based on critical attributes for geothermal exploration. The critical attributes are groundwater temperature and tracer (e.g.,  $\text{Li}^+$ ,  $\text{Ba}^{2+}$ ) concentration in the subsurface. Groundwater temperature captures thermal gradient or heat flow while tracer concentration indicates deep fluid circulation<sup>1,99</sup>. Moreover, they are easy to measure and USGS installed numerous wells to measure these two attributes. To address the limitations, we estimated permeability and porosity of a 3D reservoir scale model constrained by groundwater temperature and tracer concentration.

For such a parameter estimation study, a large number of the simulation of the flow, heat flux and chemical transport are often needed. Although the high fidelity coupled thermal-hydrologic-chemical (THC) model is reliable and accurate on performing this task, the computational cost is huge. With the growth of the parallel computing hardware like Graphical Processing Units (GPU), integrating machine learning (ML) tools could greatly speed up the simulations while maintaining accuracy. In this study, we train a deep CNN model as the surrogate using a relatively small and accurate simulation dataset obtained from the coupled THC model runs using PFLOTRAN<sup>44</sup>. Next, we generated 6,000 realizations of permeability and porosity distribution coupling the CNN model and MCMC sampling. Moreover, we discuss when MCMC performs better.



## Data Generation

This study is on thermal-hydrologic-chemical physical processes involved in heat conduction and energy transfer due to fluid flow and chemical transport in a site-scale reservoir<sup>100</sup>. The governing equations for fluid flow, chemical transport, and heat transfer processes are explained in Mudunuru et al.<sup>100</sup>. This study develops a 3D model with heterogeneous and anisotropic porous geologic systems representing the Tularosa Basin in New Mexico using PFLOTTRAN. The model dimension is 6000 x 6000 x 6000 m<sup>3</sup>, discretized into 10 x 10 x 30 grid cells. We developed such a big model to capture the optimal temperature distribution in the model domain<sup>101</sup>.

The PFLOTTRAN simulator takes the following terms as the variable input: the permeability, the initial temperature profile, the heat flux on the bottom of the reservoir modeling the geothermal resource, and the tracer concentration of lithium and boron. Other modeling parameters such as fluid thermal conductivity, solid thermal conductivity, rock density, and diffusivity are known and are considered uniform over the simulation domain. Same Neumann boundary conditions are applied to the west, east, north, and south faces of the 3D rectangular domain, i.e. no flow, no heat or concentration flux. The pressure on the top and bottom faces are fixed, with the bottom pressure higher; resultantly, the flow is upward. Zero concentration and zero concentration flux are assumed on the top and bottom surfaces. The only varying boundary condition is the heat flux on the bottom face.

Aiming for a neural network surrogate model to predict the pressure, tracer concentration, and temperature field, we adopt a dataset contains various combinations of a stratified permeability field, initial temperature gradient, and heat flux on the bottom as the input, the corresponding future temperature gradient, liquid pressure, tracer concentration as the output.

The initial temperature field is determined with the initial temperature gradient, initial temperature at top surface is assumed to be 25°C. In the entire domain, the temperature is proportional of depth assuming a uniform geothermal gradient of 25°C. The bottom heat flux and initial temperature gradient are randomly drawn from the uniform choices shown in Table 6.1. The permeability field of the modeling domain is discretized into nine geologic layers. The rock types, depth, and range of permeability of each layer are listed in Table 6.2<sup>1,102</sup>. The temperature, tracer, and pressure distribution at first and last time steps are shown in Figs 6.1 and 6.2, respectively.

**Table 6.1: Input parameters ranges for the initial temperature gradient and the bottom heat flux.**

Parameter Name	Uniform random choices
Initial temperature gradient: °C/m	[0.023, 0.024, ..., 0.04]
Bottom heat flux: W/m <sup>2</sup>	[0.06, 0.07, 0.08, 0.09]

**Table 6.2: Permeability of the 9 layers. The permeability of each layer is drawn from the three choices following Gaussian distribution.**

Layers	Rock type	Thickness [m]	$\log_{10}k$ [m <sup>2</sup> ] range
Layer 1	Fluvial sediments	800	$[-13, -12, -11]$
Layer 2	Lava flow and ash flow	1000	$[-17, -16, -15]$
Layer 3	Sandstone, shale, and conglomerate	2000	$[-18, -17, -16]$
Layer 4	Sandstone, shale, and conglomerate	200	$[-18, -17, -16]$
Layer 5	Mudstone, sandstone, and siltstone	200	$[-16, -15, -14]$
Layer 6	Limestone, shale and dolomite	800	$[-12, -11, -10]$
Layer 7	Limestone and shale	200	$[-13, -12, -11]$
Layer 8	Limestone and dolomite	400	$[-14, -13, -12]$
Layer 9	Granite and metamorphic	300	$[-16, -15, -14]$

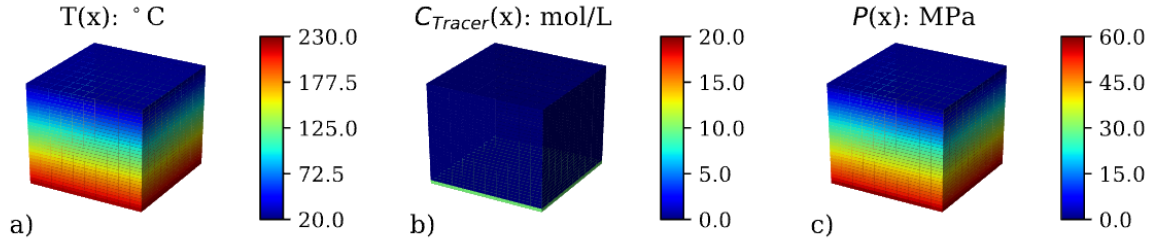


Fig. 6.1: Distribution of (a) temperature, (b) tracer, and (c) pressure at the first time step.

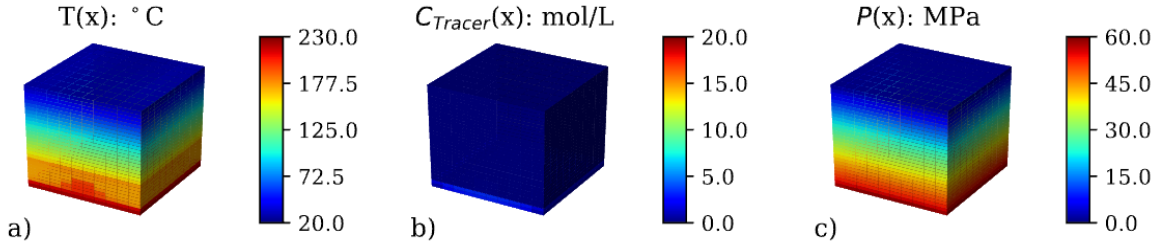


Fig. 6.2: Distribution of (a) temperature, (b) tracer, and (c) pressure at the last time step.

## Neural Network Surrogate

For the purpose of inverse analysis and MCMC approach, the model is evaluated multiple times. Consequently, the development of a surrogate model significantly accelerate the analysis. We train a deep neural network (DNN) in order to perform the same task as the PDE solver. For the surrogate model we choose an image-to-image 3D Convolutional Neural Network (CNN) with encoder decoder architecture because it performs well for simulating contaminants transports in the subsurface<sup>103,104</sup>. The input of the model is a 6 channel of  $10 \times 10 \times 30$  voxels, consisting the initial pressure, initial temperature, initial tracer concentration, permeability, porosity, and heat flux. For using heat flux as a boundary condition, the heat flux input is a 3D matrix with zero values everywhere except the bottom where the value of the boundary heat flux is given. The permeability in the vertical direction is defined as the 1/10 of the horizontal permeability and therefore the vertical input was not as an input as it would be redundant.

The kernel of the CNN model consists of  $3 \times 3 \times 3$ . For capturing physics in the dataset, the number of layers in the encoder part is increased while the number of voxels is decreased after every convolution. The proposed architecture is based on the DenseNet which transfer the features from all the proceeding layers to facilitate back propagation of gradient information<sup>105</sup>. The softplus is used for activation function. The decoder part takes the same steps as the encoder but in a reverse order; resultingly, the output matrices have the same dimensions as the input. The initial number of filters after the first convolution and the rate of increase of the filters after each following convolution for the encoding are two hyperparameter that are investigated for their influence in the model accuracy. The  $L_1$  norm is used as the loss/cost/objective function for training the model.

