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Detailed Subsurface Analysis and Experimental Evaluation of GeoTES for Effective Long-term Energy Storage

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ABSTRACT

As fossil fuel-based energy sources are replaced by Variable Renewable Energy (VRE) technologies, efficient long-duration energy storage solutions are critical to managing seasonal variations in VRE generation and consumption. Geologic Thermal Energy Storage (GeoTES) offers a promising long-duration storage solution, helping to balance differing summer and winter energy demands and providing lower levelized costs of storage (LCOS) compared to other thermal storage options. In 2024-2025, teams at the National Renewable Energy Laboratory (NREL), Idaho National Laboratory (INL), and Lawrence Berkeley National Laboratory (LBNL) successfully identified suitable GeoTES reservoirs, examined GeoTES systems charged by concentrating solar power (CSP) and renewable electricity via heat pumps (Carnot Battery), and validated a techno-economic analysis (TEA) model for GeoTES. In 2026, Idaho National Laboratory (INL) conducted extensive subsurface characterization at selected GeoTES sites in Texas and California, involving geological evaluations and site-wide lithological and hydrogeological characterization through the mining and digitization of existing geological data. The collected data facilitated the construction of a detailed 3D geological model, enabling visualization and assessment of reservoir heterogeneity, lithology, fault structures, and potential leakage pathways. Reactive transport modeling and reservoir simulations demonstrate the viability of these sites for both storing and extracting heat in the subsurface, highlighting the critical role of advanced geological modeling and simulation in developing promising large scale, long-duration energy storage solutions.

1 INTRODUCTION

Improving the efficiency and flexibility of energy systems remains one of the most urgent challenges in the energy transition. As the deployment of variable renewable energy (VRE) sources like solar and wind accelerates, so does the need for long-duration energy storage (LDES) capable of balancing generation and demand across diurnal and seasonal timescales. While lithium-ion batteries have matured for short-duration applications, they remain cost- and performance-limited for multi-day or seasonal storage.

Geologic Thermal Energy Storage (GeoTES) offers a scalable, low-carbon solution to this gap. By injecting heated fluids into permeable subsurface formations, such as brackish aquifers or depleted oil and gas reservoirs, GeoTES systems store thermal energy that can later be recovered for electricity generation or direct-use heating. These open-loop systems are particularly well-suited for infrastructure-rich regions and can be coupled with surface technologies like concentrating solar thermal (CST) or Carnot batteries (CBs) to deliver dispatchable energy (Figure 1). GeoTES stands out as a major technology for its seasonal shifting capability and potential to reduce the Levelized Cost of Energy (LCOE) (Akindipe et al., 2024).

This paper presents recent progress from a multi-laboratory collaboration between INL, NREL, and LBNL, working alongside industry partners at two pilot sites in California and Texas. The work focuses on site selection and data acquisition, subsurface characterization and 3D modeling using Leapfrog, and preliminary reactive transport modeling. These efforts are helping to de-risk deployment and inform the design of scalable GeoTES systems for grid-integrated, long-duration energy storage.

