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A Numerical Model Case Study of the Patua Geothermal Field

John Murphy[1], Richard Holt[1] and Monte Morrison[2]

[1]Geothermal Science, Inc.

[2]CYRQ Energy

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ABSTRACT

A numerical simulation of the Patua Geothermal Field was developed and calibrated. The simulation reflects an updated conceptual model and is calibrated to significant production and initial state data measured at Patua. The flowing temperature history at Patua indicates that distinct fault zones have differing thermal properties. A dual-porosity formulation was tested and implemented in the numerical model resulting in a highly accurate calibration to the flowing temperature history.

1. **Introduction**

The Patua Geothermal Field is a moderate temperature geothermal resource operated by CYRQ Energy in the Basin and Range Province of the western United States. A numerical simulation of the field was undertaken by a multidisciplinary team to forecast field performance and improve the understanding of the geothermal reservoir. The numerical simulation was successfully calibrated to significant data gathered at Patua including initial state temperatures, flowing production temperatures, downhole pressure monitoring, and reservoir tracer testing. Further, the numerical simulation reflects a comprehensive geologic conceptual model which identified distinct fault zones which host compartmentalized production. The production history at Patua provides evidence that these faults have differing thermal properties. The calibrated numerical simulation utilizes a dual-porosity formulation to account for these differing properties.

2. Implementation of the Conceptual Model

The Patua numerical model was developed using the reservoir simulation software TETRAD. TETRAD is a three-dimensional, single or dual-porosity, multi-phase, mutli-component, thermal, finite-difference simulator (Vinsome and Shook, 1993).

The numerical model of the Patua is based on an updated geologic conceptual model (Cladouhos, 2017). That conceptual model was developed after significant drilling and several years of production and injection at the Patua field. The conceptual model identifies at least three distinct fault zones which are characterized by elevated permeability, high productivity wells, and convective thermal gradients.

The numerical model is centered on these fault zones within a significant volume of background rock which represents the surrounding area outside the geothermal system. The dimensions of the numerical model are 16 km in the X-direction by 18 km in the Y-direction. The model extends from +1500 to -3000 mRSL. The numerical model is rotated 20 degrees east of north, oriented with the strike of the fault zones, allowing for a smaller number of gridblocks in the fine mesh around these zones of high importance. The surface of the model is contoured to the local topography (National Map, 2017). Blocks above the ground surface are inactive in the simulation.

The numerical mesh for the finite-difference simulation consists of 35360 dual porosity gridblocks (70720 gridblocks total). The mesh is refined near the fault zones and the Patua wellfield, where more calibration data is available. X and Y gridblock dimensions range from 125 meters to 2000 meters. The model consists of 17 vertical layers ranging from 200 meters to 900 meters thick.

Figure 1 shows a horizontal slice of the numerical model permeability structure. Hot colors represent high permeability and cool colors represent lower permeability. Figure 2 shows a vertical slice of the numerical model permeability. Zone of high permeability are associated with fault zones and fracturing identified from well data and the geologic conceptual model. Based on calibration to reservoir engineering data, each fault zone has distinct characteristics such as permeability, porosity, and matrix-fracture connection described later in this paper.

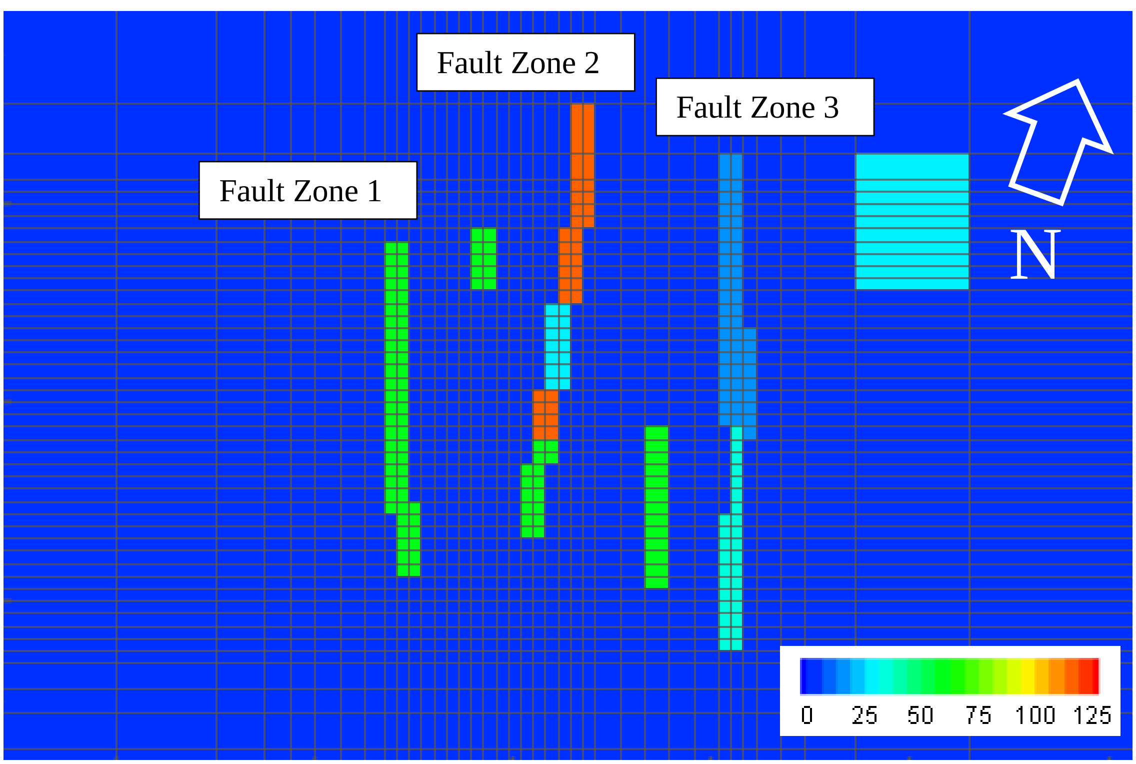

Figure 1: Horizontal Slice of Numerical Model Total Permeability in millidarcies at -1200 mRSL

