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Conceptual and Numerical Model for the Thermo Hot Springs Geothermal Area

Santiago Rocha[1] and Nolan Dellerman[2]

[1]Cyrq Energy [2]Ormat Technologies

Keywords

Geothermal reservoir modeling, Basin and Range geothermal systems, Thermo Hot Springs, Conceptual model, Numerical modeling, Volsung, Low-enthalpy geothermal, Utah geothermal energy, Structural geology, Geothermal field management

ABSTRACT

The Thermo Hot Springs Geothermal Area, located in the Escalante Valley (southwestern Utah), has been commercially producing geothermal energy since 2008, with Cyrq Energy operating a 12.5 MWe power plant. The system is a hybrid play type, a combination of fault and sedimentary controlled system, within the Basin and Range province, where high heat flow from a thin crust due to ongoing extension drives convective upflow along intersecting NNE- and WNW-striking fault zones. The deep, hot geothermal system is masked by active valley hydrology, with geothermal fluids migrating through a mix of porous, unconsolidated rocks and fractured media, resulting in heterogeneous permeability and varying productive zones. Geophysical, geological, geochemical, and production well data reveal that both structurally enhanced permeability and stratigraphic controls, particularly within a polymictic unconformity horizon acting as a mixing reservoir, influence the system. Two major unconformities are identified that control thermal fluid flow. Reservoir temperatures range from 210–400°F, with geothermal fluids mixing with meteoric groundwater, which masks the actual production temperature, stabilizing it closer to 250°F. This highlights the commercial viability of low-enthalpy geothermal systems. This paper presents the geological conceptual model and numerical modeling validation of this commercial geothermal project.

1. Introduction

The Thermo No. 1 geothermal field has undergone several phases of exploration, development, and operational adjustment since initial interest in the 1970s. Early exploration efforts were constrained by technological limitations of the time and did not lead to commercial development. However, geochemical indicators, high heat flow in shallow gradient wells, and later drilling by local interests renewed attention to the area, ultimately prompting Raser Technologies (later Cyrq Energy) to initiate field development in 2007.

Initial development focused on completing multiple production wells to target a presumed reservoir in a quartzite interval. While bottom-hole temperatures above 300°F were encountered, production temperatures remained lower due to non-isolated cooler feed zones. The field began operations supplying a binary power plant with fluid temperatures around 255°F and total flow of ~6,400 gpm.

Over time, the reservoir management strategy evolved in response to declining production temperatures and injection limitations. To support decision-making and guide future development, both geological and numerical models of the field were constructed. Informed by these models, several operational changes were implemented, including the drilling of a new make-up well in 2023. This well, located west of the legacy wellfield, was sited using improved structural targeting and completed with zonal isolation to exclude colder feed zones. It successfully produced significantly hotter fluid, resulting in a partial recovery of the plant's inlet temperature. The performance of this well provides early validation of the models discussed in this paper.

2. Geologic and Conceptual Model

The Thermo Hot Springs Geothermal Area conceptual model was built around a 3D geologic model that serves as the basis of understanding the controls on the geothermal system. The geologic model was built utilizing geologic and geophysical data sets to establish a stratigraphic and structural framework for the field. Shallow and deep temperature, geochemical, and production data, downhole logs, and regional hydrology were also incorporated into the conceptual model in addition to the geology. The conceptual model is conveyed most easily with geologic cross sections overlain by temperature isotherms (contours) and further annotated with major features and interpreted fluid pathways (vectors along, into, and out of the section).

2.1 Stratigraphic Framework

The stratigraphic framework at Thermo was established by detailed logging of cuttings from all deep wells in the field by personnel at University of Utah's Energy and Geoscience Institute in 2010 when most of the eastern wellfield was completed. Further study on the correlation of the formations to the regional stratigraphy of southwestern Utah was conducted by Anderson (2012) where many of the formations encountered in Thermo wells were correlated to regional formations that outcrop in the neighboring ranges to the north of Thermo, namely the Star Range to the NW and the Mineral Mountains to the NE.

The general stratigraphy of the Thermo field matches the regional stratigraphic fabric of the eastern Basin and Range. Broken into 4 major packages, the major time periods represented at Thermo are as follows:

- Quaternary alluvial and lacustrine deposits
- Tertiary volcanic deposits
- Mesozoic and Paleozoic sediments
- Precambrian Basement

More recently, and to create a more robust conceptual model, several investigations in the neighboring ranges were conducted. The purpose of these investigations was twofold: to understand which formations contribute to the permeability control of the geothermal system in a significant way, and to measure physical properties of the formations represented for calibration of geophysical models.

The current understanding of the stratigraphic framework at Thermo is illustrated in Figure 1.

