PRACTICAL WORKFLOW FOR TRAINING IN GEOTHERMAL RESERVOIR MODELLING

Theo Renaud, Joris Popineau, Jeremy Riffault, John O'Sullivan, Michael Gravatt, Angus Yeh, Adrian Croucher and Michael O'Sullivan

Department of Engineering Science, University of Auckland, Private Bag 92019, Auckland, New Zealand

tren012@aucklanduni.ac.nz

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ABSTRACT

Geothermal reservoir modelling is a complex and time-consuming task. While the theoretical background is generally reserved for professionals and academics, with the right training geothermal modelling is more generally accessible. Here we discuss practical and advanced simulation exercises, including idealised case studies, that can be used to introduce geothermal modelling.

Based on a synthetic high temperature geothermal case study, typical of a volcanic area, a reservoir modelling workflow has been developed for teaching the sequential steps of geothermal simulation. The students are introduced to the key stages of reservoir modelling using the geothermal simulator AUTOUGH2. An important part of the process is the use of a good visualization and post-processing tool such as TIM, for enhancing their understanding of geothermal simulation. Standardized reports are produced with compiled Python scripts to reduce the complexity of dealing with model outputs and allow the students to focus on model calibration. This allows the students to spend more time understanding how changing parameters like permeability and deep upflows affects the match between the model results and the observed data. The use of a synthetic geothermal field gives a practical example of what calibration, data analysis, production history simulation and future scenario simulation with make-up wells mean in a model with some complexity, but which is simple enough to run in a short time. This teaching material provides a valuable resource for getting students familiar with geothermal modelling and improving their understanding of the concepts of geothermal reservoir behaviour.

1. INTRODUCTION

Geothermal reservoir modelling is a complex, evolving and highly specific scientific domain, with various numerical tools released worldwide. A course on geothermal modelling combines an introduction to complex geothermal reservoir simulation topics with background knowledge on flow through porous media and thermodynamics, and so teaching tools need to be practical and succinct for conveying the appropriate message. At postgraduate level, several geothermal courses of one or two semesters have been developed in various universities such as the University of Auckland, UNU-GTP Reykjavik and Kyushu University (Zarrouk 2015). Reservoir engineering is one of the topics covered in these programs and introduces the methodology and examples of the modelling of geothermal reservoirs (Fridleifsson 2000). Master Degree Programs also provide reservoir engineering courses (Fridleifsson 2003) sometimes integrated into petroleum engineering courses (Saptadji 2010).

Short-courses, training programmes (IPCU-AGCE, 2019) or webinars as provided by LDI Training (LDI n.d.) on geothermal modelling have also been offered, sometimes associated with conferences such as the TOUGH Symposium. Depending on the time allocated to teach reservoir engineering, students can be quickly overwhelmed by the complexity of the setting up of models and running the simulator, and some key parts of the modelling process are missed. The teaching workflow presented here has been developed within the framework of an integrated workflow for geothermal modelling developed at the University of Auckland (Popineau et al. 2018).

We developed a training workflow including visualization, model set-up and calibration, and reporting of results based on the geothermal simulator AUTOUGH2 (Yeh et al. 2012), the visualization software TIM (Yeh et al. 2013) and compiled Python scripts.

Based on a synthetic geothermal case study set up with Leapfrog Geothermal®, the calibration of the natural state and production history of a geothermal reservoir is performed by the students using standardized reports. They are also able to run a future scenario with make-up wells and different production/reinjection strategies using the calibrated model. The idea is that the users can efficiently and easily move through the modelling process without being distracted by the complexity that is involved with the technical details of modelling. This framework has been used to teach courses of varying length (from one day to two weeks) and at various locations around the world (including East Africa, Japan, Indonesia, Iceland and New Zealand).

2. TEACHING MATERIALS

The supporting material for the training is composed of a conceptual model of a high temperature geothermal reservoir, associated with magnetotellurics surveys and well data, including feedzone elevations, downhole temperatures, production/reinjection mass flows, production enthalpies and transient pressures.