The output of the model is 72 channel  $10 \times 10 \times 30$  voxels, which consists of pressure, temperature, and tracer concentration for 24 time-steps corresponding to the PFLOTTRAN output timesteps. A different approach would be a auto-regressive approach that would predict the features for the next time steps and use them as input for the next time-step. The approach of using all the time-steps as the output instead of advancing the CNN for one time-step each time is selected because the outputs can have a varying time interval without cumulative errors.

The output data consist of three quantities of interest that have significantly different order of magnitude, for this reason a normalization of the data is performed, all input and output values are divided by their corresponding standard deviation. Furthermore, the quantities of concentrations of the tracers are more difficult to predict and more localized; therefore, there are weighted differently for the regions where significant changes are observed in the domain. The weight of the localized  $L_1$  norm of the tracer  $W_c$  is an additional hyperparameter that was tuned during the study to achieve the best performing surrogate model. The ADAM algorithm is used to optimize the CNN model because it is good at searching a wide range of hyperparameters<sup>106</sup>. The additional hyperparameters are the learning rate and the weight decay of ADAM algorithm. A grid search was performed for the hyperparameters and is listed in Table 6.3.

Table 6.3: Hyperparameter range for the optimization of the CNN model.

Parameter Name	Values
Initial layer number	[64, 128, 256, 512]
Growth rate	[32, 64, 128]
Learning rate	[1e-4, 1e-5, 5e-6, 1e-6]
Weight decay	[1e-4, 1e-5, 1e-6]
Tracer weight	[1, 10, 50, 100, 200, 500]

## MCMC analysis

The main objective of this step is to estimate porosity and permeability of model layers using temperature, tracer concentration, and pressure as proxies of measurements. For an efficient sampling of model parameters, the No-U-Turn Sampler (NUTS) is selected for the MCMC framework<sup>107</sup>, which is a gradient-based modified Hamiltonian Monte Carlo (HMC) approach<sup>108</sup>. For MCMC, a PFLOTTRAN forward solution is used as the ground truth. The data/measurement are the surface temperature, the heat flux, and the initial temperature

gradient. Additionally, we consider that the time-series for the temperature, tracer concentration, and pressure for voxels are scarcely distributed in three vertical columns. This sampling immitates the use of three vertical wells measuring required information. Therefore, the unknown parameters that we try to obtain through inference are the porosity and permeability.

The permeability and porosity realizations for each layer are generated using the uniform distribution with their corresponding range. Subsequently, the values are normalized and formed as the input of the trained CNN model. Next, a normally distributed random noise is added to the model outputs to capture the model and measurement errors. The final outputs are conditioned to the solution of the ground truth obtained. Finally, MCMC sampler is used to obtain the posterior distribution of the inputs. Note, experiments are performed on hardware with the following specification: Intel Xenon Gold 6126 CPU (2.6 GHz), 60GB RAM, and Nvidia V100 GPU with 16GB vRAM.

## Results

### CNN surrogate training

The 2,000 simulation results are used for the training and evaluation of the surrogate model. After the generation of the input-output pairs, the 1,600 of them are used for training and the remaining 400 pairs serve as the testing set. The evaluation of the model is based on the  $R^2$  value (Fig. 6.3). Training and testing scores are close 1 in the best performing CNN models (Table 6.4). The optimal hyperparameters for the best performing models are listed in Table 6.4.

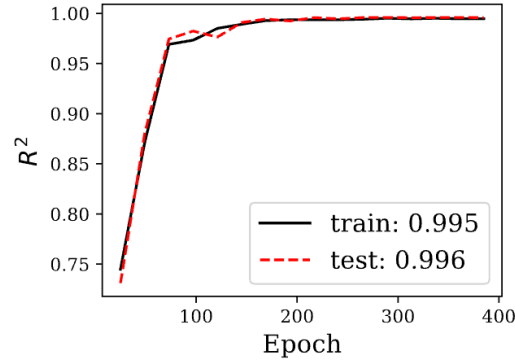


Fig. 6.3 High and consisting training and testing scores suggests a well trained model.

Table 6.4: The best performing models and their corresponding hyperparameters.

$R^2$ Train Set	$R^2$ Test Set	Initial number	Growth rate	Learning rate	Weight decay	Tracer weight
0.995	0.996	512	128	$10^{-4}$	$10^{-5}$	100
0.994	0.995	256	128	$10^{-4}$	$10^{-5}$	100
0.994	0.995	512	128	$10^{-4}$	$10^{-6}$	100
0.993	0.994	256	64	$10^{-4}$	$10^{-5}$	100
0.992	0.994	256	64	$10^{-4}$	$10^{-6}$	100
0.992	0.994	512	64	$10^{-4}$	$10^{-5}$	100
0.992	0.994	256	128	$10^{-4}$	$10^{-6}$	100
0.993	0.994	512	64	$10^{-4}$	$10^{-6}$	100
0.992	0.993	512	128	$10^{-4}$	$10^{-5}$	200
0.992	0.993	512	64	$10^{-4}$	$10^{-5}$	200

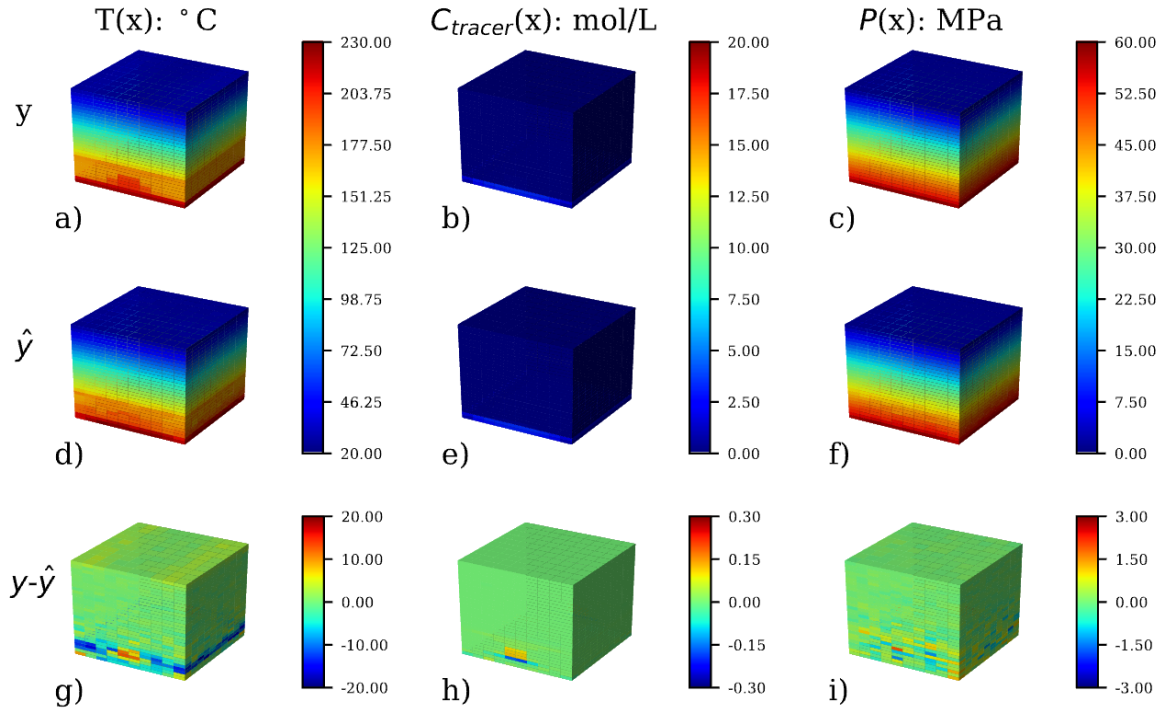


Fig. 6.4: Distribution of temperature by PFLOTRAN (a), ML model (d), and PFLOTRAN–ML model (g); tracer distribution by PFLOTRAN (b), ML model (e), and PFLOTRAN–ML model (h); pressure distribution by PFLOTRAN (c), ML model (f), and PFLOTRAN–ML model (i) after the last time step.

The CNN model is only trained for 400 epochs because after it, the  $R^2$  scores of training and testing reaches a plateau (Fig. 6.3). The optimal initial number of channels and the growth rate are relatively large compared to models with similar architecture used for other tasks. The potential reasons are relatively larger outputs and more time steps in the outputs. However, similar  $R^2$  values for training and testing sets indicate that the model is not overfitted instead of complexity in the dataset (Fig. 6.3). The minimum difference between

the prediction of temperature, tracer, and pressure by PFLOTTRAN and ML model also suggests a well trained ML model (Fig. 6.4).