Top Down View

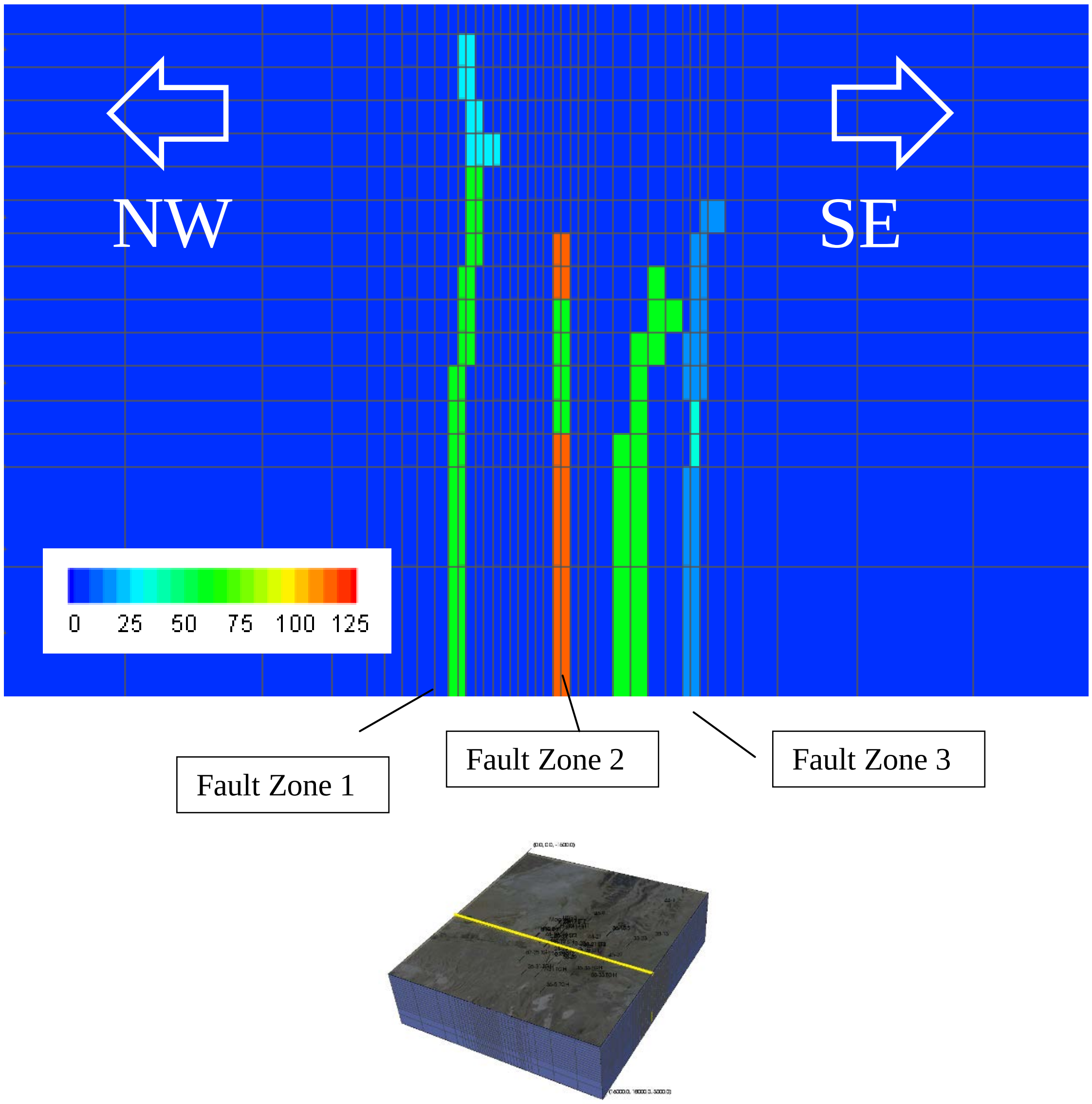

Figure 2: Vertical Slice of Numerical Model Total Permeability. View from Southwest (Slice Location Shown)

3. Calibration of the Natural State Model

The Patua geothermal field exists in a compressed liquid state with an elevated background temperature gradient. Zones of high permeability from faults and fracturing permit high temperature fluid to circulate to shallower depths resulting in convective temperature profiles and convective cells. Outflows from the geothermal system are limited to surface expressions in the west of the field, geologically associated with the headwall extension of Fault Zone 1, as identified in the conceptual model (Cladouhos, 2017).

The natural state simulation of the Patua geothermal field was accomplished using elevated, constant temperature boundary conditions on the bottom of the model, discrete upflows of high temperature fluid in the convective fault zones, and a constant pressure boundary on the top of the model allowing for inflow and outflow of fluid across that surface. The surface is maintained at pressures above atmospheric conditions to ensure that the simulation grid stays in the liquid phase. Simulating the vadose zone was outside the scope of this simulation.

Figure 3 shows a summary of the boundary conditions used in the Patua numerical model. Figure 4 shows the varying constant temperature boundary conditions on the bottom of the numerical model, at an elevation of –3000 mRSL (approximately 4500 meters below the ground surface). The higher temperature boundary reflects the extension of the high conductive gradient observed in well 16-29 to the model bottom. The lower temperature boundary reflects lower conductive gradients observed in wells further from the production zone.