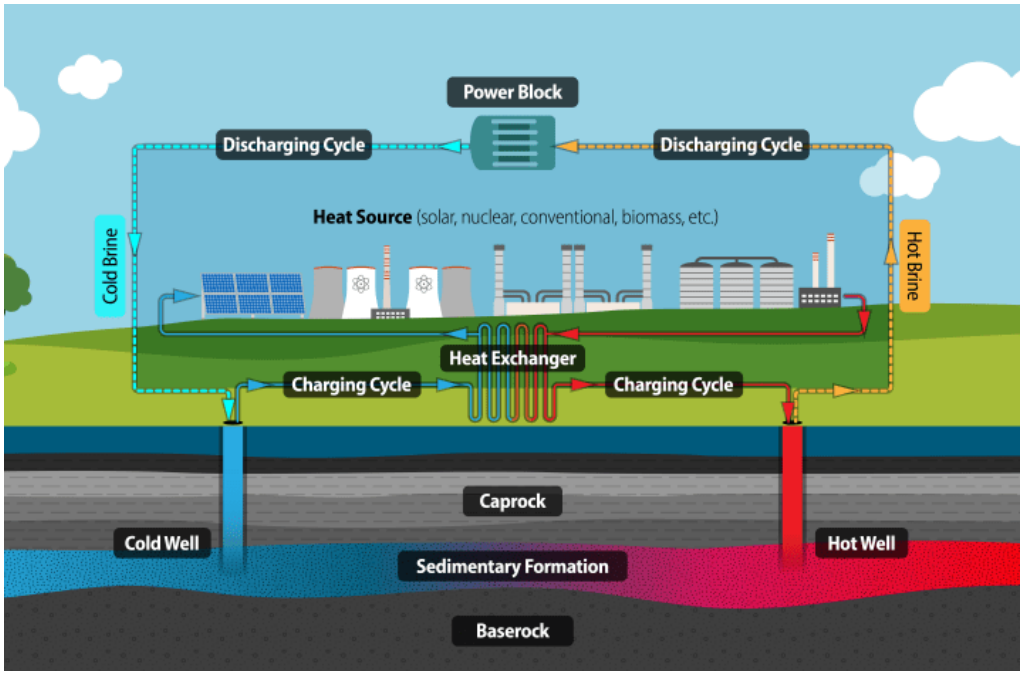


Figure 1: Conceptual diagram of a GeoTES system (U.S. Department of Energy)

2 OBJECTIVES

The overarching objective of this project is to evaluate the feasibility and scalability of GeoTES systems through a comprehensive, multi-phase approach. This includes identifying and characterizing subsurface reservoirs, assessing key geological, petrophysical, and hydrogeochemical properties—such as stratigraphy, permeability, porosity, and thermal containment—and developing integrated geologic models to evaluate thermal storage potential and operational viability. Additional efforts focus on experimental validation through geochemical testing and thermal cycling simulations, as well as system integration to inform full-scale performance assessments. Ultimately, the project aims to define the design parameters, operational constraints, and techno-economic thresholds necessary for commercial deployment across diverse geologic settings. While these are the broader goals, this paper specifically presents progress on subsurface characterization, 3D geologic model development, and preliminary modeling and simulation at two pilot sites.

3 SITE DESCRIPTIONS

Two notable demonstration sites are advancing the application of GeoTES for large-scale energy management in the United States. In West Texas, EarthBridge Energy is developing a flexible, long-duration GeoTES system that utilizes surplus renewable energy—such as solar and wind—by storing thermal energy in subsurface reservoirs (Figure 2b). Their approach employs advanced heat pump and Carnot battery technologies to transfer and store heat within porous formations saturated with brackish water, selected for their favorable permeability and porosity. The pilot project will feature a single injection-production well pair, and pending results, progress toward commercial-scale deployment with multiple well doublets designed to deliver grid-scale thermal output. Meanwhile, Premier Resource Management (PRM) is pioneering GeoTES integration with concentrated solar thermal (CST) technology in California's San Joaquin Valley (Figure 2a). PRM's initiative targets low-oil-saturation reservoirs, specifically the Point of Rocks Member of the Kreyenhagen Formation, which offers high porosity and permeability for efficient thermal energy storage and recovery. The phased development plan begins with a demonstration project supplying electricity to the grid during peak demand periods, with future expansion leveraging newly drilled wells to maximize the system's energy storage and delivery capabilities. Collectively, these sites exemplify the potential for GeoTES to support renewable energy integration, grid reliability, and flexible power generation through innovative use of subsurface resources.

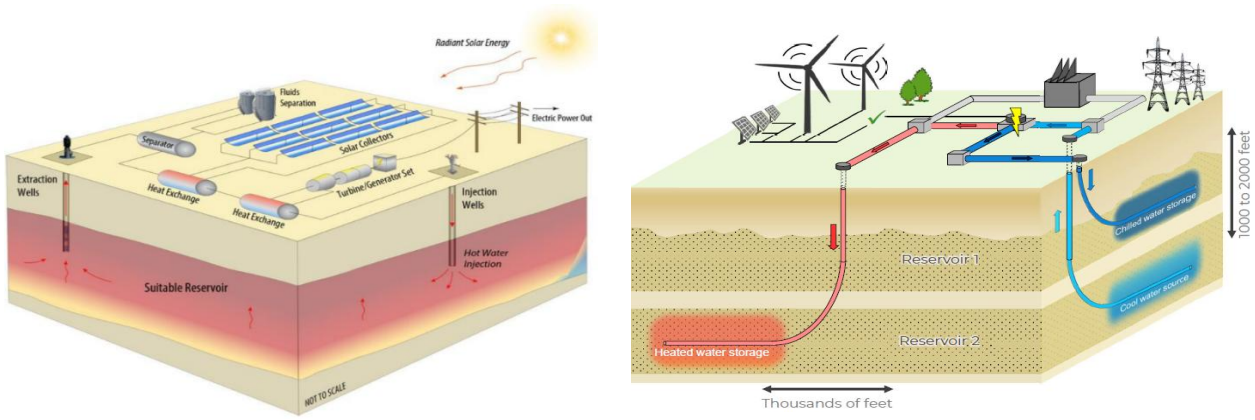


Figure 2: Schematics of the two GeoTES systems. (a) Premier Resource Management system using concentrating solar thermal energy. (b) Earthbridge Energy system using a heat pump.