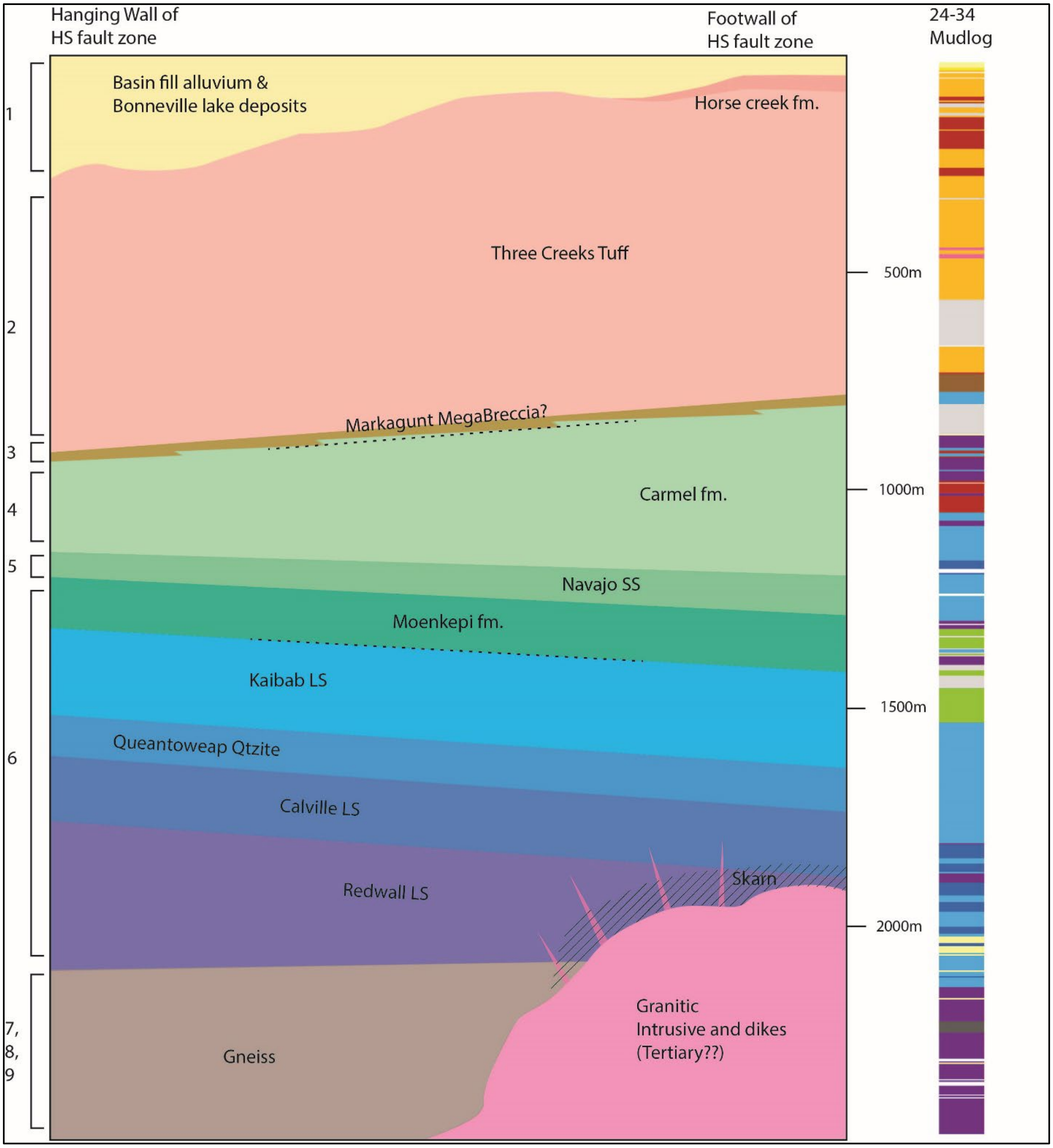

Figure 1: Schematic diagram of the Thermo stratigraphic framework. Dotted lines represent major unconformities. Numbers in the left column correspond to the geologic model units: 1. Alluvium 2. Volcanics 3. Polymict 4. Upper Carbonate 5. Sandstone 6. Lower Carbonate 7. Skarn, 8. Granite 9. Basement

2.2 Structural Framework

The structural framework at Thermo was initially established by a fairly detailed (1:62,500 scale) map published by the USGS (Rowley, 1978). This mapping recognized two major structural trends present at Thermo; NNE-striking structures, and WNW-striking structures. These two major structural trends have held up to contemporary interpretations and still form the basis of the structural framework at Thermo. Furthermore, the author of the 1978 geologic map recognized that the Thermo Hot Springs surfaced where these two apparent structural trends intersected.

A series of recent field mapping exercises mostly aimed at validating the 1978 Rowley map added additional detail and some reinterpretation to the fault map. The aid of LiDAR, and interpretations of gravity and magnetics also served to further validate and map concealed faults as well.

The general structural framework at Thermo can be restated as being dominated by two major structural trends. The dominant trend is NNE-striking Basin and Range structures. The major structural feature being a NNE-striking down-to-the-west normal fault zone west of the legacy (eastern) wellfield that projects to the hot springs. This fault zone explains the major gravity gradient from east to west (dark orange to blue, Figure 2). The hot springs themselves demonstrate the dominant NNE-structural grain as they emanate from two distinct en-echelon travertine/sinter mounds that trend in a NNE-direction. The less dominant WNW-trend is likely an older, overprinted set of structures. These structures are evident in fault exposures to the south and west of the field, and further supported by two conspicuous WNW-oriented gravity gradients that bound the field on the north and south respectively (Figure 2). Rowley 1978 speculated that the Thermo Rhyolite, a young (~10ma) rhyolite outcrop NE of the field is likely related to the WNW-structural zone present here. This indicates that this could be a deep-seated structural zone, and likely plays a significant role in the structural controls of the system.

2.3 Conceptual Model Explanation

The Thermo Hot Springs Geothermal Area is understood to be hybrid play type, characterized by both fault-controlled permeability, analogous to many Basin and Range geothermal systems, and a matrix-stratigraphic permeability associated with an unconformity. The proposed conceptual model in this study identifies a heat source, a permeability structure, a thermal recharge pathway, a characterized reservoir, an interaction with shallow hydrology, and a geochemical description of the system.

The heat source identified in this system is identified as high heat flux due to the thin crust as a result of ongoing extension in the Basin and Range tectonic province. While the thermal gradient varies along the depth of the system, the deep high temperature resource is masked by an active, cold groundwater system.

Detailed analysis of production data paired with the contemporary understanding of the detailed stratigraphy have led to the interpretation of a “hybrid” play type. Hybrid play type in this context means that subsurface fluid flow is likely driven by both anomalous structurally enhanced permeability, and stratigraphic permeability (Figure 3). The stratigraphic controls serve to act as an intermediate-depth outflow / mixing reservoir where deep geothermal fluids mix with shallow meteoric groundwater. The “polymict” unconformity marker bed is thought to represent the bulk of the stratigraphic permeability. Testing and surveys from the active wellfield confirm the high contribution (permeability) due to the unconformity and a minor contribution from structural components. The eastern wellfield receives >65% of its production from at or near this unit as evidenced by the production temperatures relative to the static temperatures measured in the wellbores. The main structural features that do support vertical flow appear to be oriented 30–60 degrees from the inferred present-day maximum horizontal stress (SHmax) of the system. This could be indicative of rotation of the local stress field or a similar magnitude of stress between the overburden and maximum horizontal stress (Normal Faulting-Strike Slip regime). Current studies are being undertaken in order to better estimate the critically stressed faults of the field.