The permeability structure and boundary conditions were calibrated to the initial state temperature measurements gathered from the wells drilled at Patua. Individual well temperature profiles were used for further calibration. Fault Zone 2, which hosts wells separated by 2 km of horizontal distance, was identified in the conceptual model as a convective cell with isothermal zones of high temperature in the south (upflowing) and isothermal zones of lower temperature in the north (downflowing). Figure 5 shows a vertical slice through that fault zone comparing the measured and simulated natural state contours. The natural state simulation successfully re-creates that convective cell as well as the elevated conductive temperatures observed in deep drilling.

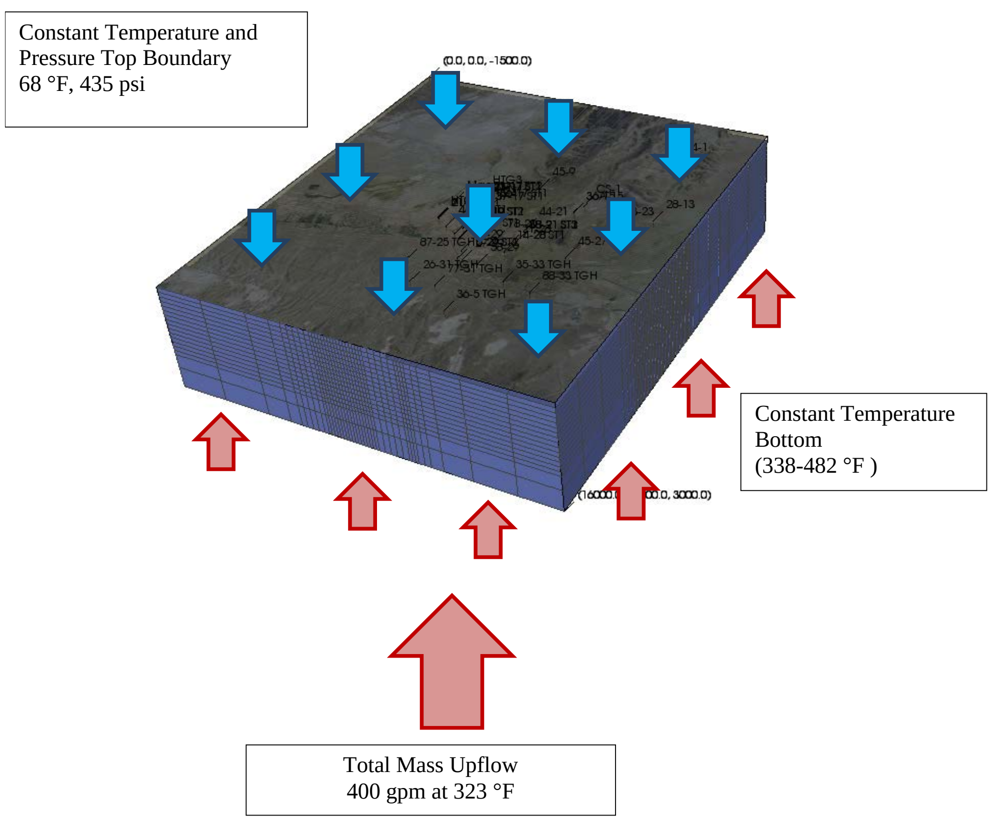

Figure 3: Boundary Condition Summary

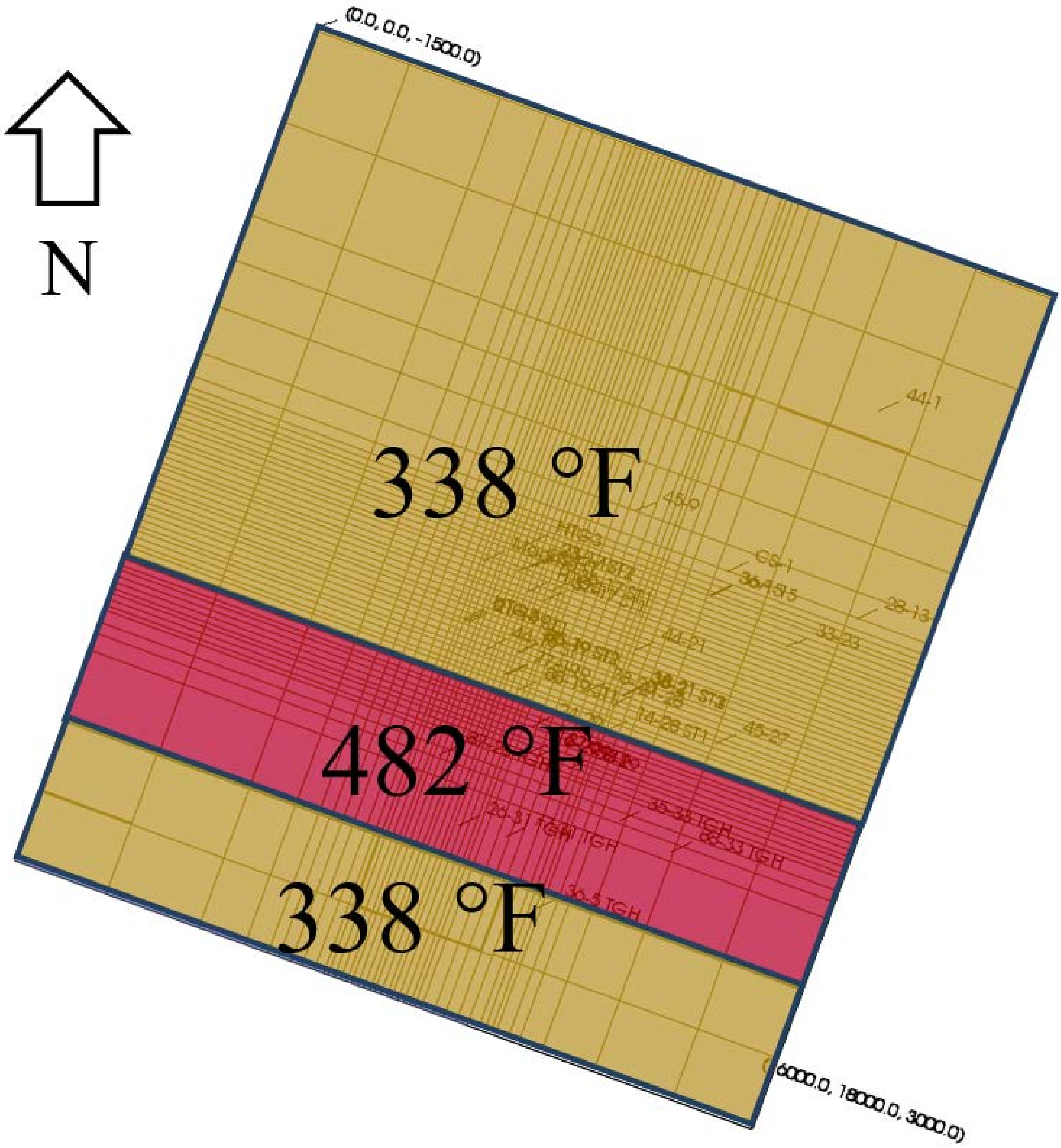

Figure 4: Constant Temperature Boundary Conditions on Model Bottom