## MCMC Inference

We draw a total of 6000 samples and discarded 2000 samples in the burn-in stage; therefore, the estimation of the parameters relies on 4000 samples. MCMC inference of porosity and permeability values for the first three (bottom) layers is consistent (Figs 6.4–6.5). However, there are discrepancies in the porosity and permeability prediction for top six layers. Note, the first layer has high tracer concentration while top layers have low tracer concentration.

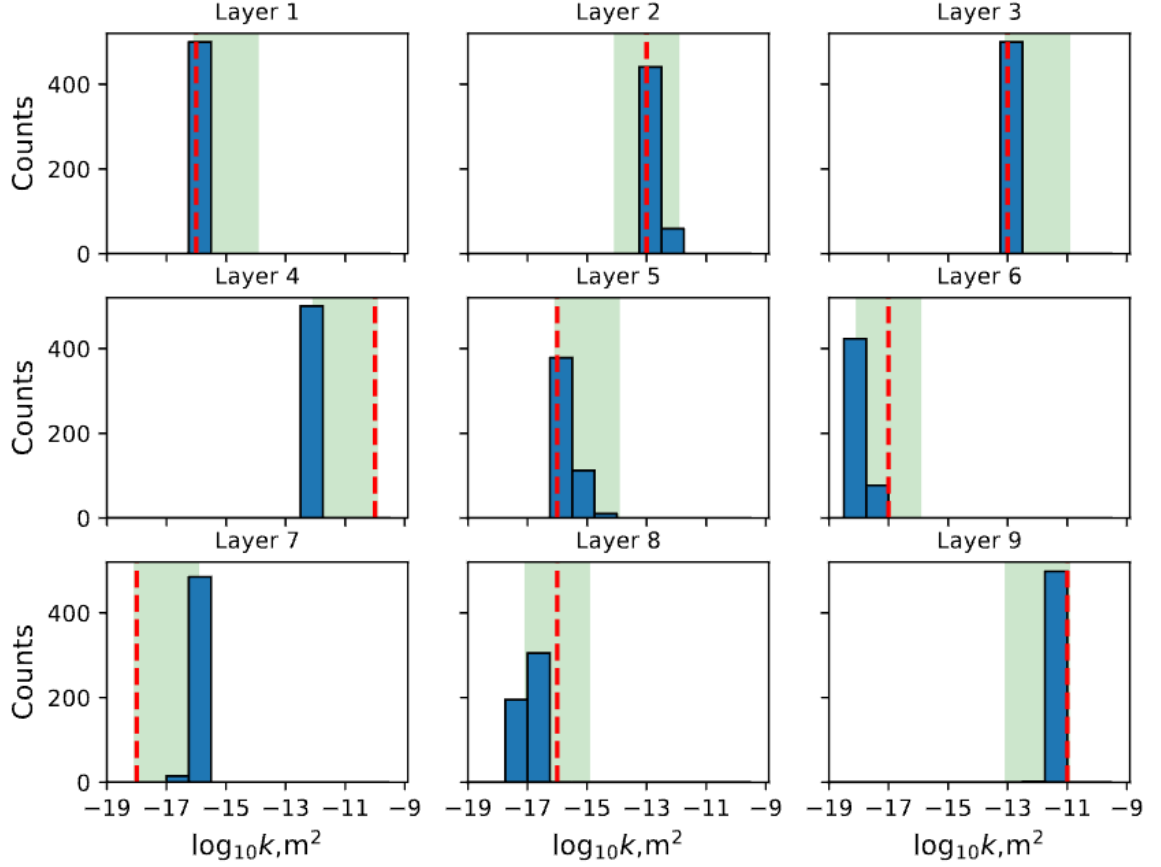


Fig. 6.5: Histograms of assimilated permeability on each layer. The green shaded area indicates the range of initial guess and the dotted line the ground truth.

The discrepancy of the real value and the estimated value for the higher layers can be explained by the fact that the tracer plume is not reaching above the third layer and therefore there is no information that can be assessed by the model. It is worth noting that for the first layer for which there is the most flow of the tracer the standard deviation of the estimated parameters are in the order of 0.05 and 0.01 for permeability and porosity accordingly. The difficulty of the MCMC method to estimate the parameters of the higher layers shows the importance of the correct regularization as the tracer moves upwards is diluted and the concentration decreases by an order of magnitude. Therefore, if there was no normalization

the MCMC would not be able to provide any reliable information for the second and third layer.

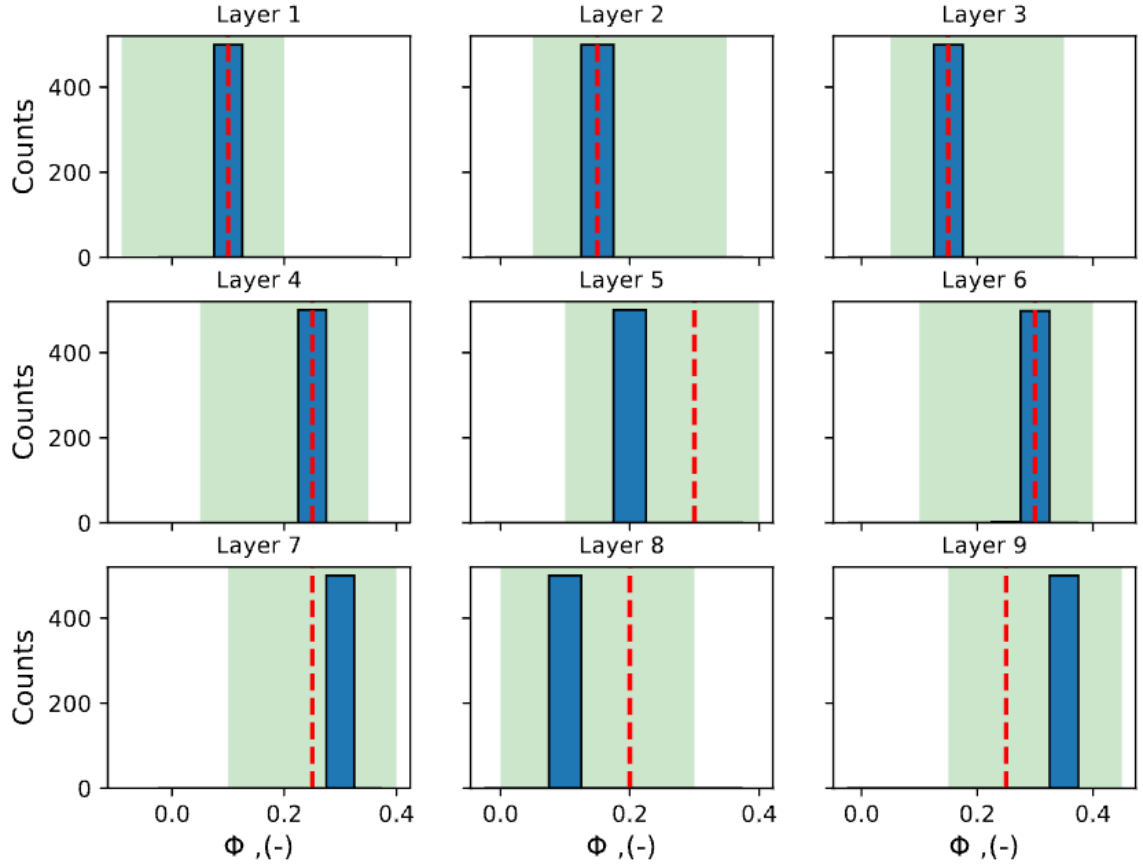


Fig. 6.6: Histograms of assimilated porosity on each layer. The green shaded area indicates the range of initial guess and the dotted line the ground truth.

The NUTS sampling uses the information of gradient facilitating the faster convergence of the distribution. The main advantage of the use of the neural network surrogate model is the efficient calculation of every iteration as the average time for sampling is 1.5 secs. Additionally, the PFLOTRAN or other subsurface simulators are not developed to leverage the GPU architecture; thereby, its integration with probabilistic programming platform would be more challenging. The use of open-source and off-the-self solution for both the surrogate model and the MCMC inference do not only decrease the development time but also increase the efficiency as the implementation have been developed and maintained to fully utilize modern hardware.

## Conclusions

For this study the use of MCMC with NUTS sampling was proposed to infer permeability and porosity of a geothermal reservoir. The model used was a surrogate CNN trained on data generated by PDE-based model. For the inference of the parameters an example of the generated dataset was used as ground truth and the model is conditioned to data on virtual vertical wells with sparse information. The analysis concludes in the following finding:



- The CNN-based surrogate model can reproduce the results of the PDE-based solution of both thermal and advection process.
- The MCMC with the use of surrogate model can evaluate the unknown parameters if enough information is provided, as it happens for the first layers.
- For the areas where there is no change of concentration and temperature the inference of the permeability and porosity is not reliable, as the inverse problem is ill-posed.
- The use of surrogate model can significantly decrease the computation time as the complex PDE-based model is evaluated only 2000 times which is the number of realizations needed for the training of the model.