4 SUBSURFACE CHARACTERIZATION

A critical early phase of this project involved establishing strong collaborative relationships between the national laboratories and industry partners. These partnerships were instrumental in identifying and initiating evaluation of two candidate sites for GeoTES deployment: one located in California's San Joaquin Valley and the other just east of El Paso Texas. Both PRM and EarthBridge provided foundational datasets for their respective sites, enabling the project team to begin assessing the geologic suitability of each location for long-duration thermal energy storage. These datasets included well logs, stratigraphic interpretations, production histories, and hydrogeologic data. These resources were essential for initiating subsurface characterization and geologic model development. The following subsections present the results of this characterization for each site, including stratigraphic and structural frameworks, petrophysical and thermal properties, fluid chemistry, and reservoir configuration. These analyses inform the development of 3D geologic models and support preliminary simulation efforts aimed at evaluating thermal storage capacity, injectivity, and long-term containment under cyclic loading conditions.

4.1 EarthBridge Site (West Texas)

The West Texas site lies within Hueco Basin, which forms part of the northern Trans-Pecos province of the Rio Grande Rift, an extensional zone of the Cenozoic marked by deep sedimentary basins and igneous intrusions (Collins et al., 1996; Heywood & Yager, 2003).

The Hueco Basin is a fault-bounded half-graben depression bounded by the Franklin Mountains to the west and the Hueco Mountains to the east. Its structural floor consists of Precambrian crystalline basement rocks overlain by Paleozoic carbonates, including the El Paso and Hueco Groups, and capped by Cretaceous clastic and Miocene-Quaternary alluvial sediments (Knowles & Kennedy, 1958; Collins et al., 1996). Basin formation occurred during the Miocene-Pliocene Basin and Range extension, producing a west-tilted half-graben geometry with vertical displacements exceeding 2.5 km (Budhathoki et al., 2018). Seismic and drilling data indicate that basin-fill thickness increases westward beneath El Paso to as much as 3 km, with multiple fault-bounded sub-basins (Heywood & Yager, 2003). The upper Hueco Bolson deposits form the main aquifer, while the underlying Tertiary lacustrine facies serve as semi-confining layer. The Hueco Limestone and El Paso Group form the basal aquitard. Hydraulic conductivities range from 30-150 ft/day in coarse zones, decreasing sharply in finer facies (Heywood & Yager, 2003). Freshwater typically extends to depths of 980-2000 ft, below which groundwater becomes saline (Ging et al., 2020).

Recharge occurs primarily through mountain-front infiltration, ephemeral streamflow, and artificial recharge at the Hueco Bolson Recharge Project, which injects reclaimed water into the aquifer (Buszka et al., 1994). Decades of intensive pumping have produced drawdowns exceeding 60 m and induced mixing between fresh and brackish water (Heywood & Yager, 2003). Isotopic evidence indicates that much of the groundwater is Pleistocene in age, recharged during cooler climatic conditions, with minimal modern replenishment (Ging et al., 2020). Beneath the basin-fill sediments, geothermal exploration at the Fort Bliss-McGregor Range has identified three principal reservoir targets; the Ordovician El Paso Group dolomites, the Cambrian Bliss Sandstone, and the underlying Precambrian Red Bluff Granite. The El Paso Group comprises of thick-bedded dolomites and limestones that display extensive fracturing, providing effective permeability and secondary

porosity. The Bliss Sandstone enhances vertical fracture connectivity between the carbonate and the Red Bluff Granite which forms the crystalline basement and serves as a deep thermal reservoir with high heat flow (Barker et al., 2014; Brandt, 2015). Adjacent to the site is the Hueco Tanks syenite pluton, which represents an older Oligocene (~34 Ma) intrusion that predates the basin fill (Barker & Austin, 1981). It intruded the Paleozoic carbonates and was later uplifted and exposed through erosion and faulting. The syenite is composed primarily of alkali feldspar and nepheline, with local contact metamorphism of host limestones producing marble and hornfels (Barker & Austin, 1981). Structurally, the site lies within the eastern margin of the Hueco Bolson, aligned with multiple north-south trending normal faults parallel to the basin axis, as well as secondary north-west trending faults (Figure 3) (Collins et al., 1996; Granillo, 2004).

Geothermal investigations mapped several warm wells (50-71ºC) along the eastern Hueco Bolson margin, with anomalous gradients linked to fault conduits and possibly residual magmatic heat (Barker & Austin, 1981). The temperatures measured from Fort Bliss wells indicate 80-93ºC at depths of 0.9 km and over 120ºC at 4-5 km depth, confirming a steep geothermal gradient consistent with Rio Grande Rift extension (Barker et al., 2014; Brandt, 2015). These geological and thermal conditions define the Hueco Basin as a promising geothermal province.