The active hydrology is identified from the recharge of the mountain areas which drain to the Escalante Valley. This serves as the system's recharge which flows down-gradient towards the northeast in the valley with an estimated contribution of 1000-2000 acre-ft/yr (20-40 kg/s) (Mower and Sandberg, 1982). While this active system partially masks the deeper system, it serves as the pressure support for the overall geothermal system. Evidence of this is the sustained pressure of the system over the field's history (Figure 9). A wide range of geothermometers also exists across the field (260 - 440°F), adding to the uncertainty of potential deep hot fluid temperatures, but also serving to confirm the hybrid play type concept.

The current conceptual model supposes major fault-controlled convective upflow centered at the hot springs fault intersection (Figure 3 and Figure 4). Although the hot springs exhibit a mixed geochemical signature, the mixing can be explained by the intermediate-depth mixing interval observed elsewhere in the field and doesn't necessarily indicate the hot springs are a shallow distal outflow of the system. There is also deep convective upflow along the NNE-striking west-dipping fault zone along strike to the SW from the hot springs at least as far as where 73-32 is completed. 73-32 encountered both NNE-striking faults and fractures as well as WNW-striking faults and fractures as interpreted in the Acoustic Borehole Imager (ABI) log. As such, the control on the upflow encountered by this well could be the apparent intersection of the WNW-structural zone that projects into the NNE-striking fault zone in this vicinity. The convective part of the system is not constrained to the SW of 73-32 along strike of the NNE-striking fault zone. Figure 4 shows an oblique cross-section (SW-NE) view of the conceptual model discussed above.

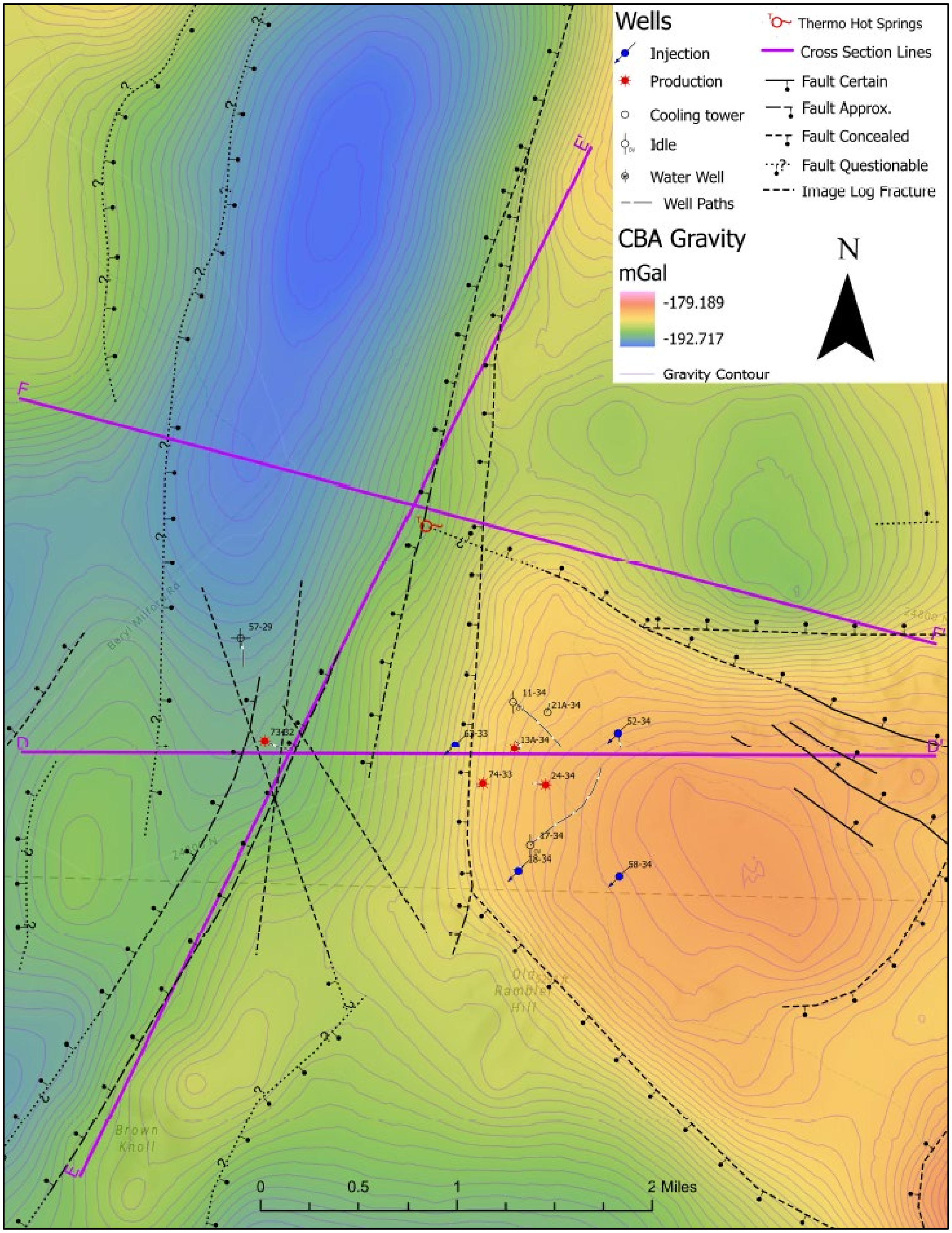

Figure 2: Wellfield and fault map overlain on complete Bouguer anomaly gravity map.