2.1 Reservoir model

The synthetic model is set up as a representative geothermal reservoir on which to demonstrate the modelling process. The geology for this case study was generated by GNS Science, based on existing New Zealand geothermal fields and typical geothermal formations. In summary, the geological context corresponds to a representative geothermal system with volcanic formations, with sedimentary surface deposits intercalated and intersected by three faults. Deep upflows at temperatures of up to 270°C create a

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geothermal system. Figure 1 is a 3D representation of the conceptual model, including the low conductivity clay cap. The deepest formation is defined as a basement and is covered, in ascending order up to the surface, with ignimbrite, rhyolite, sediments, andesite, dacite, alluvium and superficial deposits. Figure 2 presents a layer of the model grid, which has a total of 11764 blocks. It represents an area of 13 km × 15 km. The three faults shown in Figure 1 are separately defined with their own dedicated rocktypes. The grid is refined in the central area where the wells are located, as displayed in Figure 2.

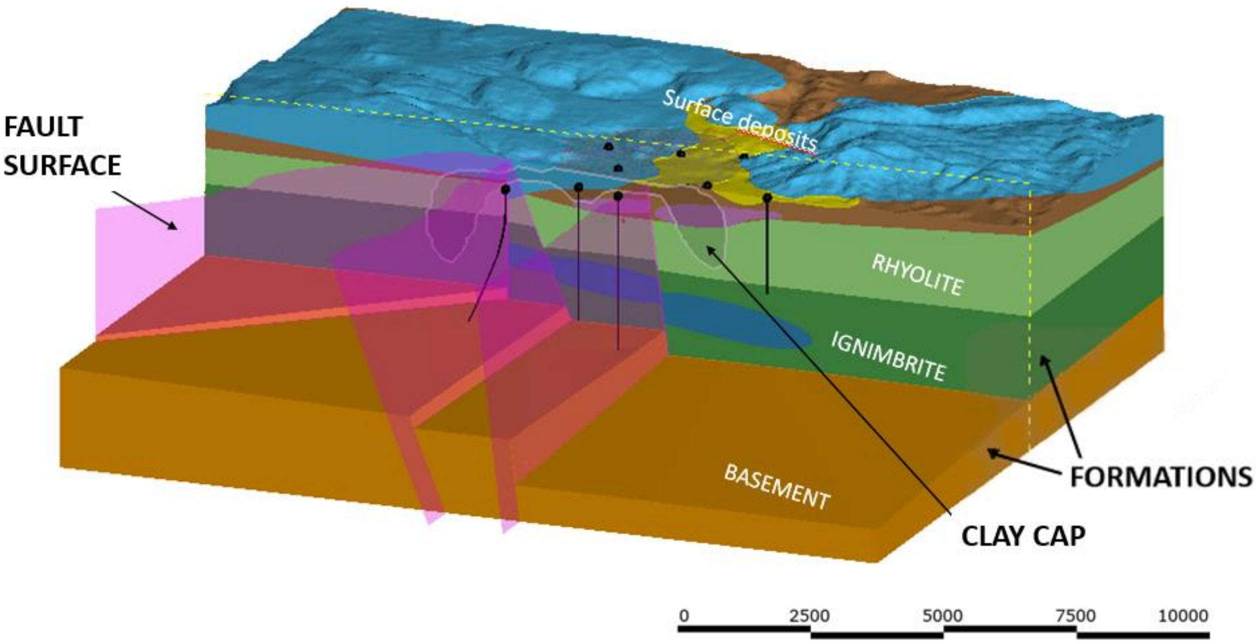

Figure 1: 3D representation of the conceptual model of the synthetic system, showing a faulted high temperature volcanic geothermal reservoir.

