COMPARISONS OF AUTOUGH2 AND WAIWERA ON GEOTHERMAL FIELDS

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ABSTRACT

One of the main constraints of geothermal reservoir model development is the time it takes to calibrate geothermal models. Model calibration requires running the model for each change in parameters made to improve the match to available data. In recent years, Waiwera, a parallelised geothermal simulator, has been under development with the aim of speeding up geothermal model runs. While drawing on our experience with AUTOUGH2 (a serial geothermal simulator), Waiwera exploits parallelisation and has been coded with better underlying numerics, which means the speed-up achieved is very significant.

Previously, we presented benchmark comparisons between AUTOUGH2 and Waiwera. Here we offer comparisons on models of real geothermal fields, both in terms of results and run-time. We now use Waiwera in most commercial and research projects, including Lihir, San Jacinto, Ohaaki, Wairakei, Monserrat and Rotorua. With certain settings, when run on 40 cores, we see a speed-up of up to sixty times, meaning a model that took seven hours to run on AUTOUGH2 now takes seven minutes to run on Waiwera. This speed-up has four main advantages: model calibration is faster, more refined grids can be used, larger systems can be modelled such as the whole of the Taupo Volcanic Zone and uncertainty quantification of model forecasts is more efficient. AUTOUGH2 and Waiwera results for the simulation of a synthetic high enthalpy geothermal system are presented alongside those for a model of the San Jacinto geothermal field in Nicaragua developed by Polaris Energy Nicaragua S.A..

1. INTRODUCTION

Recently, the modelling of geothermal fields has rapidly evolved as a result of several decades of numerical improvements. It is now possible to tackle modelling of more complex systems and to achieve more robustness with the simulations. Since MULKOM, a multiphase fluid and heat flow simulator released in the late 1980s (Pruess 1988), a large number of simulators have emerged (O'Sullivan et al, 2001). Originally derived from MULKOM, TOUGH2 is now one of the standard research and industry geothermal simulators (Pruess 1991, Finsterle et al. 2014). STAR (Pritchett, 1995), HYDROTHERM (Hyaba et Ingebritsen 1994), FEHM (Zyvoloski, 2007) have provided alternative platforms for modelling heat transfer and fluid flow in porous or fractured media. TETRAD (Vinsome et Shook 1993) and ECLIPSE (Stacey et Williams 2017) were initially set up for oil and gas application, but report good capabilities for geothermal modelling.

For investigating the natural state of large magmatic-hydrothermal models, including multi-component fluids, the Complex Systems Modelling Platform (CSMP ++) has been recently developed to help understand deep processes in the roots of geothermal systems (Weis et al. 2014). However, code parallelisation has opened new opportunities for simulating computationally demanding numerical models of large geothermal fields. These models can have hundreds of wells and complex production histories. The TOUGH-suite has evolved to TOUGH3 (Jung et al. 2017), incorporating the PETSc solvers, which improves the serial and parallel performances of the simulations. The underlying design of the TOUGH-suite of codes has not evolved much over time, using strict format for input files. Waiwera, an open-source parallel geothermal flow simulator, has been developed at the University of Auckland in collaboration with GNS Science (Croucher et al. 2020). The code is parallelised using the PETSc scientific computation library, and uses simple and flexible input JSON files.

AUTOUGH2 (Yeh et al. 2012) is a variant of TOUGH2 developed at the University of Auckland. Previous benchmark tests with Waiwera have shown a high consistency with AUTOUGH2 results, but with much better steady-state convergence behaviour (Croucher et al. 2020). To date, the Waiwera simulator has not been formally compared against AUTOUGH2 for large scale geothermal models for both natural state and production history simulations. This paper presents a comparative study of simulations of geothermal fields with AUTOUGH2 and Waiwera, highlighting the benefits and limitations. The two geothermal models we present here are a synthetic model and a model of the San Jacinto geothermal field in Nicaragua developed by Polaris Energy Nicaragua S.A.

2. MODEL SETUPS

In this section, we describe the two models used for comparison in this paper. The first is a synthetic large scale geothermal model developed to show geothermal processes and the second is a model of the San Jacinto Geothermal field in Nicaragua. Both models use an air-water Equation of State (EoS) and hence the comparisons presented in this paper are between AUTOUGH2's 'EWA' EoS and Waiwera's 'wae' EoS. For comparison, we use the root-means squared error defined by,

$$\boldsymbol{RMSD} = \sqrt{\frac{\sum_{i=1}^{N}(x_i - y_i)^2}{N}}, \tag{1}$$

to quantify the difference between the results from AUTOUGH2 and Waiwera.