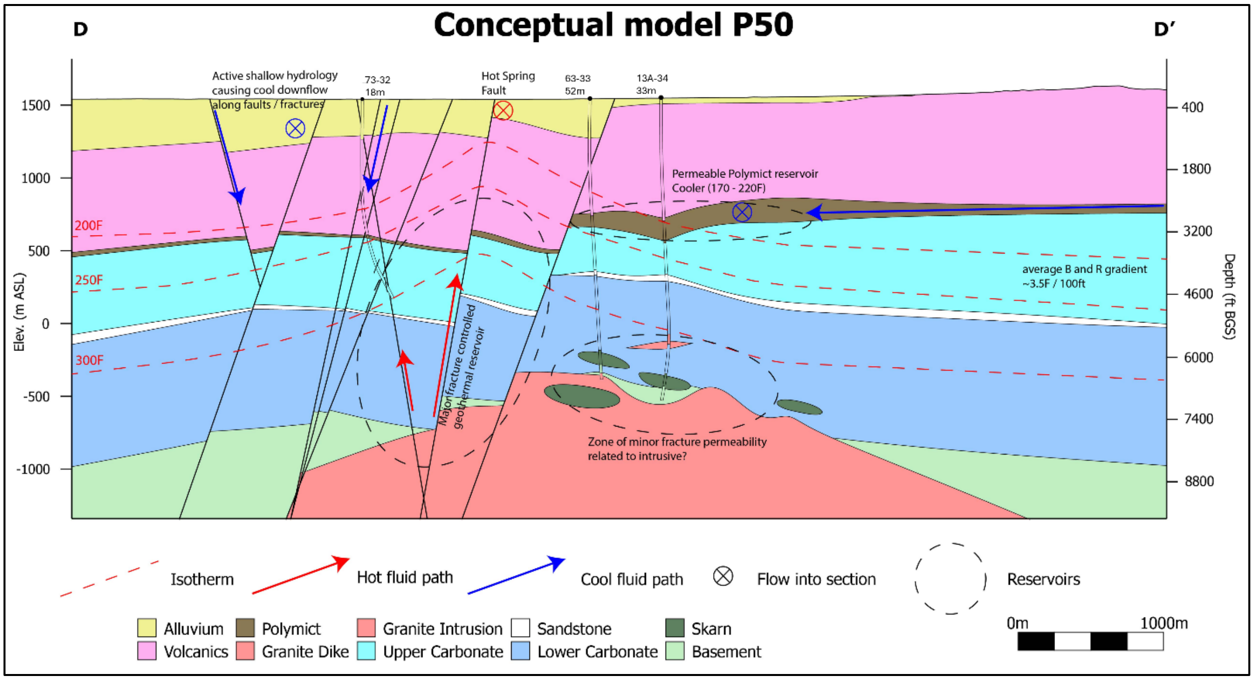

Figure 3: Conceptual model cross-section across western well and middle of eastern legacy wellfield. Location shown on Figure 2.

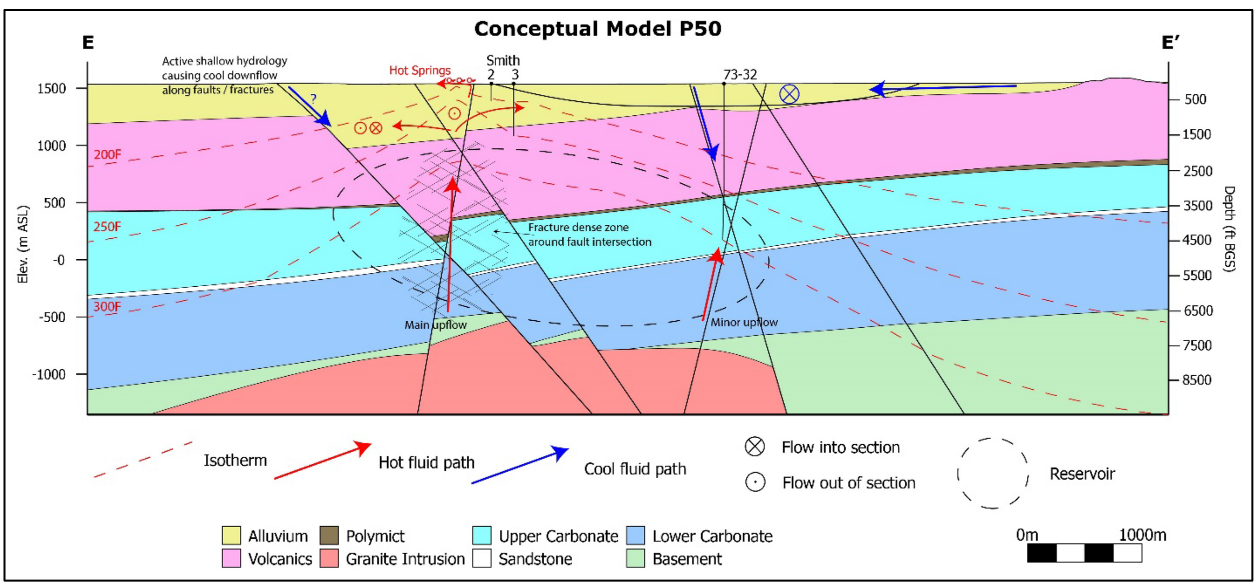

Figure 4: Conceptual model cross-section across hot springs near Smith wells and bottom hole location of western well. Location shown on Figure 2.