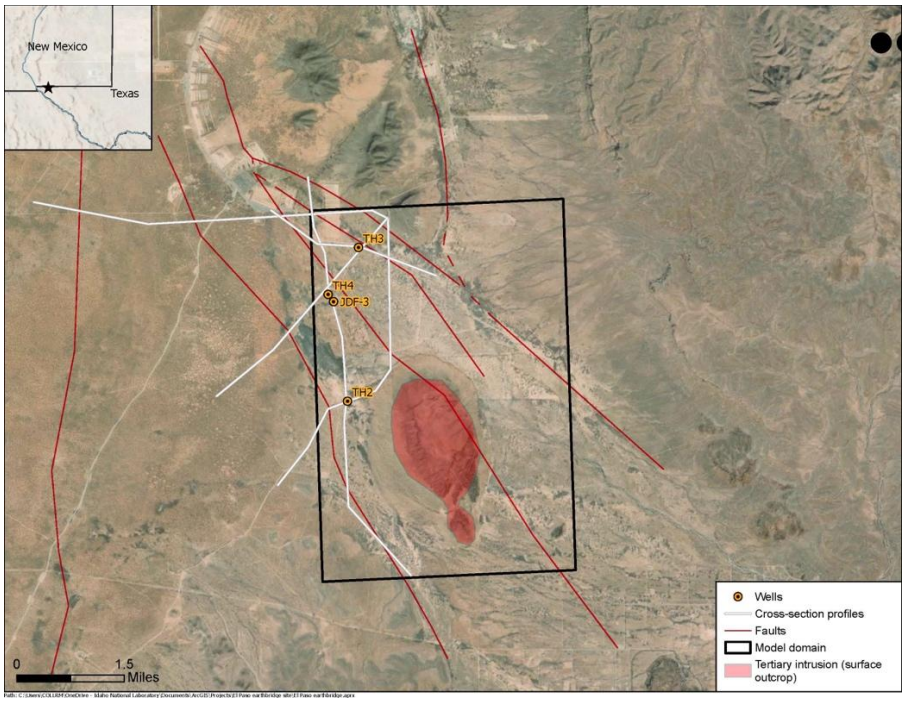


Figure 3: Landsat image with interpreted fault locations from Granillo, 2004.

4.2 Premier Resource Management Site (San Joaquin Valley, California)

The southwestern San Joaquin Valley (SJV) is underlain by a structurally complex and stratigraphically diverse sedimentary basin shaped by prolonged tectonic subsidence, marine transgression, and episodic sedimentation. Bounded by the Sierra Nevada to the east and the Coast Ranges to the west, the basin rests atop a Mesozoic crystalline basement composed of Coast Range ophiolite (~160 Ma) and Sierra Nevada granites (~110 Ma), which are unconformably overlain by Cretaceous through Quaternary strata (Scheirer and Magoon, 2007). The most prospective intervals for GeoTES development occur within the Eocene to Pliocene section.

At the core of PRM's GeoTES demonstration (Umbro et al., 2025; 2026) is the Point of Rocks (POR) Sandstone, a member of the Eocene Kreyenhagen Formation. The Kreyenhagen is a marine shale unit, 400–800 feet thick, composed predominantly of calcareous mudstone and shale (Giannetta and Behl, 2022). It includes two lower members: the Canoas Siltstone and the POR Sandstone, interpreted as transgressive deposits restricted to the western half of the basin. Stratigraphically, the Kreyenhagen underlies the Tumey Formation and overlies Cretaceous units, serving as both a regional aquitard and a prolific source rock, with total organic carbon (TOC) values up to 4.7 wt% and an average of 2.7 ± 1.1 wt% (Peters et al., 2007). Oils sourced from this formation are thermally mature and of marine origin (Lillis and Magoon, 2007).

Overlying the Kreyenhagen is the Pliocene Tulare Formation, a regionally extensive unit composed of interbedded lacustrine clays and sands. It forms the uppermost confining aquitard beneath the Quaternary

alluvium and plays a critical role in limiting vertical fluid migration (San Joaquin Council of Governments, 2022). The Tulare groundwater is characterized by a calcium chloride signature and elevated salinity, though sample coverage is limited. The Canoas Siltstone, underlying the POR, serves as a lower confining unit. Its fine-grained, silty lithology enhances its sealing capacity, contributing to the overall containment system.