2.2 Synthetic high enthalpy geothermal model

2.2.1 Geological settings

The synthetic model represents a typical geothermal reservoir. It enables us to run tests, implement new features in our modelling workflow and provide training on geothermal modelling. GNS Science set up the underlying geological model, based on a mix of geothermal formations from existing New Zealand geothermal fields.

Figure 1 describes the conceptual model of the synthetic volcanic geothermal system and shows the geological units, including a fault network. The system covers a total area of 13 km by 15 km, the top elevation of the system is 1000 masl, and the deepest formation lies at -3500 masl.

The topography includes hills, rivers and lakes, all of which are represented, and there are alluvium and sedimentary surface deposits. Typical volcanic formations such as rhyolite, ignimbrite, andesite and dacite are included above a basement. Three dipping faults intersect the area. The volcanic formations included can be seen as a simplified representation of a high enthalpy geothermal system, where there have been various eruptive episodes and altered formations. A high conductivity zone defined by synthetic magnetotelluric data (MT) is implemented, representing a clay cap alteration overlying the geothermal system. Nine wells with vertical or deviated profiles with various feedzone intersections are modelled in the central and peripheral zones.

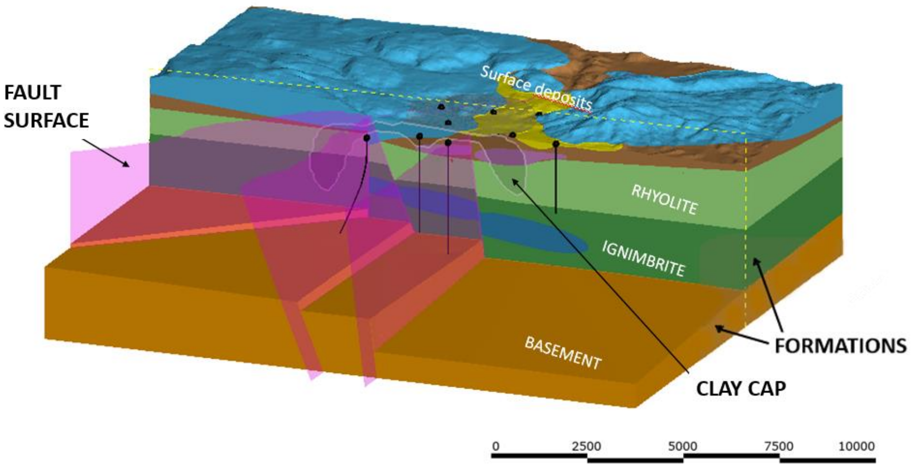

Figure 1: 3D representation of the conceptual synthetic model of the synthetic system, showing a faulted high temperature volcanic geothermal reservoir.

2.2.2 Reservoir model settings

The reservoir model is composed of 11764 blocks, with local refinements in the central area. The layer thickness ranges from 20 m in the surface formations to 500 m in the basement, as shown in Figure 2.

The rock types in the model are defined by the geological model, the alteration model and the faults shown in Figure 1. The permeabilities of these rock types range from 5e-13 m^2 (0.5 D) (usually in the surface to represent soils that allow the water table to settle) to 1e-16 m^2 (0.1mD)(usually located in the relatively impermeable alteration model). All rock types have a density of 2500 kg/m^3 with a constant specific heat of 1000 J/kg/K and a uniform thermal conductivity of 2.5 W/m/K. Rock type porosities vary between 1 % and 30 %, determined as a result of production history calibration. Deep upflows at temperatures of up to 270°C are implemented in the bottom layer to allow hot fluids to rise along the faults, thus developing the geothermal system.