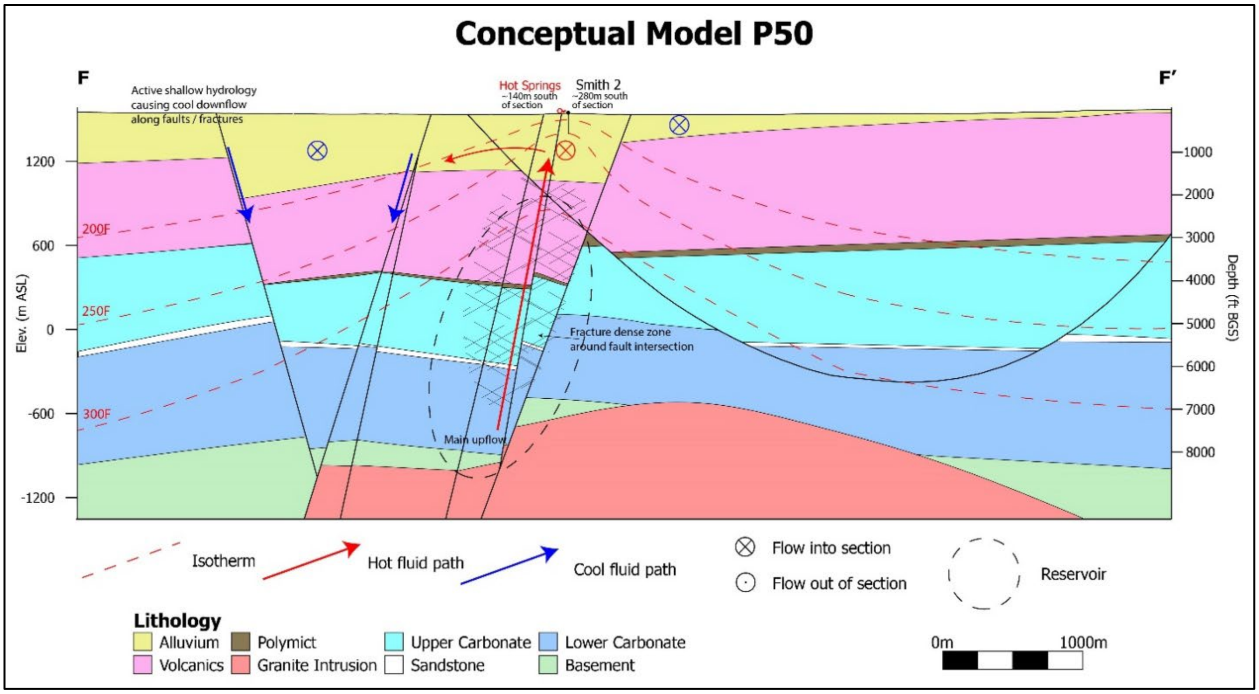

Figure 5: Conceptual model cross-section across hot springs. Location shown on Figure 2.

3. Numerical Model

As part of efforts to improve wellfield management, various reservoir models have been developed for the project in the past, most of which were created by third-party consultants. To maintain full control of the model and ensure easier access and greater usefulness, Cyrq Energy has dedicated its efforts to building an in-house reservoir model using the Volsung reservoir modeling software package (Franz and Clearwater, 2021). The following sections briefly describe the modeling process, including the Leapfrog-Volsung transfer, which enables the direct integration of geologic volumes and fractures into the reservoir model.

3.1 Model Domain

The proposed model covers a 24,000 × 28,000 ft domain designed to include the main hydrological controls of the system: the Escalante Desert at its center, extending from the southwest to the northeast, Antelope Peak to the northwest, and the Black Mountains to the southeast. The center of the model corresponds to the current operating field and the Thermo Hot Springs, the primary hydrothermal surface feature. The model extends to a depth of 11,500 ft to capture most of the identified intrusive body, with additional refinement near the surface to better represent the hydrological system. A non-uniform grid with local refinement around the wellfield allows for detailed thermal and hydraulic resolution near the wells, while maintaining computational efficiency in the recharge areas. Following the identified SHmax orientation in the area, the grid was aligned at an azimuth of 14 degrees. The model contains 276,146 grid blocks—a large grid count, but one that Volsung's parallelized architecture and GPU-accelerated linear solvers can process efficiently without run-time limitations (Franz et al., 2019).

3.2 Initial and Boundary Conditions

The numerical model was discretized following the lithological units described in the conceptual model section (Figure 1), with additional rock units introduced to represent the structural framework. Initial runs used typical property values for average rock types (Robertson, 1988; Wolff, 1982) and were subsequently refined based on the known production structures in the current wellfield. The structural units employed a Multiple Interacting Continua (MINC) approach for fracture discretization and solution (Pruess, 1992). Fault units oriented 30–60 degrees from SHmax were assigned higher horizontal permeability values (on the order of hundreds of millidarcys) to represent the observed higher-permeability structures in the system. It is important to note that a geomechanical framework is being completed at the time of writing, and the assumed orientations and preferred pathways described here are still subject to review from a geomechanics perspective.

Boundary conditions were defined in the numerical model based on the description in Section 2 (Figure 6). The heat source is represented by a constant bottom-boundary temperature of 400 °F, with additional mass input of 120 klb/hr at the same temperature introduced through the identified deep structural features. A top boundary was placed to simulate atmospheric conditions (15 psi and 70 °F). Side boundaries simulate the hydrological gradient of the Escalante Valley and the natural drainage from the surrounding mountains into the valley. These are represented by a constant cold-water mass inflow of 160 klb/hr at 80 BTU/lb, along with constant pressure support of 50 psi from the southeast, corresponding to the Black Mountains region. Outflow from the system is modeled at the Thermo Hot Springs, with a discharge rate of 16 klb/hr.