In this study it is shown that CNN surrogate model can reproduce PDE-based solutions and can be used for inference, they have the same limitations with the PDE-based solutions. In our case, the area where there was not significant movement of the tracer it was possible to retrieve the rock parameters reliably. The gain of the proposed workflow is that the time consuming PDE-based simulation are used to explore the parameter space to train the model and then is substituted with the faster CNN-based to sample the unknown parameters which is used more time and the gradient information is needed.

## Chapter 7: INGENIOUS and GeoDAWN Data Processing

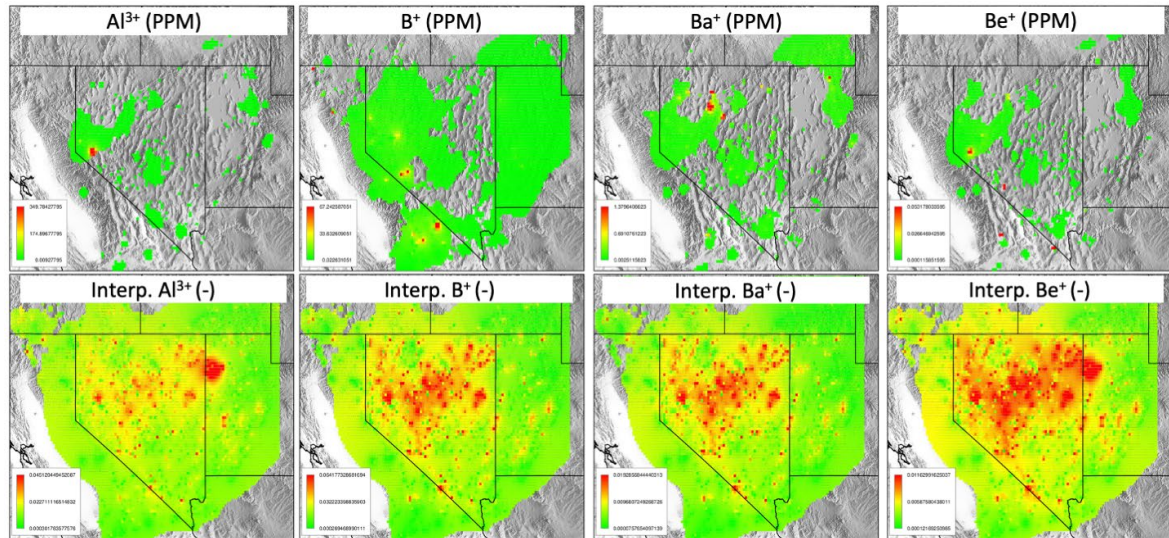
### INGENIOUS

The U.S. Department of Energy's Geothermal Technologies Office has collected plenty of data through INnovative Geothermal Exploration through Novel Investigations Of Undiscovered Systems (INGENIOUS) Project with an aim to accelerate discoveries of new, commercially viable hidden geothermal systems in the Great Basin, NV, US. The INGENIOUS Project has released its data in 2022 on the geothermal data repository available at (<https://gdr.openei.org/submissions/1391>)<sup>109</sup>. The dataset includes a total of 24 geological, geophysical, and geochemical attributes. Data counts for each attribute significantly vary. Some attributes have too fine resolution data while others are too sparse, and others are in between two. The main purpose of this task is to bring them in the same scale so that ML practitioners can load the data and use it for their purpose without going through excruciating preprocessing steps. We curated and processed the dataset. Next, we some time used only inverse distance weighting (IDW) or use both NMFk and IDW algorithms for predicting data in unsampled locations.

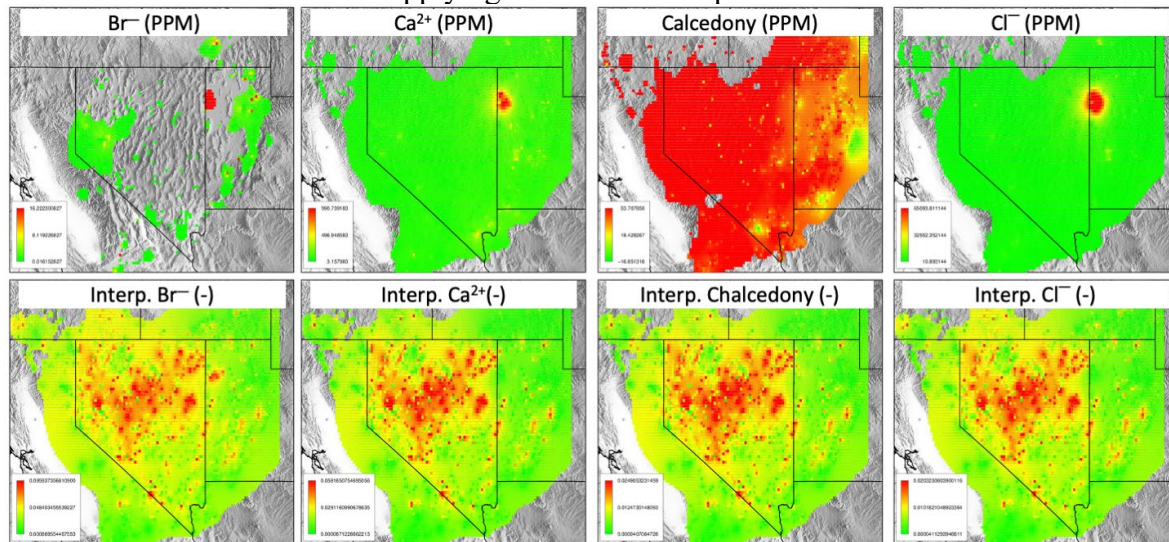
This regional scale dataset provides information for predicting geothermal favourability in the Great Basin region. The geochemical attributes include  $\text{Al}^{3+}$ ,  $\text{B}^+$ ,  $\text{Ba}^{2+}$ ,  $\text{Be}^{2+}$ ,  $\text{Br}^-$ ,  $\text{Ca}^{2+}$ , chalcedony,  $\text{Cl}^-$ ,  $\text{HCO}_3$ ,  $\text{K}^+$ ,  $\text{Li}^+$ ,  $\text{Mg}^{2+}$ ,  $\text{Na}^+$ , quartz, total dissolved solids (TDS), groundwater temperature. These data are heavily sparse. To remove the sparsity, we used NMFk followed by IDW for interpolation. The common locations were 14,341 geochemical data locations in the Great Basin<sup>36</sup>. The scaled data are shown in Figs 7.1-7.4.

Other geological and geophysical attributes include depth to the basement, dilation rate, magnetic anomaly, seismicity ( $\text{N50\_alpha\_}10^{-12}/\text{yr}$ ), strain rate, shear rate, temperature@2m, and heat flow (Figs 7.5-7.6). Depth to the basement, dilation rate,

magnetic anomaly, seismicity ( $N50\_alpha\_10^{-12}/yr$ ), strain rate, and shear rate contain fine resolution data while temperature@2m and heat flow contains both coarse resolution and sparse data (Figs 7.5-7.6). We applied IDW to upscale the fine resolution data and downscale the coarse resolution data (Figs 7.5-7.6).

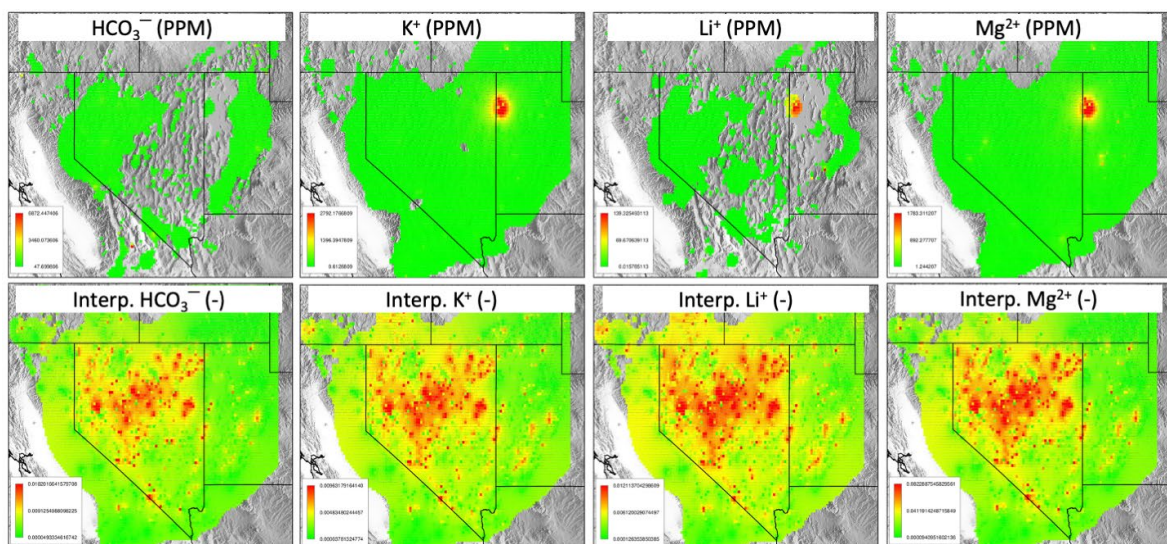


**Fig. 7.1:** Top and bottom rows represent ingenious and interpolated data, respectively. Here, each attribute was fine scaled applying IDW on NMFk prediction.