The POR Sandstone is a fine-grained, argillaceous, light gray to tan unit interbedded with thin (<10 ft) calcareous shale layers that act as vertical flow barriers. Within PRM's lease area, the POR exceeds 3,000 feet in gross thickness, though only the upper 200–300 feet will be utilized for thermal energy storage (Scheirer, & Magoon, 2007). The depositional environment is interpreted as a deep-marine turbidite system, consistent with its high porosity (32%) and permeability (676 mD) based on sidewall core analyses. These properties support its suitability for cyclic fluid injection, heat storage, and recovery. While the formation contains some hydrocarbons, it is predominantly brine-saturated (>90%), with produced water TDS ranging from 14,791 to 18,000 mg/L (average: 16,075 mg/L), classifying it as moderately saline.

Structurally, the POR has been displaced by thrust faulting across the project area (Figure 4). It forms the crest of an Eocene-age structural high in the western expansion zone and dips steeply eastward into a synclinal trough exceeding 10,000 feet in depth between the expansion area and North Belridge (Scheirer & Magoon, 2007). These structural geometries create multiple hydrocarbon traps, particularly in the upper POR, where impermeable shale and fault offsets provide both vertical and lateral seals.

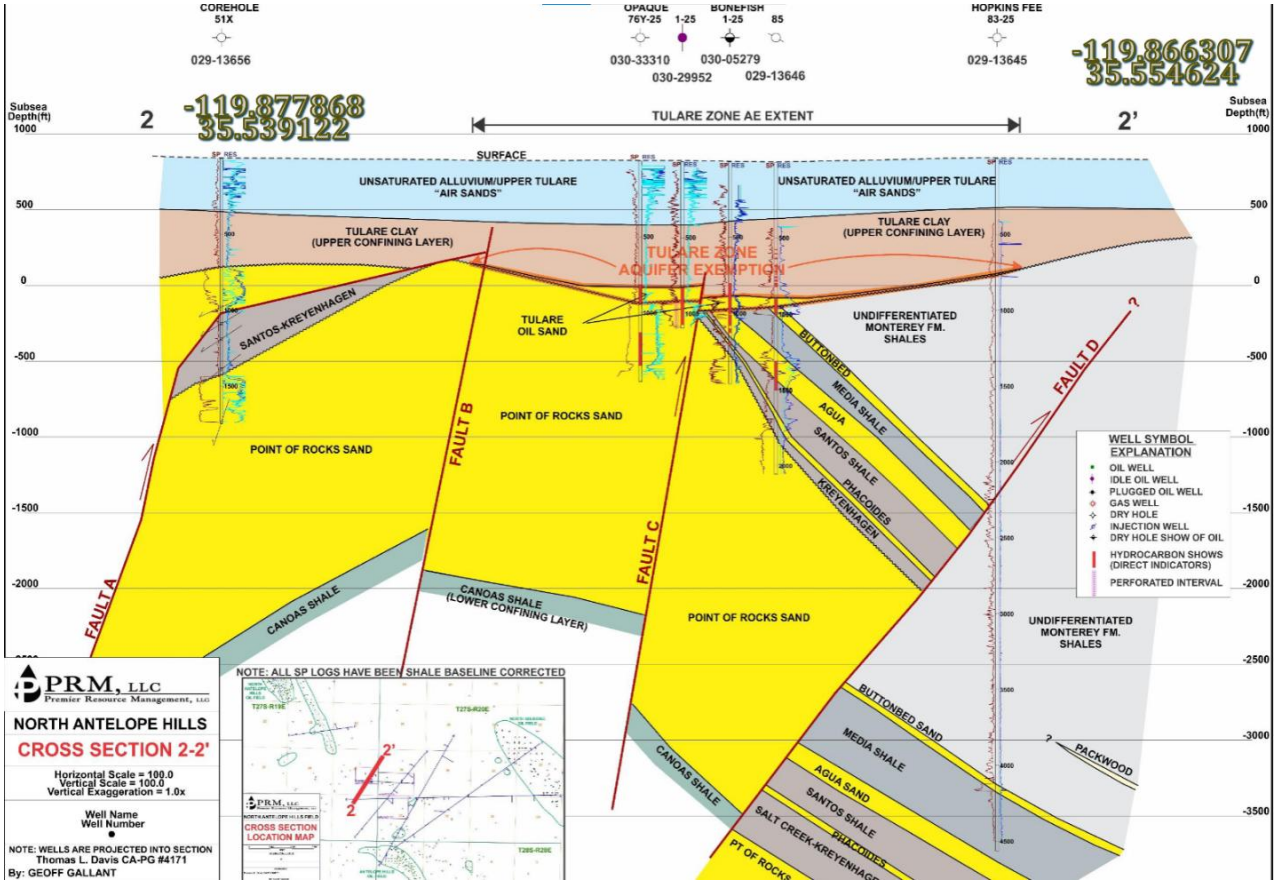


Figure 4: Cross section of the PRM project site showing the Kreyenhagen Formation and associated structural features and lithologies. The POR sandstone is up to 3,000 ft thick and is bound by Kreyenhagen shale and Tulare clay on the top and by the Canoas shale on the bottom (courtesy of PRM).