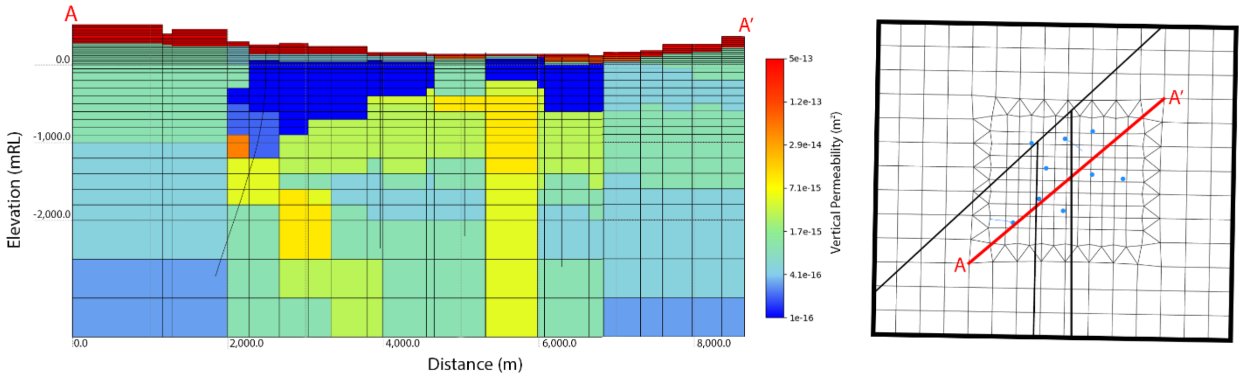

Figure 2: NW-SE cross section of the synthetic model, showing the vertical permeability.

2.3 San Jacinto geothermal field

2.3.1 Geological settings

The San Jacinto geothermal area is located in the northwest part of Nicaragua, Central America, at an elevation of 200 m (Figure 3). This region belongs to the "Los Marrabios" chain, elevated during quaternary volcanic episodes. The area is affected by regional northwest-trending right-lateral tectonic movements intersected by NNE-striking transversal faults (Ostapenko et al. 1998). With the area hosting significant hydrothermal activities, the local geothermal potential has been studied since the early 1950s (Ostapenko et al. 1998).

The geology of San Jacinto is mainly composed of igneous, intrusive and pyroclastics with sedimentary formations from previous volcanic episodes. Deep wells have between drilled in the 1990s, from a minimum depth of 728 m to a maximum depth of 2339 m, giving information for the design of a preliminary conceptual model with two reservoirs around the depth of 350 m and 850 m with potential connections with a regional aquifer (Ostapenko et al. 1998). The thickness of the low resistivity-hydrothermally altered caprock boundary is expected to be 200-300 m with upflows following the NNE tectonic trend, probably connected to the NNE faults. Recent developments by Polaris Energy Nicaragua S.A. includes drilling new wells and monitoring to help in refining the conceptual model. The reservoir temperature is around 250-300°C, with shallow steam zones in the central production area arising as a result of boiling brought on by production. Several steam zones have appeared, notably one at 180°C at a depth of -50 m and another at 230 °C at -500 m.

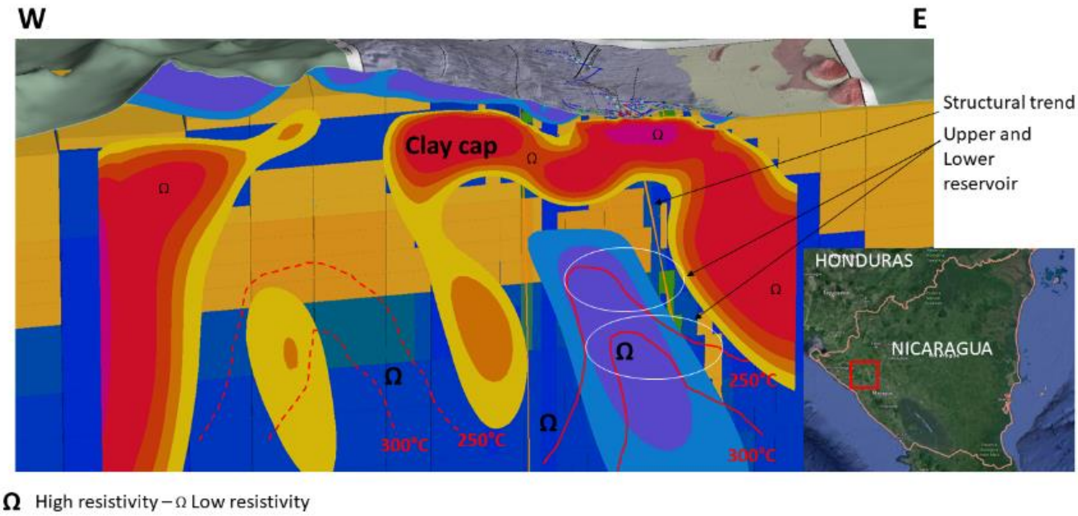

Figure 3: Slice of the San Jacinto conceptual model with isotherms and resistivity boundary zones. Blue, green and orange represent respectively low, medium and high horizontal permeability blocks. San Jacinto is located in the North West of Nicaragua.