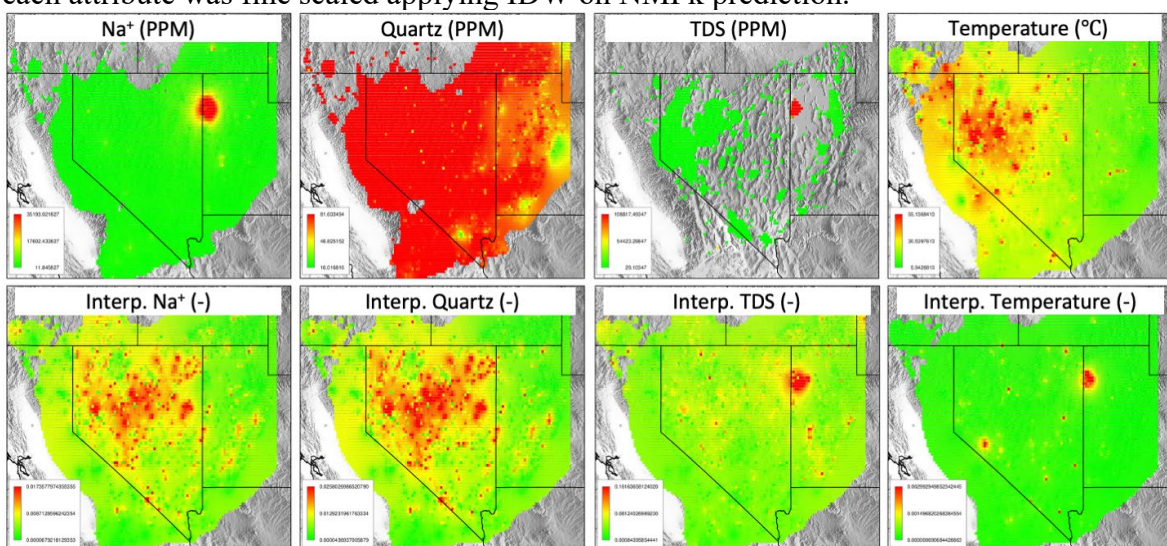


**Fig. 7.2:** Top and bottom rows represent ingenious and interpolated data, respectively. Here, each attribute was fine scaled applying IDW on NMFk prediction.



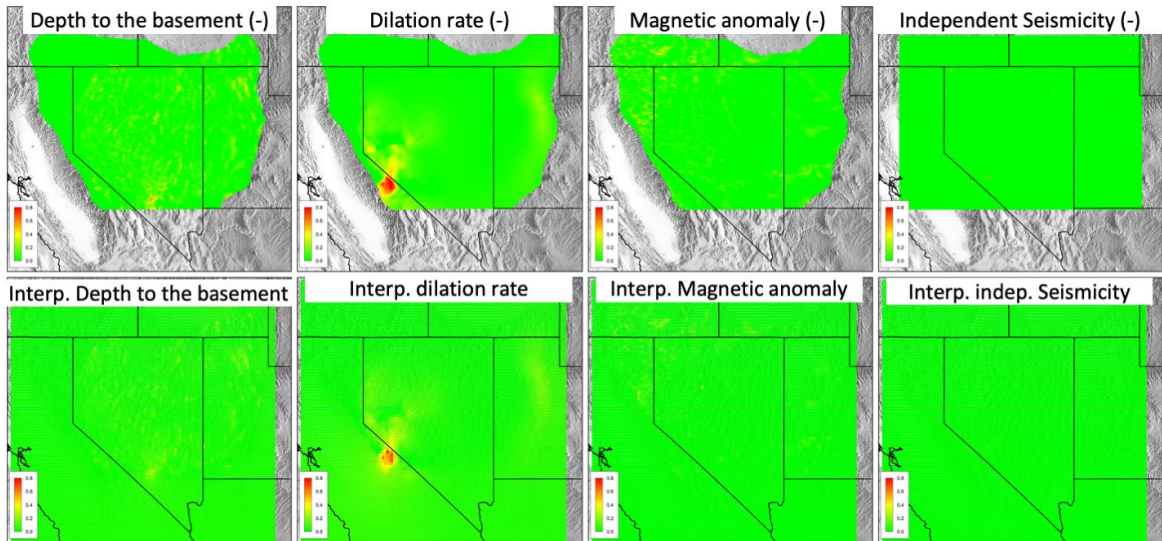


**Fig. 7.3:** Top and bottom rows represent ingenious and interpolated data, respectively. Here, each attribute was fine scaled applying IDW on NMFk prediction.

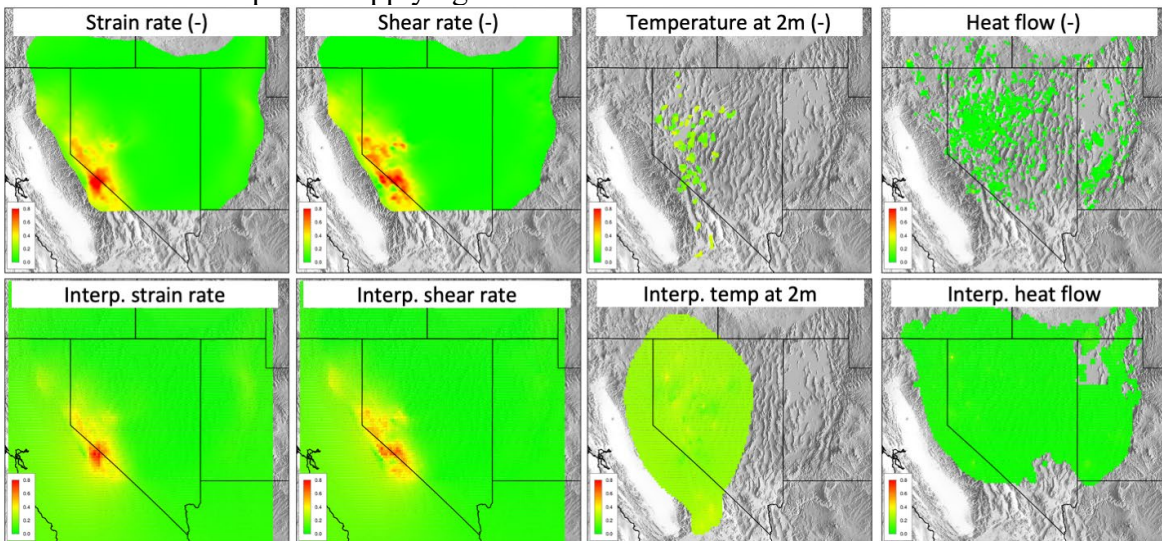


**Fig. 7.4:** Top and bottom rows represent ingenious and interpolated data, respectively. Here, each attribute was fine scaled applying IDW on NMFk prediction.





**Fig. 7.5:** Top and bottom rows represent ingenious and interpolated data, respectively. Here, each attribute was upscaled applying IDW.