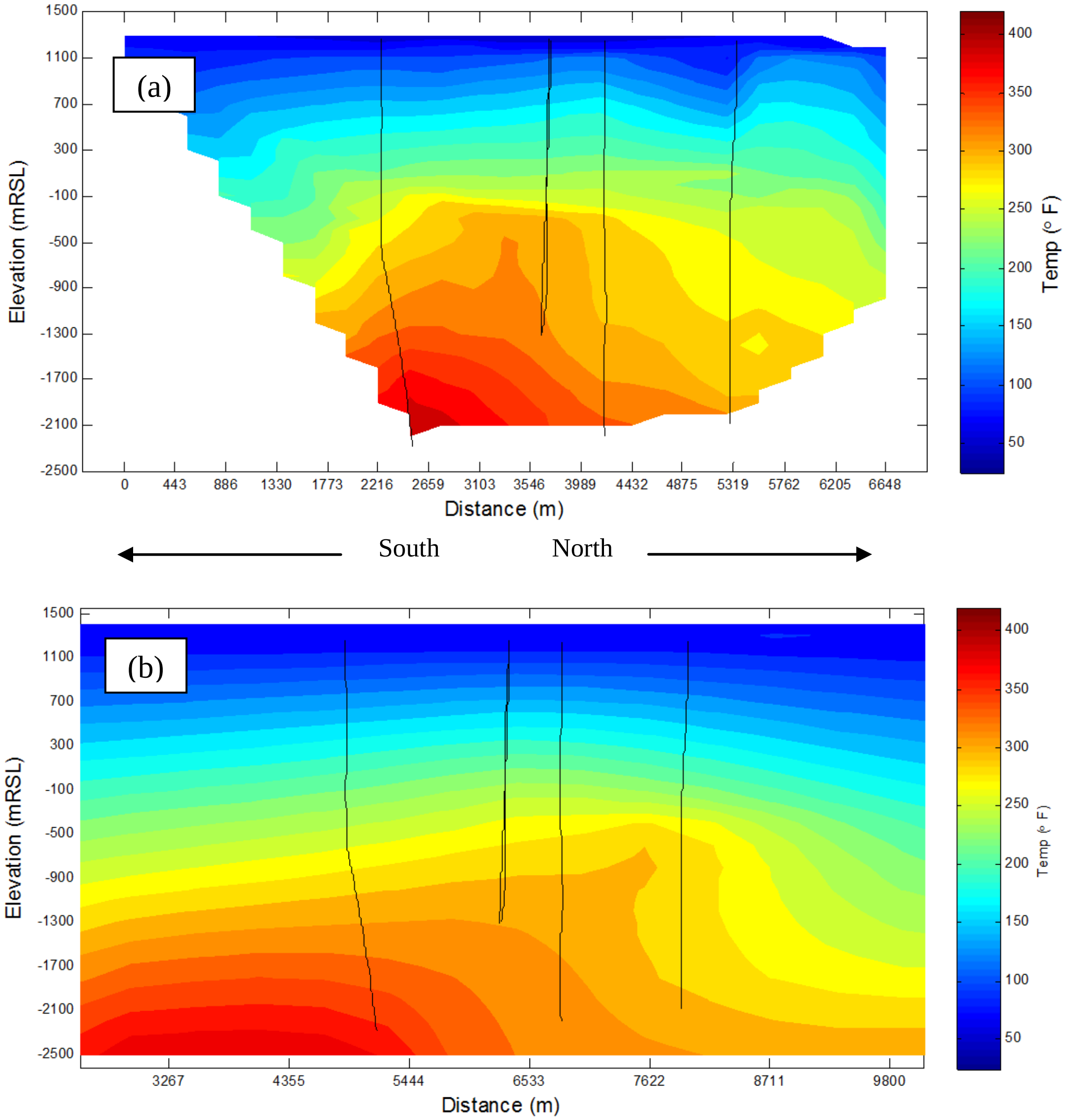

Figure 5: Measured (a) and Simulated (b) Natural State Temperature Contours on Faults Zone 2

4. Simulation of the Production History

Production at the Patua Geothermal Field started in 2013. Throughout the field history, flow rates for production and injection wells were recorded which were input into the numerical model. Each well is represented by discrete feedzones in the numerical model. These feedzones were identified using on drilling data, flowing downhole surveys, and well intersections with the conceptual model fault zones. The numerical model simulates the measured flow history from these wells explicitly. The outputs from the numerical model are flowing enthalpy and reservoir pressure, which allows the model to be calibrated to measurements of these same parameters in the form of measured flowing production temperatures and bubble tube pressure monitoring.