Reservoir heterogeneity is evident in the vertical and lateral variability of porosity, permeability, and lithofacies. While the POR and Tulare sands offer high-quality storage intervals, interbedded clays and fault offsets introduce anisotropy that must be accounted for in thermal modeling. The integrity of the overlying Tulare clays and underlying Canoas Siltstone is essential for minimizing heat loss and preventing fluid migration.

No active surface expressions of fault leakage or thermal anomalies have been observed near the PRM site. Historical oil field operations in the area suggest long-term containment of hydrocarbons within the target intervals. However, further geomechanical analysis and pressure monitoring will be necessary to evaluate seal integrity under cyclic thermal loading conditions.

5 3D GEOLOGICAL MODEL DEVELOPMENT

In preparation for subsequent modeling and simulations, INL developed a subsurface model using Leapfrog and data from the EarthBridge site near El Paso, TX. Due to the limited number of wells in the area, the team incorporated five 2-D cross-sections derived from gravity surveys (Granillo, 2004) to estimate subsurface lithologies. Additional cross-sections and well data from the Hueco Tanks Geothermal Area (Barker et al., 2015) were also integrated into the model.

Using the available data—wells, faults, cross-sections, and gravity surveys—the team inferred the lithology within the study area (Figure 5). To better constrain the Leapfrog interpolation in data-sparse regions, synthetic wells were introduced. These synthetic boreholes were strategically placed on the perimeter of the Tertiary body, along the cross sections and at the model boundaries to improve the fidelity of the stratigraphic surfaces, fault geometries, and volumetric estimations, particularly in areas lacking observational data. Since the fault offset was known along the main faults and the geometry of the Tertiary intrusion can be somewhat inferred from gravity surveys, the geology of the synthetic wells was estimated using the surrounding geology for context.

After an iterative process to constrain the contact surfaces using the well data in addition to the polylines digitized from the cross-sections and the surface geology, the surfaces were converted to volumes. The resulting geologic volume was segmented into four block models by the main faults (Figure 6). The geologic model domain was made larger than what was needed for reactive transport modelling in the event that the location of the test site was altered. The volumetric model was then clipped to refine the study area to the east of the tertiary intrusion and converted into a 20-meter block model, suitable for use in TOUGH by reactive transport modelers (Figure 7).

A similar modeling workflow will be applied to the PRM site in the SJV, where a greater abundance of well data is available. Preliminary results of the contact surfaces and well data in the area of the GeoTES location can be seen in Figure 8.

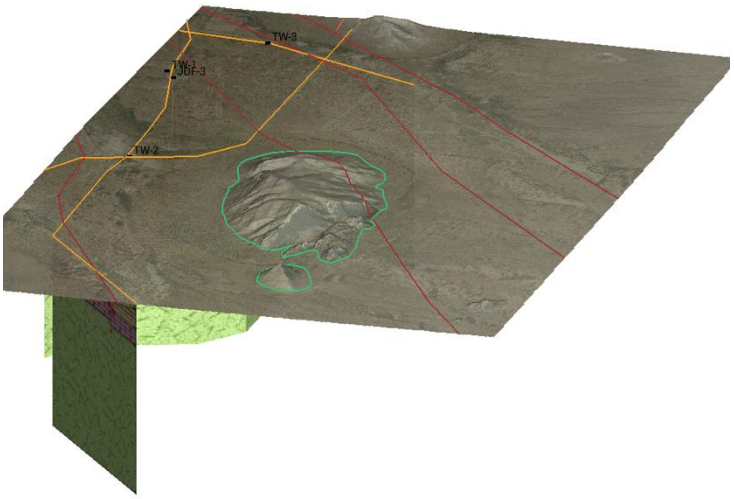


Figure 5: The skeleton of the Leapfrog model of the EarthBridge site in El Paso, TX looking approximately North with a plunge, showing the four wells, 4 sub-vertical faults trending NW-SE, three of the 2-D cross sections and surface lithology/topography (inside the green line is the Tertiary intrusion, outside of the green line is alluvium).