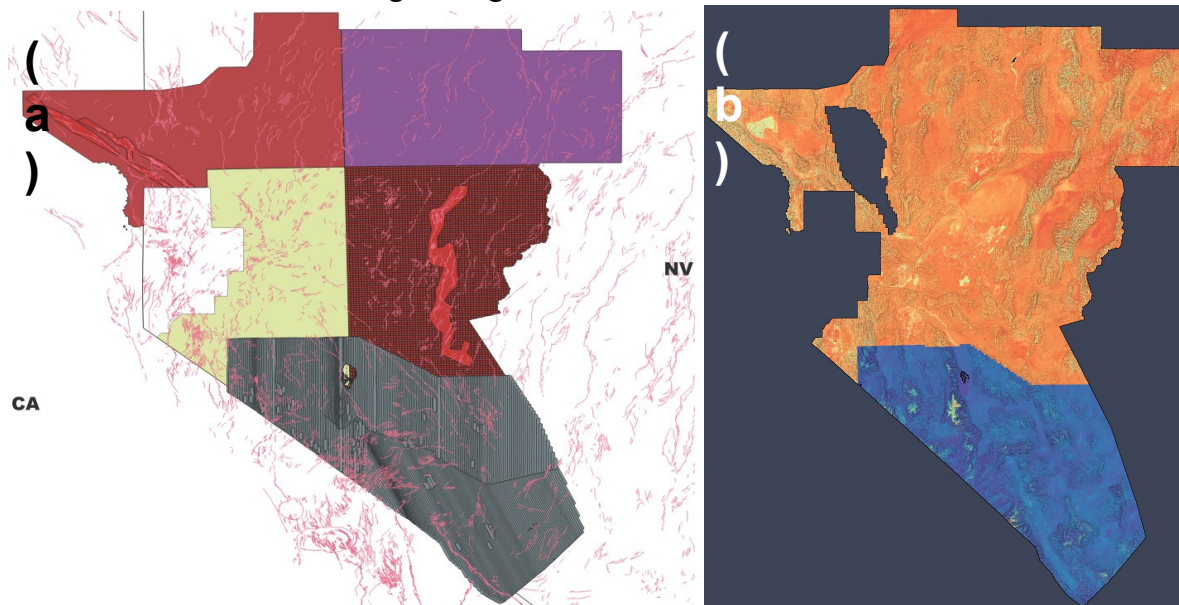


**Fig. 7.6:** Top and bottom rows represent ingenious and interpolated data, respectively. Applying IDW, strain and shear rates were upscaled while temperature at 2m depth and heat flow were fine scaled.

## GeoDAWN

A recent interagency agreement—Geoscience Data Acquisition for Western Nevada (GeoDAWN)—unites EERE’s Geothermal Technologies Office (GTO) with the USGS Earth Mapping Resource Initiative (Earth MRI) and 3D Elevation Program<sup>110</sup>. The purpose of this initiative is to collect LiDAR and electromagnetic data for finding hidden geothermal resources and critical minerals. Next, use advanced machine learning algorithm to analyze the data and to discover new geothermal and critical mineral resources. So far, this project disseminated LiDAR point cloud (LPC) within Nevada and parts of CA region (Fig. 7.7). Such a dataset has a huge potential to reduce the risks and costs associated with geothermal exploration and production.

For an appropriate utilization of this dataset, we need to create labels of favorable geothermal settings with corresponding LPC data. Labeling such a dataset is a non-trivial task because they are huge (in terabytes scale) and contains in 1000s of tiles. We have to sort the tiles in an orderly fashion and find their neighboring tiles. Then, label each tile whether they contains favorable geothermal settings. For this purpose, we wrote a python script that can sort the tiles and find their neighboring tiles.



**Fig. 7.7:** Each color represents a unique flight line duration that was used to collect lidar data at different times (a) and intensity distribution of the collected lidar data (d).

## REFERENCES

1. Vesselinov, V. V. *et al.* Discovering hidden geothermal signatures using non-negative matrix factorization with customized k-means clustering. *Geothermics* **106**, 102576 (2022).
2. Mudunuru, M. K., Vesselinov, V. V. & Ahmmed, B. GEOTHERMALCLOUD: Machine learning for geothermal resource exploration. *JMLMC* **3**, (2022).
3. Frash, L. P. Geothermal Design Tool (GeoDT). in *Proceedings of the 46<sup>th</sup> Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, February 15* vol. 17 (2021).
4. Frash, L. P. Optimized Enhanced Geothermal Development Strategies with GeoDT and Fracture Caging. in *Proceedings of 47th Workshop on Geothermal Reservoir Engineering* vol. 47 (2022).
5. Ahmmed, B. & Frash, L. A FORGE Datathon Case Study to Optimize Well Spacing and Flow Rate for Power Generation. in *48th Stanford Geothermal Workshop* (2023).
6. Mudunuru, M. K., Ahmmed, B. & Frash, L. P. Deep Learning for Modeling Enhanced Geothermal Systems. in *PROCEEDINGS of 48th Workshop on Geothermal Reservoir Engineering* (2023).
7. Singh, A., Thakur, N. & Sharma, A. A review of supervised machine learning algorithms. in *2016 3rd International Conference on Computing for Sustainable Global Development (INDIACom)* 1310–1315 (2016).
8. Sharma, P., Austin, D. & Liu, H. Attacks on Machine Learning: Adversarial Examples in Connected and Autonomous Vehicles. in *2019 IEEE International Symposium on Technologies for Homeland Security (HST)* 1–7 (2019). doi:10.1109/HST47167.2019.9032989.
9. Feldman, D., Margolis, R., Denholm, P. & Stekli, J. *Exploring the potential competitiveness of utility-scale photovoltaics plus batteries with concentrating solar power, 2015–2030*. (2016).
10. Gu, J. *et al.* Recent advances in convolutional neural networks. *Pattern Recognition* **77**, 354–377 (2018).

11. Sherstinsky, A. Fundamentals of Recurrent Neural Network (RNN) and Long Short-Term Memory (LSTM) network. *Physica D: Nonlinear Phenomena* **404**, 132306 (2020).
12. Breiman, L. Random Forests. *Machine Learning* **45**, 5–32 (2001).
13. Lagaris, I. E., Likas, A. & Fotiadis, D. I. Artificial neural networks for solving ordinary and partial differential equations. *IEEE transactions on neural networks* **9**, 987–1000 (1998).
14. Raissi, M., Perdikaris, P. & Karniadakis, G. E. Physics-informed neural networks: A deep learning framework for solving forward and inverse problems involving nonlinear partial differential equations. *Journal of Computational Physics* **378**, 686–707 (2019).
15. Vesselinov, V. V., Middleton, R. S. & Talsma, C. COVID-19: *Spatiotemporal Social Data Analytics and Machine Learning for Pandemic Exploration and Forecasting*.
16. Alexandrov, B. S. & Vesselinov, V. V. Blind source separation for groundwater pressure analysis based on nonnegative matrix factorization. *Water Resources Research* **50**, 7332–7347 (2014).
17. Lee, D. D. & Seung, H. S. Learning the parts of objects by non-negative matrix factorization. *Nature* **401**, 788–791 (1999).
18. Wold, S., Esbensen, K. & Geladi, P. Principal component analysis. *Chemometrics and Intelligent Laboratory Systems* **2**, 37–52 (1987).
19. Hyvärinen, A. & Oja, E. Independent component analysis: algorithms and applications. *Neural Networks* **13**, 411–430 (2000).
20. De Lathauwer, L., De Moor, B. & Vandewalle, J. A Multilinear Singular Value Decomposition. *SIAM J. Matrix Anal. Appl.* **21**, 1253–1278 (2000).
21. Cichocki, A., Zdunek, R. & Amari, S. Nonnegative Matrix and Tensor Factorization [Lecture Notes]. *IEEE Signal Processing Magazine* **25**, 142–145 (2008).
22. Shi, J. Q., Murray-Smith, R. & Titterton, D. M. Hierarchical Gaussian process mixtures for regression. *Stat Comput* **15**, 31–41 (2005).
23. Los Alamos National Laboratory. SmartTensors: Artificial Intelligence and Machine Learning using Unsupervised, Supervised, and Physics-Informed Methods. <https://tensors.lanl.gov/>.
24. Böttcher, A. & Wenzel, D. The Frobenius norm and the commutator. *Linear Algebra and its Applications* **429**, 1864–1885 (2008).
25. Vesselinov, V. V., Mudunuru, M. K., Karra, S., O'Malley, D. & Alexandrov, B. S. Unsupervised machine learning based on non-negative tensor factorization for analyzing reactive-mixing. *Journal of Computational Physics* **395**, 85–104 (2019).
26. Lu, G. Y. & Wong, D. W. An adaptive inverse-distance weighting spatial interpolation technique. *Computers & Geosciences* **34**, 1044–1055 (2008).
27. Burrough, P. A., McDonnell, R. A. & Lloyd, C. D. *Principles of Geographical Information Systems*. (OUP Oxford, 2015).
28. Cumming, W. & Mackie, R. 3D MT resistivity imaging for geothermal resource assessment and environmental mitigation at the glass mountain KGRA, California. *GRC Transactions* **31**, 331–334 (2007).
29. Coppo, N. *et al.* 3-D magnetotelluric investigations for geothermal exploration in Martinique (Lesser Antilles). Characteristic deep resistivity structures, and shallow resistivity distribution matching airborne TEM results. *arXiv preprint arXiv:1501.06541* (2015).
30. Johnston, J. M., Pellerin, L. & Hohmann, G. W. Evaluation of electromagnetic methods for geothermal reservoir detection. *Transactions- Geothermal Resources Council* (1992).
31. Muñoz, G. Exploring for Geothermal Resources with Electromagnetic Methods. *Surv Geophys* **35**, 101–122 (2014).
32. Caldwell, T. G., Bibby, H. M. & Brown, C. The magnetotelluric phase tensor. *Geophysical Journal International* **158**, 457–469 (2004).
33. Grimm, R. *et al.* A magnetotelluric instrument for probing the interiors of Europa and other worlds. *Advances in Space Research* **68**, 2022–2037 (2021).
34. Burns, E. R., Ingebritsen, S. E., Manga, M. & Williams, C. F. Evaluating geothermal and hydrogeologic controls on regional groundwater temperature distribution. *Water Resources Research* **52**, 1328–1344 (2015).
35. Vesselinov, V., Ahmed, B., Frash, L. & Mudunuru, M. K. GeoThermalCloud: Machine Learning for Discovery, Exploration, and Development of Hidden Geothermal Resources. in *47th SGW* (2022).
36. Ahmed, B. & Vesselinov, V. V. Machine learning and shallow groundwater chemistry to identify geothermal prospects in the Great Basin, USA. *Renewable Energy* **197**, 1034–1048 (2022).
37. Siler, D. L., Pepin, J. D., Vesselinov, V. V., Mudunuru, M. K. & Ahmed, B. Machine learning to identify