2.3.2 Reservoir model settings

The reservoir model contains 39651 blocks and extends to the depth of -3200m. The dual porosity model used for production simulations has 88743 blocks. Figure 4 shows the grid refinement in the plan view and the topography in the central part of the reservoir with a cross-section of the natural state temperature. Thirty-five wells currently have been drilled in the area which provide a good understanding of the geology. The permeability distribution is guided using the latest MT data, respecting the structural trends. Deep upflows, indicated by the high resistivity plume towards the East, are responsible for producing the local high-temperature distribution. Throughout the system fairly low vertical permeabilities have been identified, with local higher values in the reservoirs and along the N-S structure. A low variation in lithology elevations between wells has been observed. Hence, a layered stratification is used, but with decreasing permeability with depth as shown in Figure 3. The water levels near the surface play an essential role during the production history, and so the vadose zone near the model surface is included to allow groundwater levels to change in response to deeper pressure changes. Because of the intensive reinjection and complex pressure response in the field, a dual-porosity model is implemented to allow separate matrix and fracture flow enabling a more detailed representation of the rapid thermodynamic changes that have been observed.

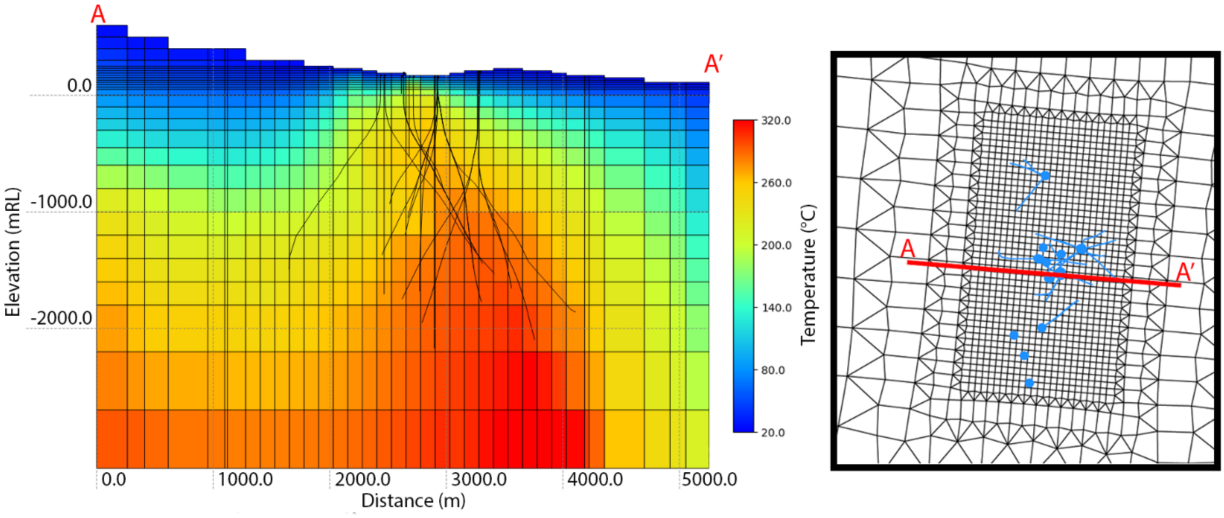

Figure 4: Left. W-E Slice of the grid with the well profiles and natural state temperature. Right. Plan view of the grid, including well tracks and slice location.

3. RESULTS

The same type of initial conditions were set up for both models, i.e. a warm geothermal gradient of 30°C/km and a hydrostatic pressure gradient. The surface temperature is 27°C for the Synthetic model and 22°C for the San Jacinto model with an atmospheric pressure condition of 101325.0 Pa.

3.2 Simulation outputs

In this section, we show results for the comparison of output from natural state and production simulations. We demonstrate this on the synthetic model but note that both Waiwera and AUTOUGH2 also produce matching results for San Jacinto.

displays the natural state results of the synthetic model, in five wells using Waiwera and AUTOUGH2. Both simulators show consistent results in the calculation of temperature profiles, with RMSD values below 0.02 as described in Table 1.

Table 1: RMSD error values between the AUTOUGH2 and Waiwera results for the wells shown in Figure 5.

Wells	WELL 1	WELL 2	WELL 3	WELL 4	WELL 5
RMSD	1.5e-02	2.3e-02	2.8e-02	5.0e-03	2.0e-02

Comparable results are obtained for the production history in the synthetic model, with a good correspondence between Waiwera and AUTOUGH2 results for the pressure, temperature, mass flow rate and enthalpy, as shown for Well 3 in

Figure 6.