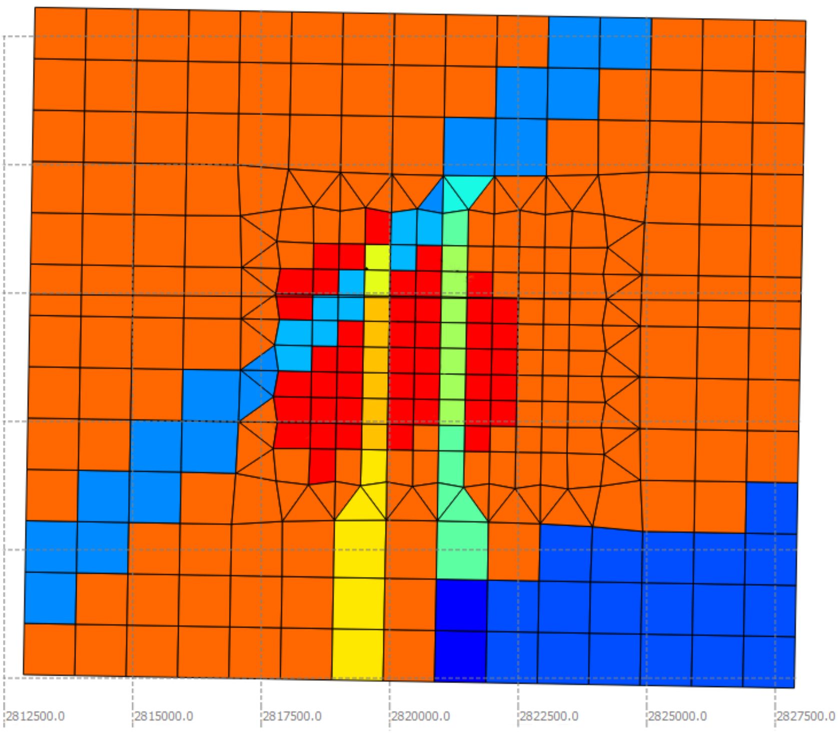

Figure 2: Rocktype distribution at the bottom layer of the model. Plot produced with TIM.

The synthetic permeability distribution of the rocktypes is set to enable a large deep upflow, mainly through the faults. Horizontal and vertical permeabilities range from 5.0e-12 m² (or 5 D) for the surface formations to 1.0e-16 m² (or 0.1 mD) for the altered formations in the clay cap. Porosities are in the range from 1% to 30 %. The density of all formations is set to 2500 kg/m³, the specific heat is set constant to 1000 J/kg/K and the thermal conductivity is set to 2.5 W/m/K everywhere in the model. Figure 3 shows a slice of the synthetic natural state temperature in the model, highlighting a typical high temperature convective plume.

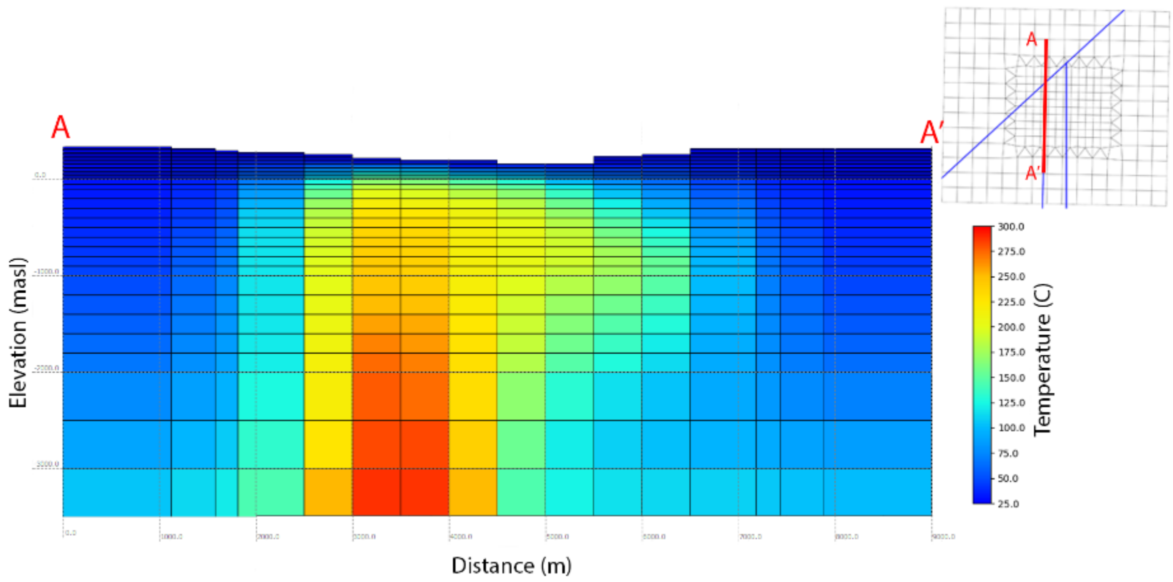

Figure 3: Slice through the model showing the temperature distribution in the natural state.