Production wells at Patua have exhibited a variety of temperature behaviors in response to production and injection. Some wells have remained at constant temperature since startup while others underwent initial temperature declines followed by partial temperature stabilization or lower temperature decline rates. Several reservoir tracer tests were conducted at Patua which were also simulated in the numerical model and provide an opportunity to further calibrate the model to reflect the relationship between injectors and producers.

Figure 6 shows the measured and simulated total field production temperature, which illustrates the high degree of matching between the simulation and measurements. Pressure monitoring wells were utilized to calibrate the model permeabilities. Figure 7 shows the calibration to monitoring pressure in Fault Zone 2.

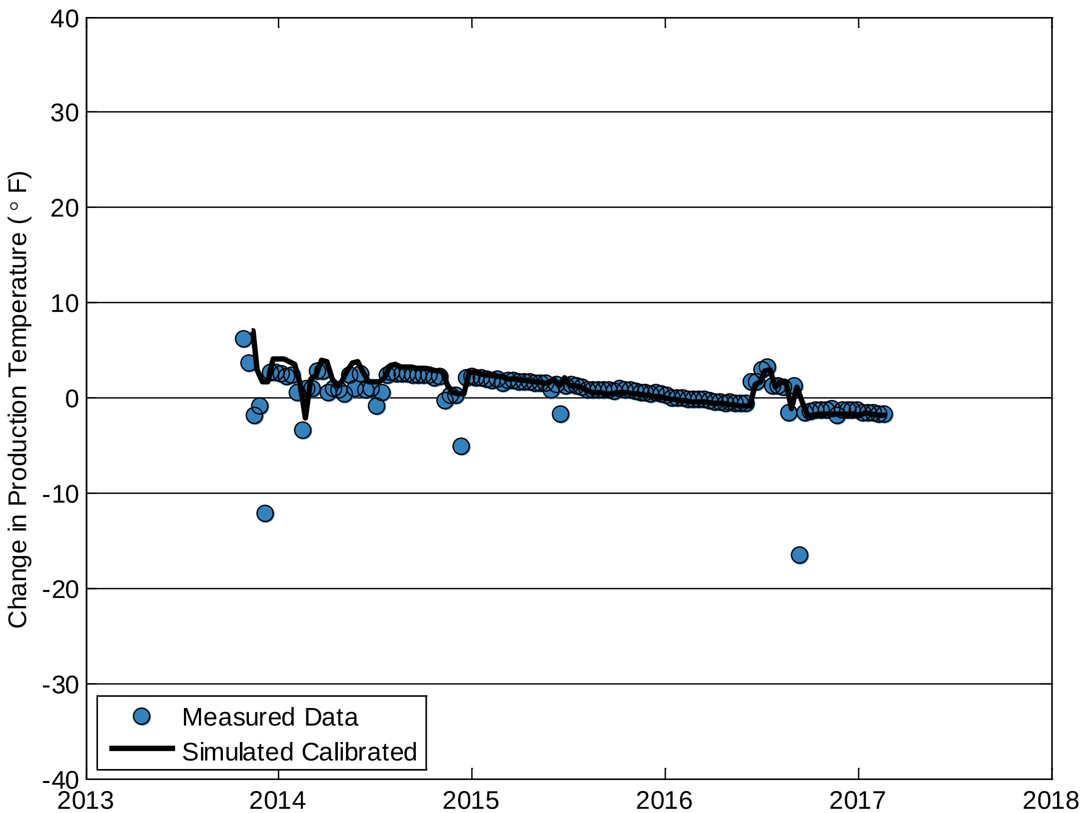

Figure 6: Total Field Measured and Simulated Change in Production Temperature

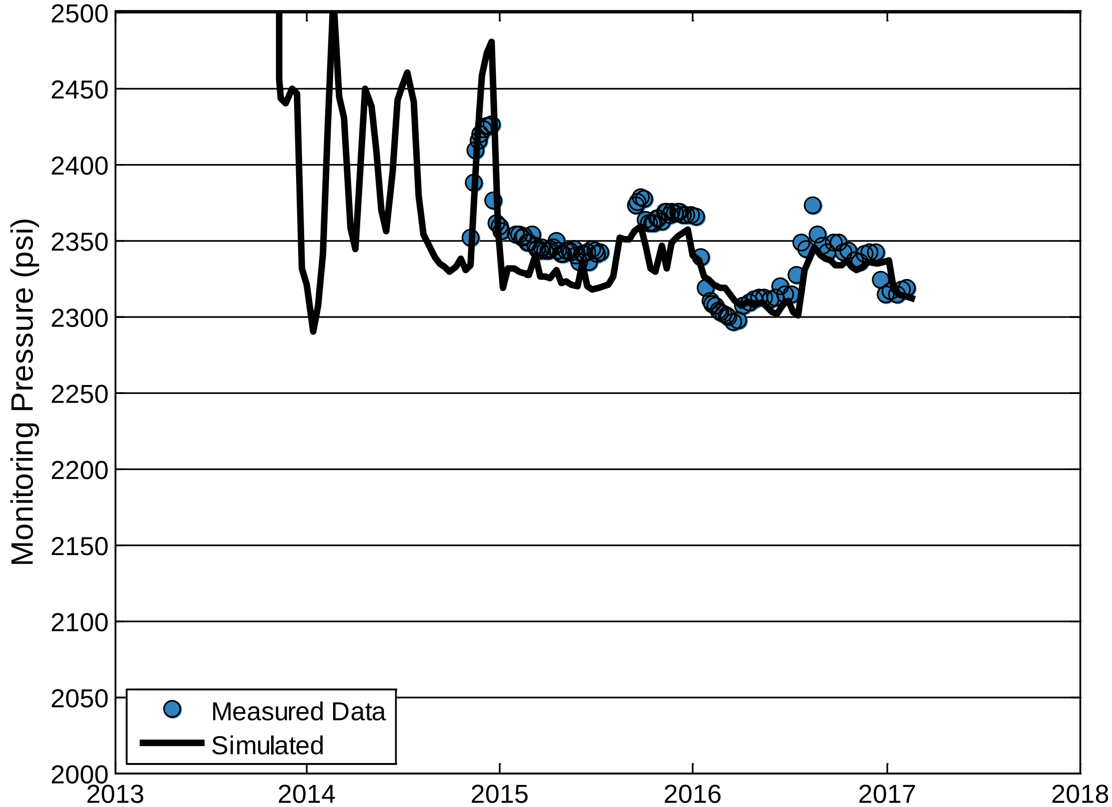

Figure 7: Fault Zone 2 Measured and Simulated Monitoring Pressure

In wells that have exhibited temperature decline at Patua, reductions in flow rates have resulted in temperature stabilization and recovery. This reflects a property of the reservoir in which the flow paths which are swept by injection fluid are hydraulically and thermally connected to a matrix which stores further energy and is not fully depleted by sweeping injection fluid.