3.3 Computational comparison efficiency

The use of Waiwera for parallel calculation has been demonstrated to speed up the simulation time with an increased number of processes in strong scaling test (Croucher et al. 2020). AUTOUGH2 models for this comparison were run on a Debian Linux desktop machine with a 12-core Intel Xeon E5-2670 CPU (2.60GHz). Waiwera models were run on either the same desktop as AUTOUGH2 or on the New Zealand eScience Infrastructure (NeSI) "Maui" supercomputer using up to 40 cores.

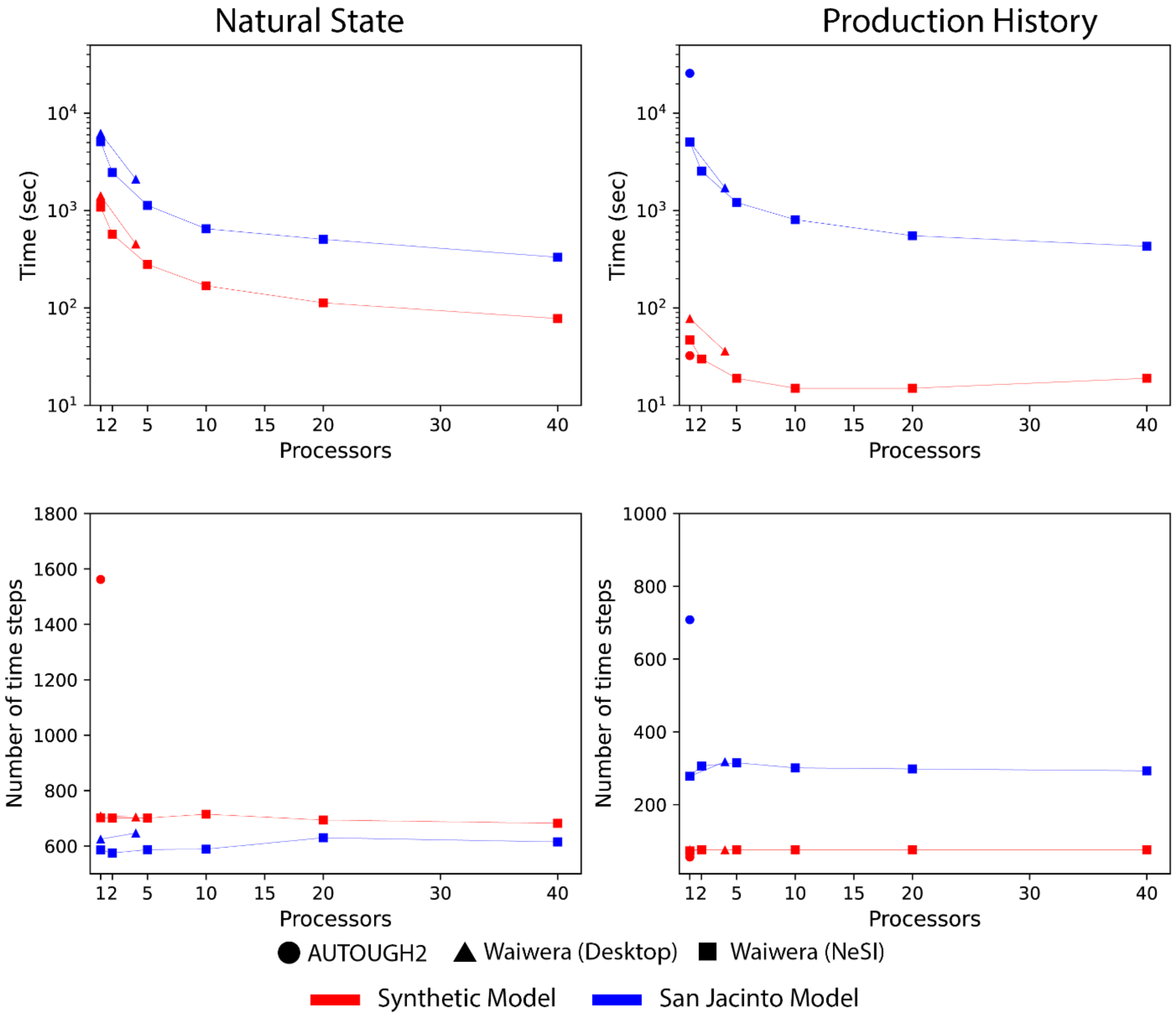

Figure 7 and Table 2 shows the simulation time and the number of iterations for running the Synthetic and the San Jacinto model using AUTOUGH2 or Waiwera in serial or parallel configuration.