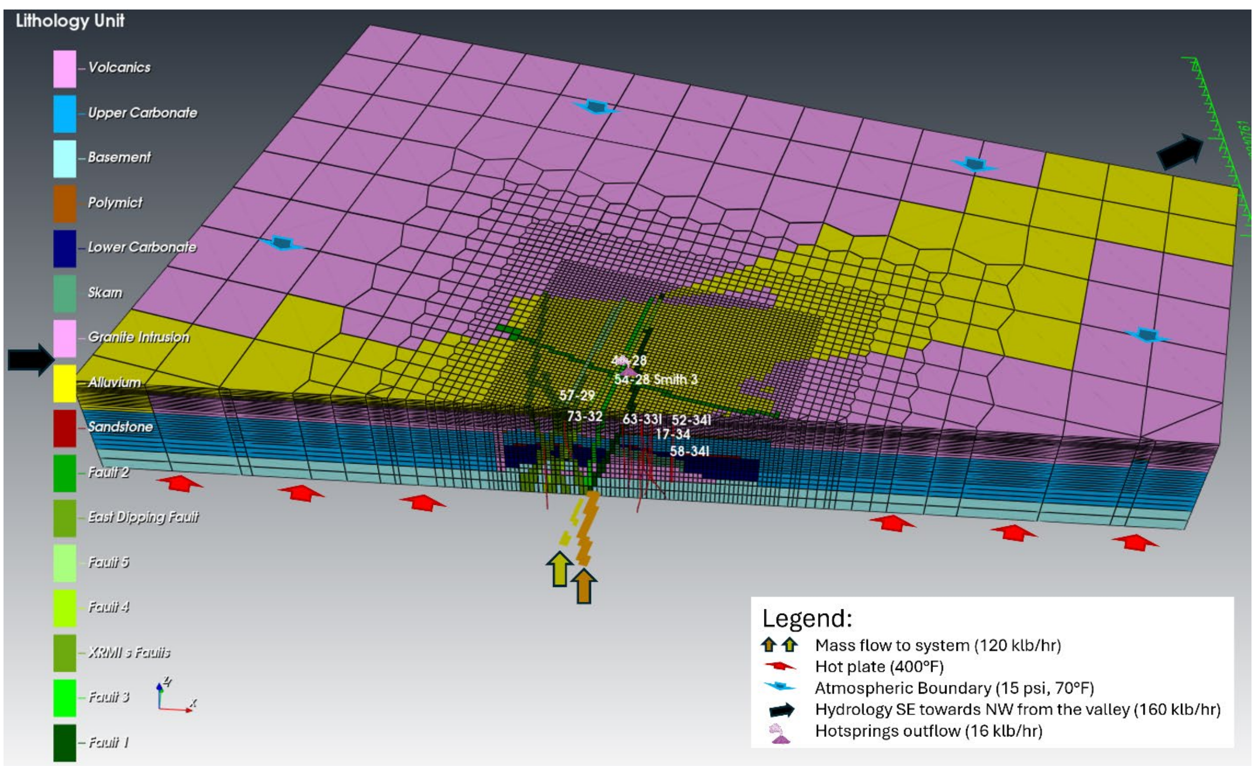

Figure 6: Numerical model domain, lithological framework, structural features, and applied boundary conditions including heat, mass input, hydrological gradients, and outflow representation.

3.3 Natural State

Multiple natural-state simulations were performed to better calibrate the static properties of the modeled units. Only static pressure-temperature (PT) corrected profiles were used to match the natural state. Each simulation was run until the model reached convergence after 30 million years of simulated time.

The pressure and temperature surveys used for calibration were obtained from the original wells drilled and logged before initial power production. These data were corrected using the Brennand method (Brennand, 1984) to represent true static natural-state temperatures. A similar approach was applied to calibrate the various pressure readings from pre-exploitation PT surveys. This calibration is particularly important in a system like Thermo Hot Springs Geothermal Area, where permeable zones occur at different intervals, and most surveys of natural conditions were affected by prior wellbore activities (e.g., injection or flow tests).

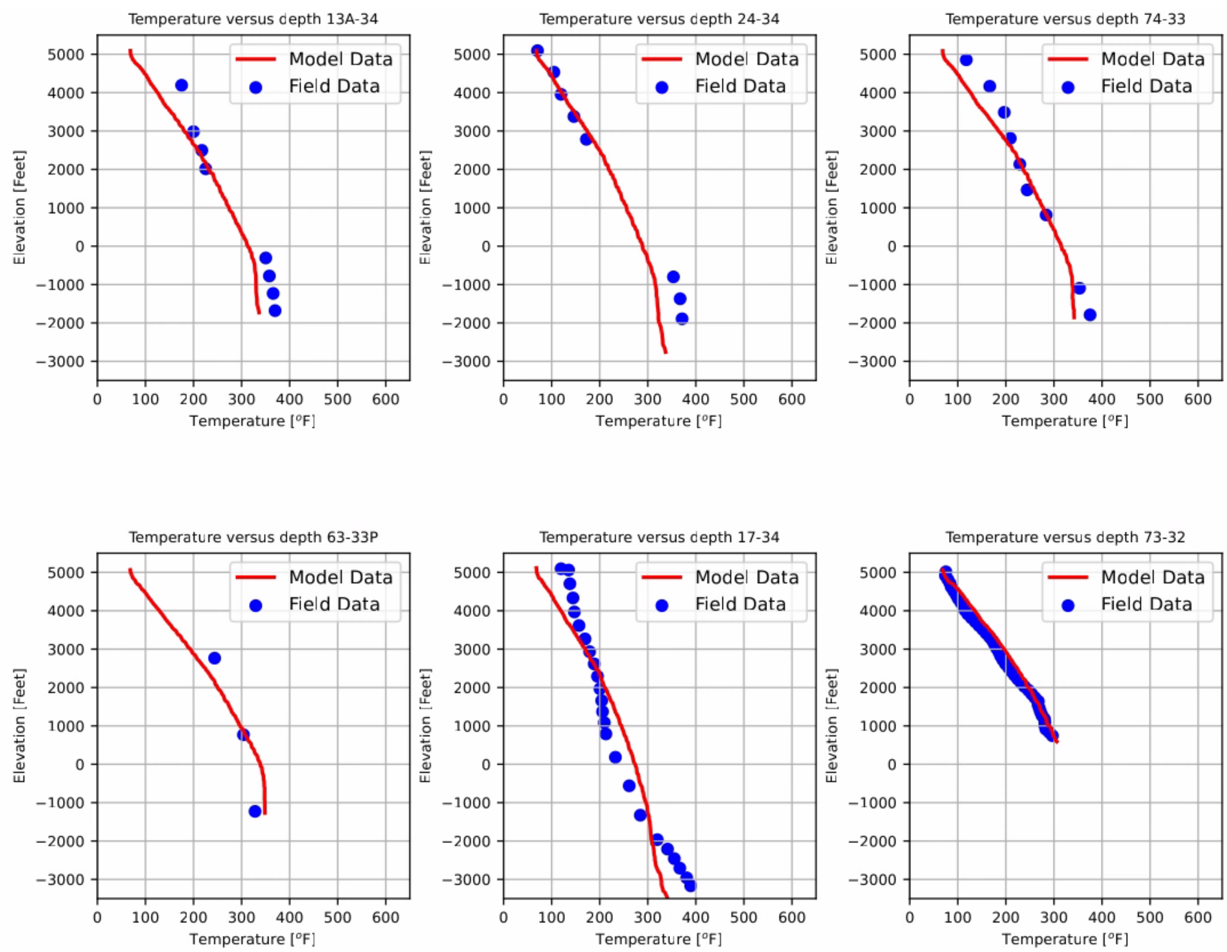

Figure 7: Natural-state model matches to temperature profiles in the main production wells of the field.