The temperature history of well 88-19 is a strong example of this behavior. Starting in January 2016, injection into 85-19 was reduced. 85-19 has shown a strong connection to 88-19 based on tracers and temperatures. In July 2016, nearby production well 77-19 was shut-in. Prior to these changes, temperatures in 88-19 were declining at around 11 °F/year. During the period of reduced flow rates, the temperature of 88-19 stabilized and increased slightly. Figure 8 shows the measured change in temperatures of 88-19 and the operational changes during this period.

Figure 8 also shows the simulated change in temperature of 88-19, which is closely matched to the measurements. This period of reduced flow rate was an important calibration point for the numerical model. By utilizing a dual-porosity simulation grid (Warren and Root, 1963), the matrix domain of each gridblock stores some thermal energy which is accessed when rates are reduced due to pressure and temperature gradients between the two domains. The matrix-fracture connectivity is calibrated using fracture spacing, the thermal capacity of the fracture domain, and the volume and permeability ratios between the matrix and the fracture domains.

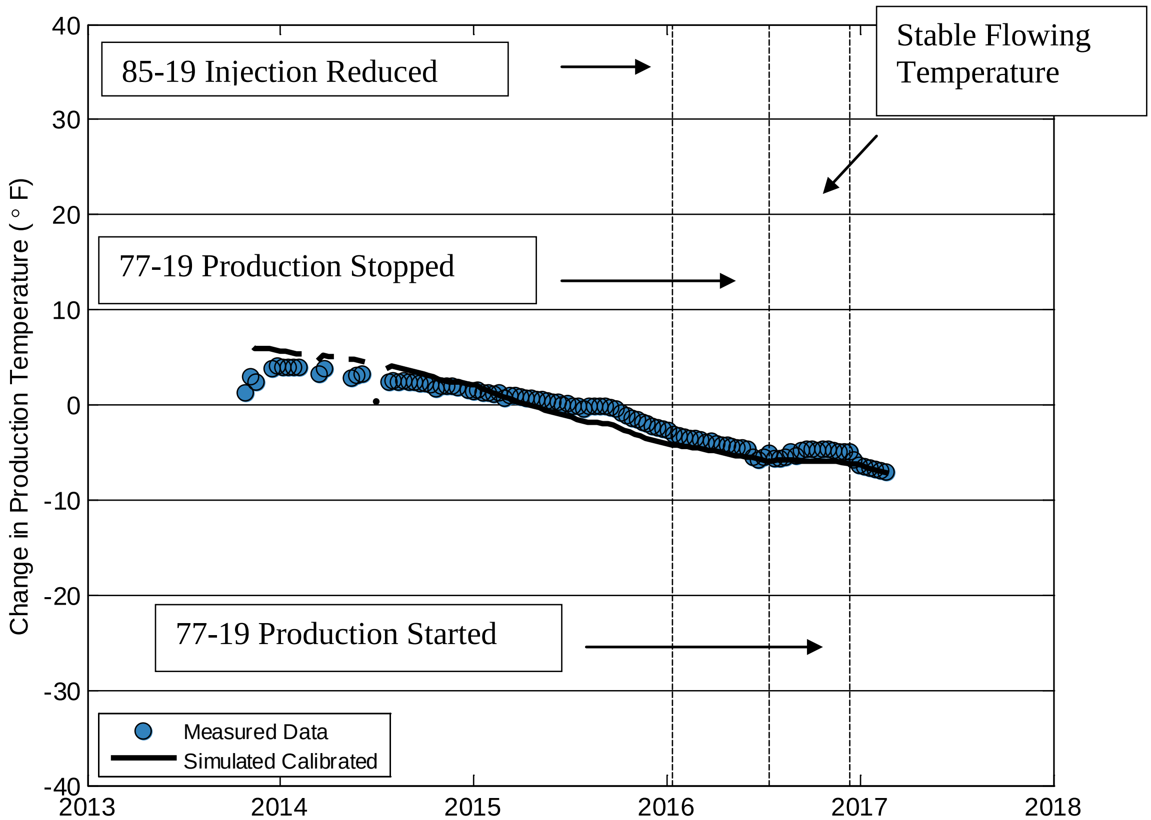

Figure 8: 88-19 Measured and Simulated Change in Production Temperature

Figure 9 illustrates the simulated temperature behavior for 88-19 as these dual-porosity parameters are varied. When the matrix and fracture are well connected, the reservoir behaves like a single-porosity reservoir. Thermal breakthrough is delayed as the whole volume and energy of each gridblock is swept. When rates are reduced, there is little remaining energy stored in the matrix and the temperature decline continues with no stabilization.