A significant speed-up of the simulations is observed between AUTOUGH2 and Waiwera using 40 CPUs on NeSI. For the synthetic model, the simulation run eight times faster for the natural state. For larger models, such as San Jacinto, Waiwera runs approximately 60 times faster (as seen for the production history model). Even using five or ten cores decreases the computational time significantly. For a single core natural state simulation Waiwera is slower for the synthetic model than AUTOUGH2 but is significantly faster for San Jacinto (with the AUTOUGH2 simulation not converging in reasonable time). However, a four-core natural state desktop simulation on Waiwera is significantly faster for both the synthetic model and San Jacinto. We note that the speed up experienced by adding more cores on the desktop machine is not as great as the speed up observed from running on a high-performance cluster such as NeSI. One explanation is the speed up depends on how well connected the cores are. On NeSI the connection between cores is designed specifically for parallel computing whereas a desktop is more designed to allow multiple independent processes at once and hence the connection between cores is worse. The number of time steps needed to reach the end of the simulation remains approximately constant while using Waiwera in parallel and is less than when using AUTOUGH2. For optimal simulation performance we recommend using a high-performance computer or a dedicated Linux box with well-connected cores. However, significant speed up can be achieved with Waiwera by using more cores on a regular desktop PC.

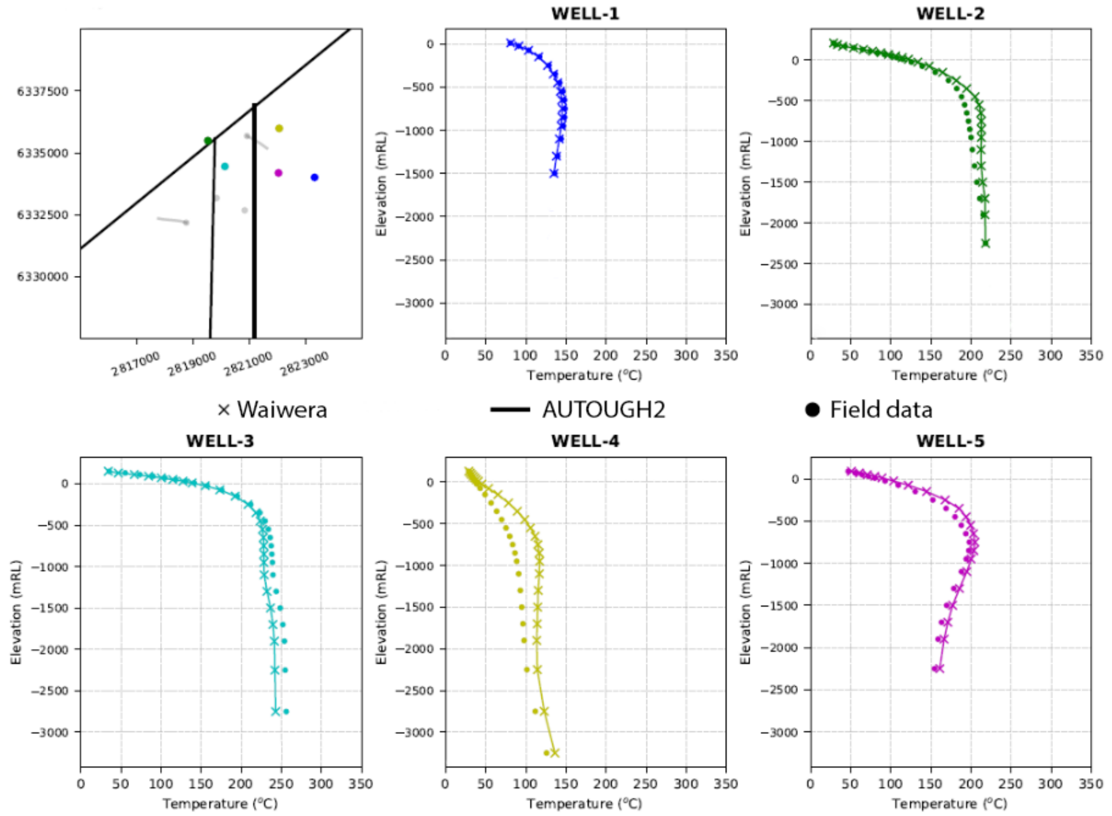

Figure 5: Natural state results comparison of the synthetic model between AUTOUGH2 and Waiwera.