- geologic factors associated with production in geothermal fields: a case-study using 3D geologic data, Brady geothermal field, Nevada. *Geothermal Energy* **9**, 17 (2021).
38. Ahmmed, B., Vesselinov, V. V., Rau, E., Mudunuru, M. & Karra, S. *Machine learning and a process model to better characterize hidden geothermal resources*. (2022).
  39. Bennett, C. R. & Nash, G. D. *The Convergence of Heat, Groundwater & Fracture Permeability: Innovative Play Fairway Modelling Applied to the Tularosa Basin*. (2017).
  40. Ahmmed, B. & Vesselinov, V. V. *Exploration of groundwater and geothermal characteristics of Tohatchi Hot Springs aquifer at local and regional scales*. (2022).
  41. Ahmmed, B., Lautze, N., Vesselinov, V. V., Does, D. & Mudunuru, M. K. *Unsupervised machine learning to extract dominant geothermal attributes in Hawaii Island Play Fairway data*. (Geothermal Resources Council, 2020).
  42. Ahmmed, B. & Vesselinov, V. V. Prospectivity Analyses of the Utah FORGE Site using Unsupervised Machine Learning. in *Geothermal Rising, San Diego, CA* (2021).
  43. Pedregosa, F. *et al.* Scikit-learn: Machine Learning in Python. *Journal of Machine Learning Research* **12**, 2825–2830 (2011).
  44. Lichtner, P. C. *et al.* PFLOTRAN User Manual: A Massively Parallel Reactive Flow and Transport Model for Describing Surface and Subsurface Processes. <https://www.osti.gov/biblio/1168703> (2015) doi:10.2172/1168703.
  45. Christopher Frey, H. & Patil, S. R. Identification and Review of Sensitivity Analysis Methods. *Risk Analysis* **22**, 553–578 (2002).
  46. Saltelli, A. Sensitivity Analysis for Importance Assessment. *Risk Analysis* **22**, 579–590 (2002).
  47. Finsterle, S. Practical notes on local data-worth analysis. *Water Resources Research* **51**, 9904–9924 (2015).
  48. U.S. Energy Information Administration. *December 2021 monthly energy review (Section 1)*. (2021).
  49. Hamm, S. G. *et al.* Geothermal Energy R&D: An Overview of the U.S. Department of Energy's Geothermal Technologies Office. *Journal of Energy Resources Technology* **143**, (2021).
  50. Tester, J. W., Beckers, K. F., Hawkins, A. J. & Lukawski, M. Z. The evolving role of geothermal energy for decarbonizing the United States. *Energy & Environmental Science* **14**, 6211–6241 (2021).
  51. Barbier, E. Geothermal energy technology and current status: an overview. *Renewable and sustainable energy reviews* **6**, 3–65 (2002).
  52. Jolie, E. *et al.* Geological controls on geothermal resources for power generation. *Nature Reviews Earth & Environment* **2**, 324–339 (2021).
  53. Blackwell, D. D., Negraru, P. T. & Richards, M. C. Assessment of the enhanced geothermal system resource base of the United States. *Natural Resources Research* **15**, 283–308 (2006).
  54. Iliev, F. L., Stanev, V. G., Vesselinov, V. V. & Alexandrov, S., B. Nonnegative matrix factorization for identification of unknown number of sources emitting delayed signals. *PloS one* **13**, e0193974 (2018).
  55. Arnason, K., Karlsdottir, R., Eysteinnsson, H., Flóvenz, Ó. & Gudlaugsson, S. T. The resistivity structure of high-temperature geothermal systems in Iceland. in *Proceedings of the World Geothermal Congress 2000, Kyushu-Tohoku, Japan* 923–928 (2000).
  56. Seager, W. R. & Morgan, P. Rio Grande rift in southern New Mexico, west Texas, and northern Chihuahua. *Rio Grande rift: Tectonics and magmatism* **14**, 87–106 (1979).
  57. Sinno, Y. A., Daggett, P. H., Keller, G. R., Morgan, P. & Harder, S. H. Crustal structure of the southern Rio Grande rift determined from seismic refraction profiling. *Journal of Geophysical Research: Solid Earth* **91**, 6143–6156 (1986).
  58. Finger, J. T. & Jacobson, R. D. *Fort Bliss exploratory slimholes: Drilling and testing*. (1997).
  59. Ussher, G., Harvey, C., Johnstone, R. & Anderson, E. Understanding the resistivities observed in geothermal systems. in *proceedings world geothermal congress 1915–1920* (Kyushu Japan, 2000).
  60. Barker, B. *et al.* Exploration Drilling and Technology Demonstration At Fort Bliss. in *Thirty-Ninth Workshop on Geothermal Reservoir Engineering Stanford University* (2014).
  61. O'Donnell Jr, T. M., Miller, K. C. & Witcher, J. C. A seismic and gravity study of the McGregor geothermal system, southern New Mexico. *Geophysics* **66**, 1002–1014 (2001).
  62. Broadhead, R. F. Petroleum geology of the McGregor Range, Otero County, New Mexico: New Mexico Geological Society. in *53rd Field Conference, Guidebook* 331–338 (2002).
  63. Rukundo, O. & Cao, H. Nearest neighbor value interpolation. *arXiv preprint arXiv:1211.1768* (2012).
  64. Smith, W. H. F. & Wessel, P. Gridding with continuous curvature splines in tension. *Geophysics* **55**, 293–305 (1990).
  65. Krige, D. G. A statistical approach to some basic mine valuation problems on the Witwatersrand. *Journal*