2.2 Data management

All data attached to the wells are stored in individual JSON files for each well. Python scripts can interact quickly to plot reports of results or to generate new input files for the model. Some of the main stored features include the well track and the feedzones, defined respectively by an array of x, y, z coordinates, and top and bottom elevations. These JSON files also store the initial downhole surveys available for temperature profiles or transient pressure data, both used for comparison in the calibration process. For the production history, the production and the reinjection rates, together with fluid enthalpies are kept in these JSON files.

In this synthetic model, nine wells are set up, seven deviated and two vertical, reaching various depths. These wells include monitoring wells, production wells and reinjection wells. The production history starts in 2017 and ends in 2020.

Excel spreadsheets are used to set up the production history by assigning the feedzone proportions that constrain the production or injection mass flow rate for each well. Figure 4 (Left) shows a future scenario set up for make-up well Well-12 in Excel spreadsheets with the productivity indices defined (Pruess et al. 1999) for the case where it operates as a production well. For new injection wells, the mass flow rate planning can be set up with variable feedzone proportions if needed, as shown in Figure 4 (Right). In this example, Well-12 is producing for one year from the 1/08/2021 to 31/07/2022 while for a year prior to that it operates as a reinjection well between the 01/08/2020 and 31/07/2021. It switches back to operating as a reinjection well from the 01/08/2022 at a flow rate of 150 t/h and two years later the rate is reduced by 50 t/h. All the information except the input model and its results are stored separately in a dedicated folder.

1	Well Name	WELL-12		Calculate PI	No
2	Well Type	DELT			
3	Feedzones (shallowest firs	Feedzone 1	Feedzone 2	Feedzone 3	
4	WBP	5	15	29	
5	Date	Productivity indices (PI)			
6	01/08/2021	1,78E-12	1,78E-12	1,78E-12	
7	31/07/2022	1,78E-12	1,78E-12	1,78E-12	
8	01/08/2022	0	0	0	
9					
10					
11					
12					
13					
14					

1	Well Name	WELL-12					
2	Feedzone Proportions (shallowest first)						
3	Date	Feedzone 1	Feedzone 2	Feedzone 3	Total	Rate (t/h)	Enthalpy (J/kg)
4	01/01/2017	0,5	0,3	0,2	1	0	632300
5	01/01/2020	0,5	0,3	0,2	1	0	632301
6	31/07/2020	0,5	0,3	0,2	1	0	632301
7	01/08/2020	0,5	0,3	0,2	1	200	632301
8	31/07/2021	0,5	0,3	0,2	1	200	632301
9	01/08/2021	0,5	0,3	0,2	1	0	632301
10	31/07/2022	0,5	0,3	0,2	1	0	632301
11	01/08/2022	0,5	0,3	0,2	1	150	632301
12	31/07/2024	0,5	0,3	0,2	1	150	632301
13	01/08/2024	0,5	0,3	0,2	1	100	632301
14							

Figure 4: Examples of production (Left) and injection (Right) Excel spreadsheets to plan a future scenario in make-up well Well-12. WBP stands for the wellbore cut-off pressure at the feedzones.

2.3 Geothermal simulator and viewer

A compiled version of AUTOUGH2 and TIM (Yeh et al., 2012) is made available to the students. AUTOUGH2 is the University of Auckland's version of the industry-standard geothermal reservoir simulator TOUGH2 (Pruess et al., 1999). The equation of state of pure water is used, which can calculate the properties of water up to a temperature of 350°C and pressures up to 100 MPa. TIM (an open source and free graphical interface) is used to assist in the understanding of the model structures by providing views of model variables along model layers or slices (Yeh et al., 2013). Because of the relatively small number of blocks in the model grid (11764), the users can run the model quickly on their own device, with a maximum computational time ranging from a few seconds to several minutes. This allows rapid calibration of natural state and production history models. In practice, geothermal models may take substantially longer to run.