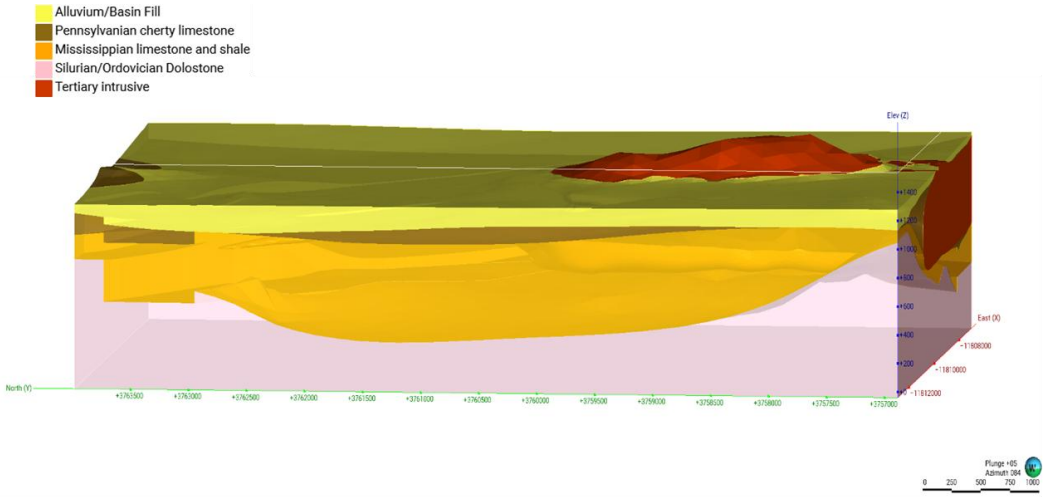


Figure 6: The resulting EarthBridge Leapfrog model looking approximately east after extrapolating surfaces and inferring the geometry of the intrusion.

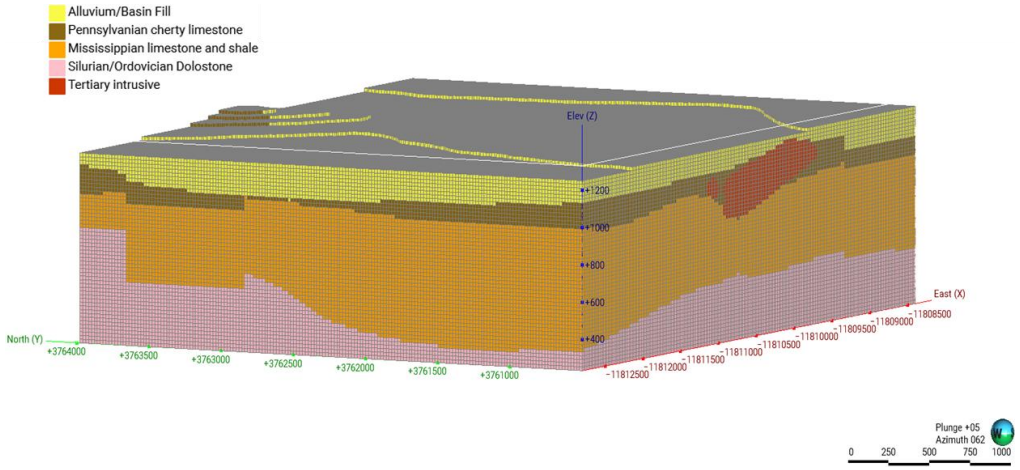


Figure 7: The resulting 20 m grid exported for reactive transport modeling for the EarthBridge site.

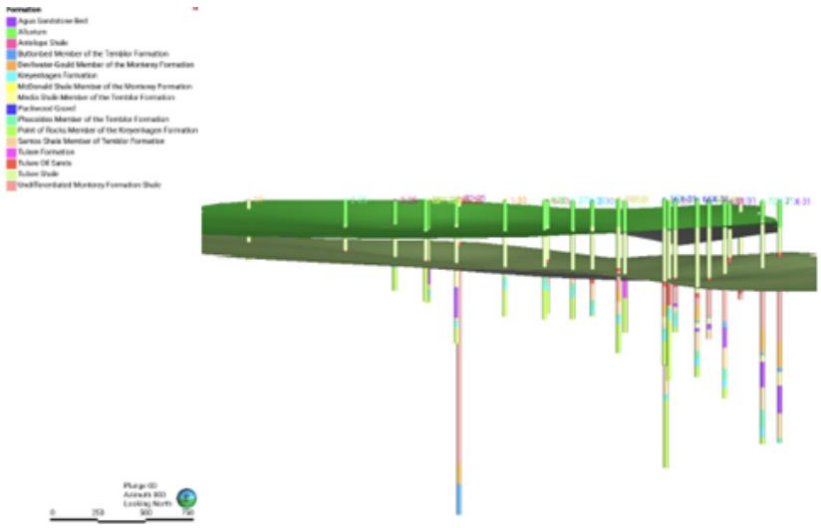


Figure 8: Shallow contact surfaces and well data from the PRM GeoTES site in San Joaquin Valley.