- of the Southern African Institute of Mining and Metallurgy **52**, 119–139 (1951).
66. Ahmmed, B., Karra, S., Vesselinov, V. V. & Mudunuru, M. K. Machine learning to discover mineral trapping signatures due to CO<sub>2</sub> injection. *International Journal of Greenhouse Gas Control* **109**, 103382 (2021).
  67. James, E. D., Hoang, V. T. & Epperson, I. J. *Structure, permeability and production characteristics of the Heber, California geothermal field*. (1987).
  68. Cherkose, B. A. & Mizunaga, H. Resistivity imaging of Aluto-Langano geothermal field using 3-D magnetotelluric inversion. *Journal of African Earth Sciences* **139**, 307–318 (2018).
  69. Henry, C. D. A preliminary assessment of the geologic setting, hydrology, and geochemistry of the Hueco Tanks Geothermal Area, Texas and New Mexico. *Virtual Landscapes of Texas* (1981).
  70. Augustine, C. Analysis of sedimentary geothermal systems using an analytical reservoir model. *Geothermal Resources Council Transactions* **38**, 641–647 (2014).
  71. Passey, Q. R. *et al.* *Petrophysical Evaluation of Hydrocarbon Pore-thickness in Thinly Bedded Clastic Reservoirs: AAPG Archie Series, No. 1.* (AAPG, 2006).
  72. Huttner, G. W. Geothermal power generation in the world 2015-2020 update report. in *World Geothermal Congress; International Geothermal Association: Reykjavik, Iceland* (2020).
  73. Dobson, P. F. A review of exploration methods for discovering hidden geothermal systems. *Geothermal Resources Council Transactions* 695–706 (2016).
  74. Tester, J. W. *The future of geothermal energy, impact of enhanced geothermal system (EGS) on the United State in the 21st century: An assessment by an MIT-led interdisciplinary panel*. (2007).
  75. Faulds, J. E. & Hinz, N. H. Favorable tectonic and structural settings of geothermal systems in the Great Basin region, western USA: Proxies for discovering blind geothermal systems. in *Proceedings of the World Geothermal Congress* vol. 6 (2015).
  76. Faulds, J. E. *et al.* Integrated geologic and geophysical approach for establishing geothermal play fairways and discovering blind geothermal systems in the Great Basin region, western USA: A progress report. *GRC Transactions* **39**, (2015).
  77. Faulds, J. E. *et al.* Discovery of a Blind Geothermal System in Southern Gabbs Valley, Western Nevada, through Application of the Play Fairway Analysis at Multiple Scales. *GRC Transactions* **42**, (2018).
  78. Faulds, J. E. *et al.* Vectoring into Potential Blind Geothermal Systems in the Granite Springs Valley Area, Western Nevada: Application of the Play Fairway Analysis at Multiple Scales. *PROCEEDINGS, 44th Workshop on Geothermal Reservoir Engineering, Stanford University* (2019).
  79. Faulds, J. E., Hinz, N., Coolbaugh, M., Shevenell, L. & Siler, D. The Nevada Play Fairway Project — Phase II: Initial Search for New Viable Geothermal Systems in the Great Basin Region, Western USA. *GRC Transactions* **40**, (2016).
  80. Siler, D. L. *et al.* Three-dimensional geologic mapping to assess geothermal potential: examples from Nevada and Oregon. *Geothermal Energy* **7**, 2 (2019).
  81. Stone, W. J. & McLin, S. *Hydrologic Tests at Characterization Wells R-9i, R-13, R-19, R-22, and R-31*. <https://www.osti.gov/biblio/884954> (2003) doi:10.2172/884954.
  82. Williams, C. F., Reed, M. J., Mariner, R. H., DeAngelo, J. & Galanis, S. P. *Assessment of moderate-and high-temperature geothermal resources of the United States*. (2008).
  83. Williams, C. F., Reed, M. J., Mariner, R. H., DeAngelo, J. & Galanis, S. P. *Assessment of Moderate-and High-temperature Geothermal Resources of the United States, institution = Geological Survey (US)*. (2008).
  84. Nash, G. D. & Bennett, C. R. Adaptation of a petroleum exploration tool to geothermal exploration: Preliminary play fairway model of Tularosa Basin. *New Mexico, and Texas: Geothermal Resources Council Transactions* **39**, 743–749 (2015).
  85. Kratt, C., Sladek, C. & Coolbaugh, M. Boom and bust with the latest 2 m temperature surveys: Dead Horse Wells, Hawthorne Army Depot, Terraced Hills and other areas in Nevada. *Geothermal Resources Council Transactions* **34**, 567–574 (2010).
  86. Biehler, S. Gravity studies in the Imperial Valley. *Cooperative Geological-Geophysical-Geochemical Investigations of Geothermal Resources in the Imperial Valley of California: Riverside, California, University of California—Riverside Education Research Service* 29–41 (1971).
  87. Olasolo, P., Juárez, M. C., Morales, M. P., D'Amico, S. & Liarte, I. A. Enhanced geothermal systems (EGS): A review. *Renewable and Sustainable Energy Reviews* **56**, 133–144 (2016).
  88. PIVOT. PIVOT Geothermal Datathon. [https://www.spe.org/datasets/2022\\_PIVOT\\_Geothermal\\_Datathon](https://www.spe.org/datasets/2022_PIVOT_Geothermal_Datathon) (2022).

89. Moore, J. *et al.* The Utah Frontier Observatory for Research in Geothermal Energy (FORGE): A Laboratory for Characterizing, Creating and Sustaining Enhanced Geothermal Systems. in *World Geothermal Congress* (2021).
90. Frash, L. P. *et al.* A Proposal for Profitable Enhanced Geothermal Systems in Hot Dry Rock. in *48th Stanford Geothermal Workshop* (2023).
91. Pandey, S. N., Vishal, V. & Chaudhuri, A. Geothermal reservoir modeling in a coupled thermo-hydro-mechanical-chemical approach: A review. *Earth-Science Reviews* **185**, 1157–1169 (2018).
92. Kristensen, L. *et al.* Pre-drilling assessments of average porosity and permeability in the geothermal reservoirs of the Danish area. *Geothermal Energy* **4**, 1–27 (2016).
93. Weibel, R. *et al.* Predicting permeability of low-enthalpy geothermal reservoirs: A case study from the Upper Triassic–Lower Jurassic Gassum Formation, Norwegian–Danish Basin. *Geothermics* **65**, 135–157 (2017).
94. Bauer, J. F., Krumbholz, M., Meier, S. & Tanner, D. C. Predictability of properties of a fractured geothermal reservoir: the opportunities and limitations of an outcrop analogue study. *Geothermal Energy* **5**, 1–27 (2017).
95. Jafari, A. & Babadagli, T. Effective fracture network permeability of geothermal reservoirs. *Geothermics* **40**, 25–38 (2011).
96. Catinat, M., Fleury, M., Brigaud, B., Antics, M. & Ungemach, P. Estimating permeability in a limestone geothermal reservoir from NMR laboratory experiments. *Geothermics* **111**, 102707 (2023).
97. Jiang, Z., Zhang, S., Turnadge, C. & Xu, T. Combining autoencoder neural network and Bayesian inversion to estimate heterogeneous permeability distributions in enhanced geothermal reservoir: Model development and verification. *Geothermics* **97**, 102262 (2021).
98. Suzuki, A., Fukui, K., Onodera, S., Ishizaki, J. & Hashida, T. Data-Driven Geothermal Reservoir Modeling: Estimating Permeability Distributions by Machine Learning. *Geosciences* **12**, 130 (2022).
99. Pepin, J. *et al.* Deep fluid circulation within crystalline basement rocks and the role of hydrologic windows in the formation of the Truth or Consequences, New Mexico low-temperature geothermal system. *Geofluids* **15**, 139–160 (2015).
100. Mudunuru, M. K. *et al.* Site-Scale and Regional-Scale Modeling for Geothermal Resource Analysis and Exploration. in *45th Annu. Stanf. Geotherm. Workshop* (2020).
101. Johnson, P. J., Stauffer, P. H., Omagbon, J. & Moore, C. R. Implications of rootless geothermal models: Missing processes, parameter compensation, and imposter convection. *Geothermics* **102**, 102391 (2022).
102. Bielicki, J. *et al.* *Hydrogeologic windows: Regional signature detection for blind and traditional geothermal play fairways, Final Reports, Los Alamos National Laboratory.* (2015).
103. Mo, S., Zabarar, N., Shi, X. & Wu, J. Deep autoregressive neural networks for high-dimensional inverse problems in groundwater contaminant source identification. *Water Resources Research* **55**, 3856–3881 (2019).
104. Zhou, Z. & Tartakovsky, D. M. Markov chain Monte Carlo with neural network surrogates: Application to contaminant source identification. *Stochastic Environmental Research and Risk Assessment* **35**, 639–651 (2021).
105. Huang, G., Liu, Z., Van Der Maaten, L. & Weinberger, K. Q. Densely connected convolutional networks. in *Proceedings of the IEEE conference on computer vision and pattern recognition* 4700–4708 (2017).
106. Kingma, D. P. & Ba, J. Adam: A method for stochastic optimization. *arXiv preprint arXiv:1412.6980* (2014).
107. Hoffman, M. D. & Gelman, A. The No-U-Turn sampler: adaptively setting path lengths in Hamiltonian Monte Carlo. *J. Mach. Learn. Res.* **15**, 1593–1623 (2014).
108. Neal, R. M. MCMC using Hamiltonian dynamics. *Handbook of Markov chain Monte Carlo* **2**, 2 (2011).
109. Ayling, B., Faulds, J. E. & Rivera, A. M. *INGENIOUS - Great Basin Regional Dataset Compilation.* <https://gdr.openei.org/submissions/1391> (2022).
110. EERE-GTO, U. USGS and EERE: Collaborating to Strengthen America’s Energy and Resource Independence. *Energy.gov* <https://www.energy.gov/eere/articles/usgs-and-eere-collaborating-strengthen-americas-energy-and-resource-independence>.

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