A natural-state match was selected as most of the profiles display a similar trend when compared to the initial conditions and corrected surveys. The match, while not completely accurate, focused on reproducing the main feedzone intervals identified in the wells. The matched permeable features of the system can be divided into two main sets: stratigraphic features, which facilitate horizontal flow, and structural features, which enable vertical movement (upflow). The structural features can be further subdivided, as most identified structures do not exhibit significant flow. The main structural features that do support vertical flow appear to be oriented 30–60 degrees from the inferred present-day SHmax of the system. Further analysis is ongoing to better correlate this structural orientation with flow behavior.

The most permeable features are associated with stratigraphic units that account for an estimated 65% of the total flow, a finding that aligns with the production behavior subsequently matched in the model. As shown in the matched temperature distributions in Figure 7, legacy wells are located outside of the main interpreted upflow of the system. In contrast, the upflow zone correlates with the main structures that trend toward the hot springs and the fault system west of the current wellfield where the most recent well (73-32) has a closest match across the entire temperature profile.

3.4 Calibration (History Match)

To calibrate the reservoir parameters, both pressure and temperature data were matched to observed values at various stages of production history. The following subsections describe the methodology used for each variable and the adjustments made to improve model alignment.

3.4.1 Temperature Calibration

Wellhead temperatures from production wells were used as a primary calibration target, helping to refine not only the reservoir thermodynamic properties but also the allocation of flow contributions from different feedzones. Initial feedzone allocations were based on available spinner data and demonstrated reasonable agreement with production temperatures under steady conditions. Additional interpretations from pressure transient analysis were used for initial permeability and porosity estimates.

However, the model initially failed to capture the full range of temperature fluctuations associated with changes in production rates. This discrepancy is attributed to the heterogeneous and compartmentalized nature of the reservoir. Many wells exhibit isolated feedzones that respond independently to changes in flowrate, suggesting the presence of hydraulically discrete compartments.

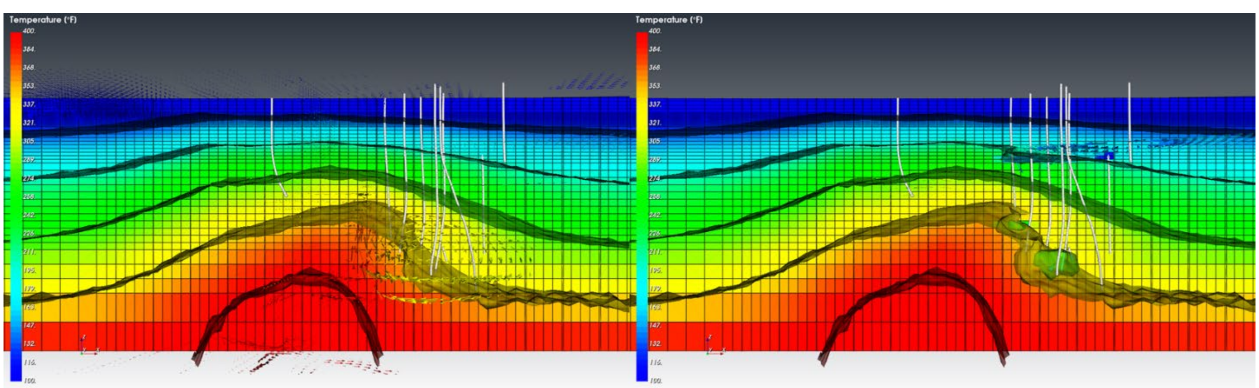

Figure 8: 3D reservoir temperature distribution and delta comparison in the Thermo No. 1 Field. Left: Simulated temperature distribution view at natural-state conditions. Right: Simulated temperature distribution after 15 years of operation across the reservoir model domain, highlighting upflow zones, stratigraphic thermal gradients, and the dominance of two particular feedzones in the system.

To improve the match, a feedzone allocation modifier was applied to two production wells. These adjustments, which altered individual feedzone contributions by no more than 5%, significantly improved the agreement between modeled and observed temperature histories. The allocation is explained by changing fluid dynamics of the well by responding to both reservoir changes in the two different production zones, and the interaction in the wellbore from these two isolated zones (Figure 8). Figure 9 displays the production history match for different parameters, including the production temperature match.