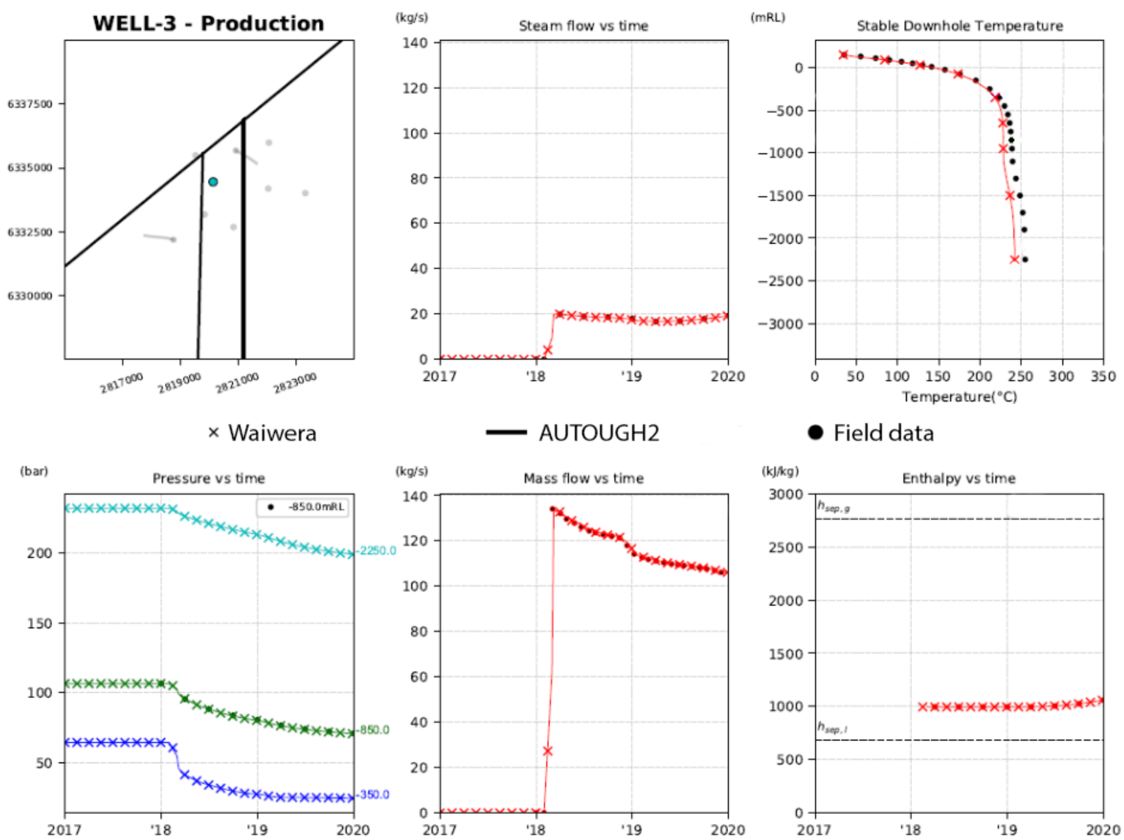

Figure 6: Production History between a Waiwera and AUTOUGH2 simulation for Well 3 in the Synthetic model.

Table 2: Computational time comparison between AUTOUGH2 and Waiwera with various processors (CPU) used. Number of time steps shown in brackets.

		Desktop (Linux)			High Performance Cluster (NeSI - Linux)		
	Simulator	**AUTOUGH2**	**Waiwera**	**Waiwera**	**Waiwera**	**Waiwera**	**Waiwera**
	Number of Cores	1	1	4	2	5	40
Synthetic	Natural State	1257 s (1562)	1420 s (709)	454 s (705)	572 s (701)	280 s (701)	78 s (682)
	Production History	32.4 s (56)	78 s (76)	36 s (76)	30 s (76)	19 s (76)	15 s (76)
San Jacinto	Natural State	>10000 (>10000)	6216 s (625)	2101 s (647)	2461 s (575)	1131 s (587)	332 s (615)
	Production History	25668 s (708)	5066 s (278)	1713 s (318)	2545 s (306)	1211 s (315)	430 s (293)