6 PRELIMINARY MODELING AND SIMULATION

We implement a staged, site-specific coupled thermo-hydro-mechanical-chemical (THMC) workflow that links the Leapfrog three-dimensional geologic framework to reservoir simulations and operational concepts at the EarthBridge sites in Texas and California (PRM / POR; Pico / Older Reservoir). The workflow emphasizes

operational feasibility, thermal containment, and mitigation of capacity fade over multi-year cycles. Building on this framework, we simulate non-isothermal, single-phase brine flow, accounting for temperature- and salinity-dependent density and viscosity. The governing equations account for advection, conduction, thermal dispersion, and rock heat capacity. Where risks warrant, reactive chemistry is included to constrain scaling potential and porosity evolution.

The 20-meter Leapfrog block models were converted into simulator-ready grids, refined to 5–10 meters near well laterals and mapped faults, and coarsened to 25–50 meters elsewhere to manage computational cost. The meshes capture key lithologic interfaces, including the alluvium–intrusion margin in Texas and the sand–shale architecture of the California POR site. Boundary conditions impose no flow at structural and stratigraphic seals and a far-field constant-pressure–temperature gradient derived from hydrostatic pressure and geothermal trends. Heat flux continuity is maintained across the caprock and basal contacts to track vertical losses. Initial conditions utilize depth-dependent pressure, temperature, and salinity—approximately 1.2 g/L brackish water in Texas and approximately 16 g/L brine in California—while preserving the native formation states. Further, measured rock and fluid properties inform the simulations: porosity of ~30% and permeability of ~1 darcy in Texas, and ~32% porosity with ~676 millidarcies permeability in California. These are complemented by facies-specific thermal conductivities, heat capacities, directional anisotropy, and shale or caprock constraints derived from well and cross-section data.

Operational scenarios are tailored to site-specific geologic and thermal conditions. In Texas, the pilot configuration utilizes a paired injector–producer system, serving as a foundation for evaluating flow dynamics, heat recovery efficiency, and potential scale-up strategies. The California site focuses on developing the upper reservoir interval through a multi-well arrangement optimized for diurnal energy storage and seasonal recharge supported by concentrated solar thermal input. In both cases, operational strategies are designed to balance efficiency, thermal containment, and caprock integrity. These site concepts integrate geological context with practical operating modes, forming the basis for subsequent simulation and optimization. Model outcomes are anticipated to exhibit a broad range of performance behaviors, spanning from sustained high thermal recovery with minimal long-term capacity decline to more rapid breakthrough responses that may necessitate adaptive well management or configuration adjustments.

7 FUTURE WORK

Our forthcoming efforts will focus on completing the integrated Leapfrog-based geological modeling and coupled THMC (thermo-hydro-mechanical-chemical) simulations for both candidate sites. To support and validate these models, we will conduct a series of batch geochemical experiments designed to replicate in-situ conditions. These experiments will enable us to assess mineral–fluid interactions, thermal stability, and the long-term geochemical integrity of the GeoTES system. By combining empirical data with numerical simulations, we aim to improve predictive confidence in system performance and inform site-specific design and risk mitigation strategies.

8 CONCLUSIONS

Subsurface characterization and modeling at both the West Texas and San Joaquin Valley pilot sites have demonstrated the critical importance of detailed geological, petrophysical, and hydrogeochemical analysis in evaluating the suitability of candidate reservoirs for GeoTES deployment. The integration of well logs, stratigraphic interpretations, and production histories enabled the construction of robust 3D geologic models, which revealed favorable reservoir properties—such as high porosity, permeability, and effective confining units—essential for long-duration thermal energy storage and recovery. Reactive transport simulations further confirmed the viability of these formations, highlighting their capacity for cyclic heat injection and extraction, as well as their potential for maintaining thermal containment over operational timescales.

These findings have significant implications for the deployment of GeoTES at scale. The demonstrated ability to identify and model suitable subsurface reservoirs supports the feasibility of expanding GeoTES systems beyond pilot projects, enabling integration with renewable energy sources and providing grid-scale, dispatchable storage. The insights gained from site-specific modeling inform best practices for reservoir selection, system design, and risk mitigation, laying the groundwork for broader commercial adoption across diverse geologic settings.

Looking ahead, future experimental work will play a pivotal role in validating and refining these models. Planned batch geochemical experiments and thermal cycling simulations will provide empirical data on mineral–fluid interactions, thermal stability, and long-term system integrity under realistic operating conditions. By coupling experimental results with advanced numerical simulations, the project aims to enhance predictive confidence,

optimize system performance, and support the development of scalable, resilient GeoTES solutions for the evolving energy landscape.

Acknowledgements

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