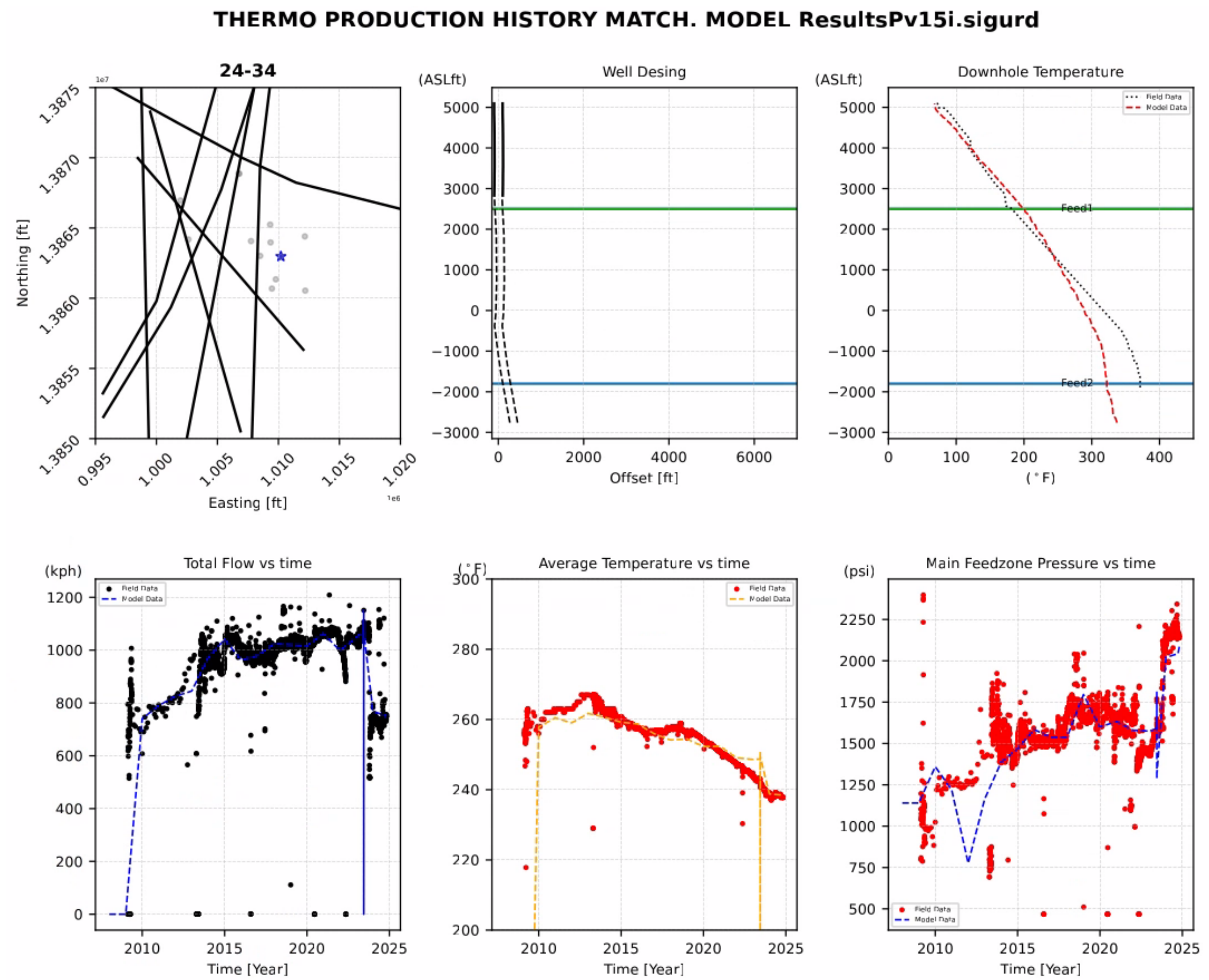

Figure 9: Summarized data plot for PW 24-34. Plots display well location, construction, PT match, flow rate, production temperature, and pressure match. Following geothermal modeling framework from O'sullivan et al. (2023).

3.4.2 Pressure Calibration

In the absence of dedicated observation wells with downhole pressure measurements, calibration was performed using bubble-tube pressure readings taken at the intake of the line-shaft pumps in the production wells (Figure 9). Additional calibration was applied during selected shut-in periods, where certain wells were temporarily taken offline (Figure 10). These events allowed for replication of the system's dynamic-to-static pressure transition and provided additional validation of reservoir response.

For pressure calibration, the model data was corrected by extrapolating pressures to a standard reference depth. This correction aims to align pressure readings with key depth intervals where pressures can be reliably analyzed in the model, as most measured points do not coincide with these primary depths. The correction equation accounts for the well's measured productivity index and the pressure difference caused by the vertical distance between the measurement depth and the main feedzone depths. This approach enables pressure adjustment when datasets reference different depth datums or when the modeled dataset reflects reservoir behavior rather than wellbore conditions.

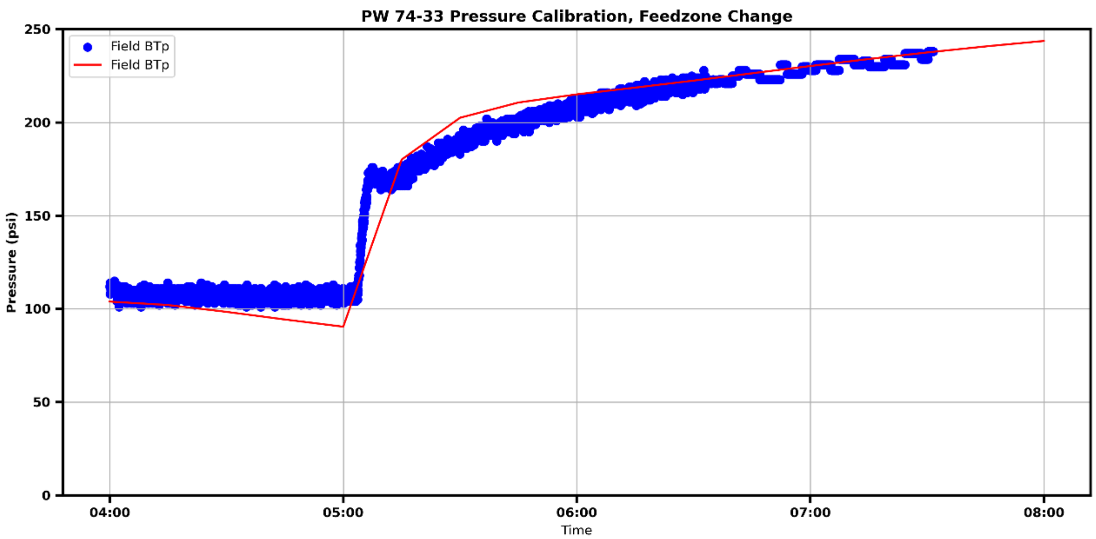

Figure 10: Pressure calibration for PW 74-33. Field data compared with model data for the main feedzone during a plant outage.

4. Future Work

Future efforts will focus on incorporating a geomechanical framework to better constrain the role of critically stressed faults and refine the permeability distribution across structural units. Additionally, improvements to the model will aim to integrate tracer test data and a more robust recharge characterization. Continued production and pressure monitoring, along with additional well data, will also support further calibration and validation of the model.

5. Conclusions

This study presents a detailed conceptual and numerical model of the Thermo Hot Springs Geothermal Area, incorporating geological, structural, geochemical, and production data. The results highlight the hybrid nature of the reservoir, where stratigraphic and structural features interact to control permeability and fluid flow. Natural-state and production-history simulations demonstrate reasonable agreement with field data, validating key aspects of the model. The framework developed here supports ongoing field management and provides a foundation for future optimization and development planning.

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