TIM enables the users to manually add in or modify deep upflows, to modify the permeabilities and porosities of rocktypes. In addition, Leapfrog Geothermal® can be used for 3D visualization of the reservoir structures and simulation results (temperature, pressure, gas saturation, etc.).

3. MODELLING WORKFLOW

3.1 Modelling objectives

The three key steps in simulation of a typical high temperature geothermal reservoir are:

- obtaining a representative natural state,
- matching the production history
- and investigating future scenarios.

Figure 5 highlights the workflow used for training with the various visualization and reporting tools. No prerequisite is required in programming as the executables can be used autonomously.

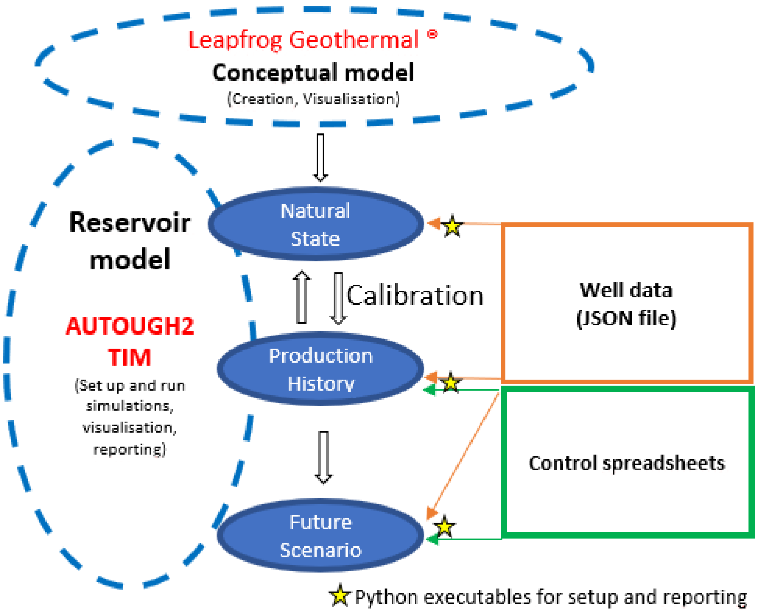

Figure 5: General training workflow applied with the synthetic model.

3.2 Natural state

Starting with a model with only a deep input of background heat and an initial conductive temperature profile, the students are invited to calibrate the natural state of the geothermal reservoir, through the implementation of deep hot water upflows. The location, magnitude and enthalpy of the upflows must all be selected.

In parallel, the permeability structure of the model must be calibrated, as homogeneous values of 1.0e-15m² (or 1 mD) are originally implemented. For example, the flow paths in the faults are expected to be predominantly vertical. Thus, changes in the fault permeability distribution are needed to bring the hot fluid to the upper layers of the reservoir as shown in Figure 3. Through calibration, students see that faults can act as flow pathways (by having high permeability) or constrain the geothermal system (by having low permeability). Also, by introducing a low permeability in the alteration zone (clay cap), the geothermal system is constrained in the vertical direction.

After various iterations, the students can expect to obtain a good match between the model results and the data provided from the downhole surveys, as shown in Figure 6 for Wells 1,2 and 3. By running a pre-compiled Python executable, the student can generate a report that compares the data and the model and provides metrics on the quality of the match.