If the fracture and matrix are poorly connected, thermal breakthrough occurs quickly through the fracture domain, which has high permeability but low thermal storage. In this case, initial temperature declines greatly exceed the measurements. However, the flowing temperature significantly recovers in response to lower flow rates as the matrix energy is relatively untouched during the higher injection periods. This stored energy enters the fracture domain when flows are reduced.

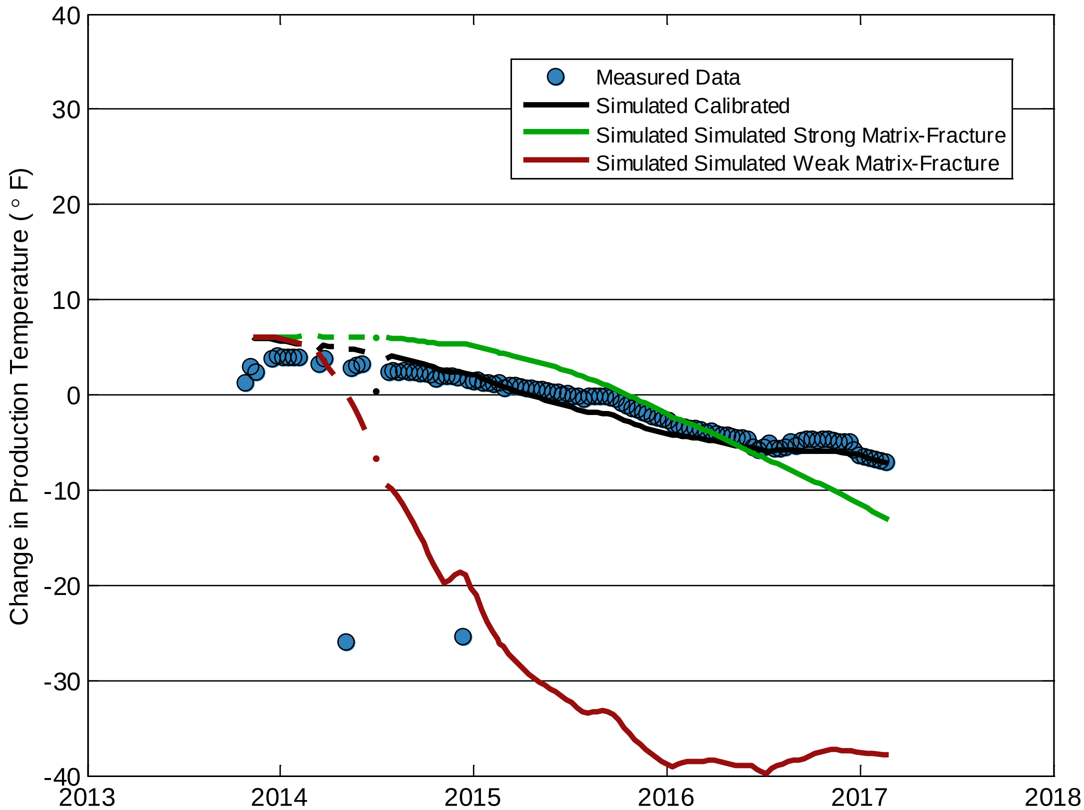

Figure 9: 88-19 Measured and Simulated Change in Production Temperature

The thermal storage properties of faults varies across the Basin and Range. The variety of temperature behaviors observed in the Basin and Range were described by Hanson et al in 2014. Some fields underwent fast initial declines followed by stabilization (Empire), while others were initially stable before temperatures began to decline (Steamboat). Brady Hot Springs (Holt et al 2004) undergoes large temperature fluctuations in response to changes in production and injection, indicative of a weak matrix-fracture connection. McGinness Hills (Lovekin et al 2016), has shown stable temperatures even at high flow rates, indicative of high thermal storage and a strong matrix-fracture connection.

Due to the existence of several compartmentalized fault zones in a single field, Patua provides a particularly useful example of this thermal storage behavior. Fault Zone 2 is characterized by temperature declines and temperature recovery under reduced rates. Fault Zone 3, however, has seen stable temperatures throughout the production history. Crucially, both Fault Zone 2 and Fault Zone 3 are utilizing producer-injector pairs which have proven to be strongly connected based on tracer testing and pressure monitoring.

Figure 10 shows the tracer test results for the 88-19/85-19 producer/injector pair in Fault Zone 2, and the results for the 21-28/38-21 producer/injector pair in Fault Zone 3. Production from the 88-19 pad is higher than 21-28, and injection into 85-19 is higher than 38-21. However, a simulation that matches tracer behavior and using the same dual porosity parameters in each fault zone results in early cooling arrival in 21-28. In reality, 21-28 temperatures have risen slightly throughout the field history with no indication of cooling. A stronger matrix-fracture connection is needed in Fault Zone 3 to match to the stable flowing temperatures in 21-28, shown in Figure 11.