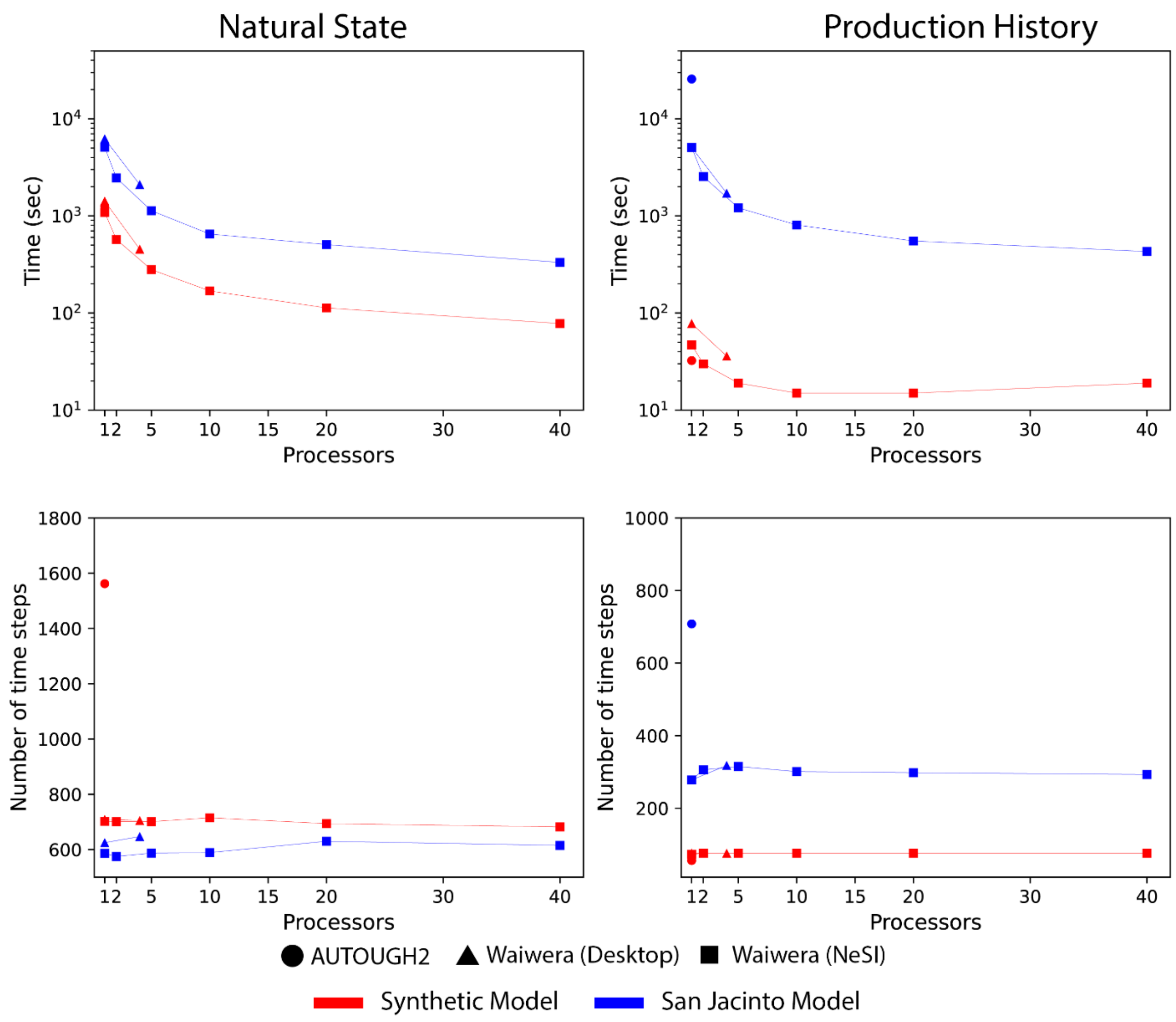

Figure 7: Simulation time and timestep versus processors used with AUTOUGH2 or Waiwera for the Synthetic and San Jacinto reservoir models.

4. CONCLUSIONS

The paper demonstrates that the Waiwera geothermal simulator is a very useful tool for modelling research and commercial geothermal fields. The results obtained with AUTOUGH2 and Waiwera are very consistent for simulations of natural state and production history models. The examples presented show simulation results can be obtained up to 60 times faster with 40 cores, with a similar number of time steps using the supercomputer NeSI. Using Waiwera with 2 to 10 cores on a good computational infrastructure such as NeSI still results in good simulation speed up. The simulation speed ups observed using Waiwera on desktop were not as large as on NeSI but still achieved significantly faster run times than AUTOUGH2 when using four cores.

Where possible, we recommend using Waiwera on a dedicated linux high performance cluster such as NeSI or a local Linux machine with well-connected cores. However, significant reductions in simulation time can also be achieved on a regular desktop using Waiwera (with multiple cores) compared to AUTOUGH2.

The considerable improvements in simulation times achieved by Waiwera allow more rapid model calibration, larger or more refined models and efficient uncertainty quantification of model forecasts. These benefits support decision making and enable modelling to add more value to geothermal projects.

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