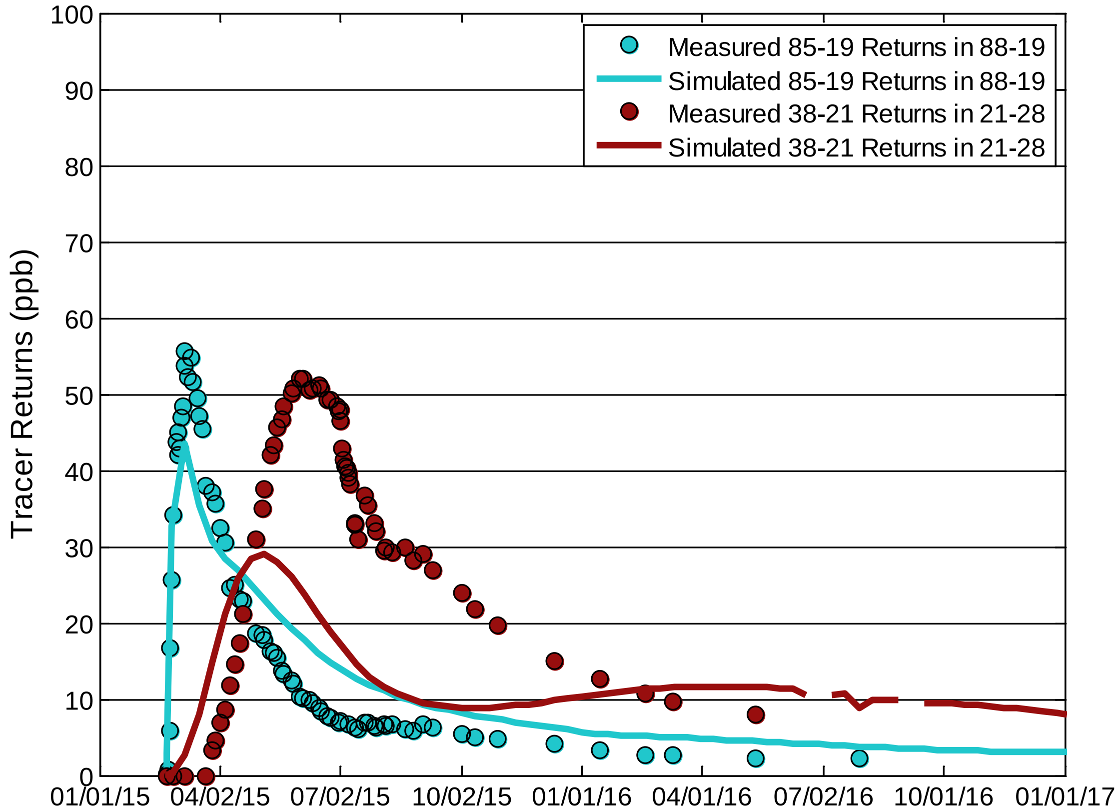

Figure 10: Tracer Return Comparison, Fault Zone 2 and Fault Zone 3

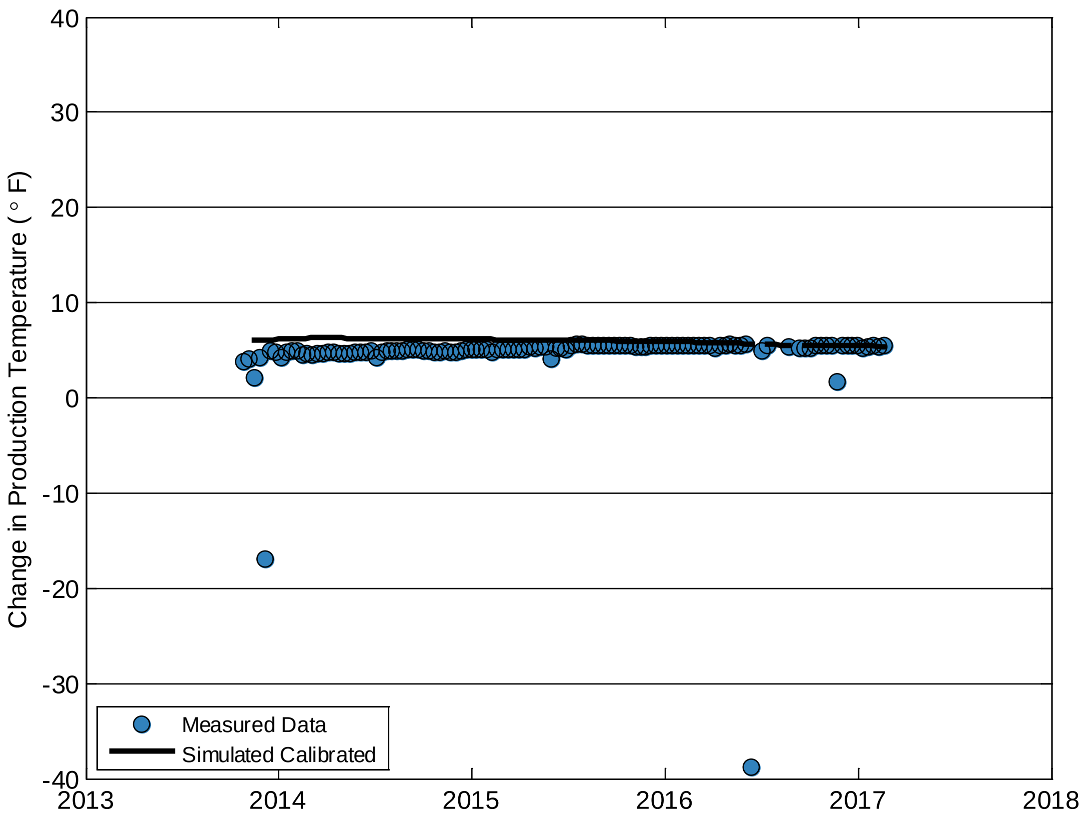

Figure 11: 21-28 Measured and Simulated Change in Production Temperature

5. Conclusion

The development of the Patua numerical model reflects an updated conceptual model and calibration to significant field data. The successful calibration increases confidence in the validity of the conceptual model, which was the basis for the accurate matches to measured data. The numerical simulation tested and implemented a dual-porosity formulation designed to match the observed temperature history at Patua. Temperature declines which stabilize or recover in response to reduced flow rates reflect a weak matrix-fracture connection allowing for thermal storage in the matrix domain. Zones which have not seen temperature declines despite evidence of strong producer-injector connections are evidence of a stronger matrix-fracture connection. Unique dual-porosity parameters were necessary in each fault zone at Patua to accurately simulate temperature history, reflective of the varying temperature performance and underlying thermal storage behavior which can be observed in fields throughout the Basin and Range geothermal area.

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