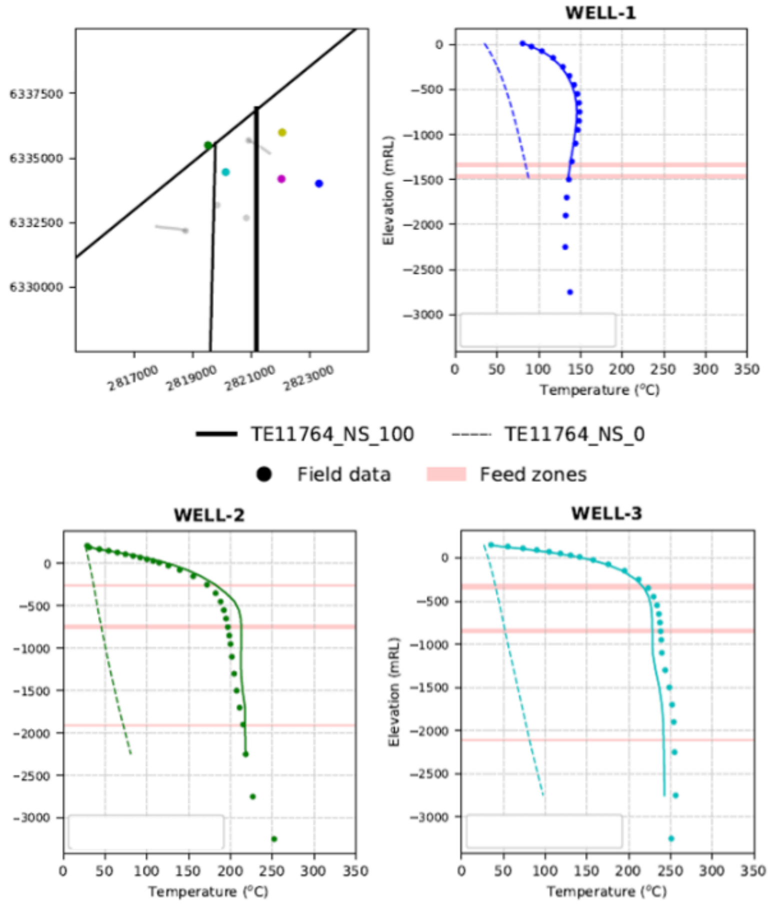

Figure 6: Natural state temperature profiles from an initial conductive thermal gradient model (NS_0) and from a calibrated model (NS_100) compared with downhole surveys. The top left plot shows the location of the wells and the three main faults in the geothermal field.

3.3 Production history

After calibrating a natural state model, the calibration of the production history model is required to ensure that the reservoir model accurately matches transient data. The simulation is run from 2017 to 2020.

Permeabilities and porosities can be changed to match the production history data, i.e., pressure vs time and production enthalpy vs time. Figure 7 presents an example of the production history of Well-3 with the total mass production of the well, the steam flow and the pressure at the feedzones. Figure 8 is an additional supporting graph of the total steam flow from the model compared with the field data of the geothermal field. The total brine, mass flow and average enthalpy are also generated.

As several feedzones per well are defined, the users must designate the proportion for each feedzone that contributes to the total flow as shown in Figure 4 (Right). This provides an additional calibration option and the students are able to adjust production proportions at various feedzone elevation in the model to better match the production of steam or brine in each well.

The Python-based executables provided allow the students to quickly generate the standard plots for each individual well and thus to speed up the calibration process. For each iteration of production history calibration, the natural state must be run again to make sure it is still a good match to data.

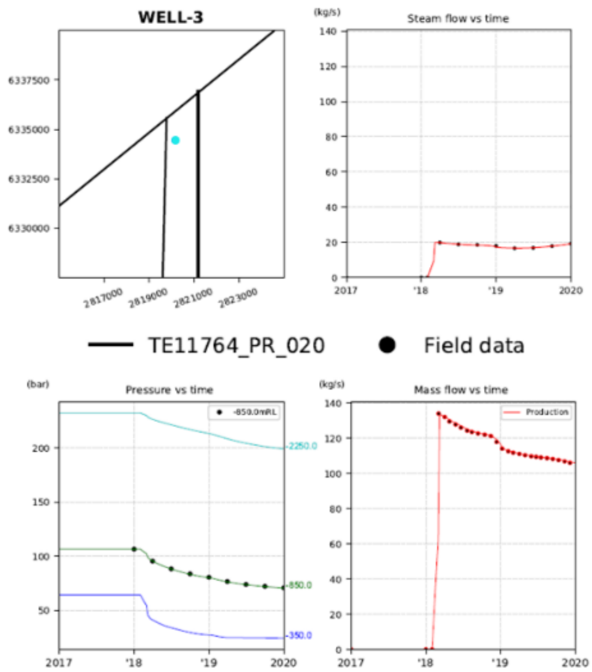

Figure 7: History matching of the production in Well-3. The pressure vs time plot shows the pressure at the feedzones elevation of Well-3.

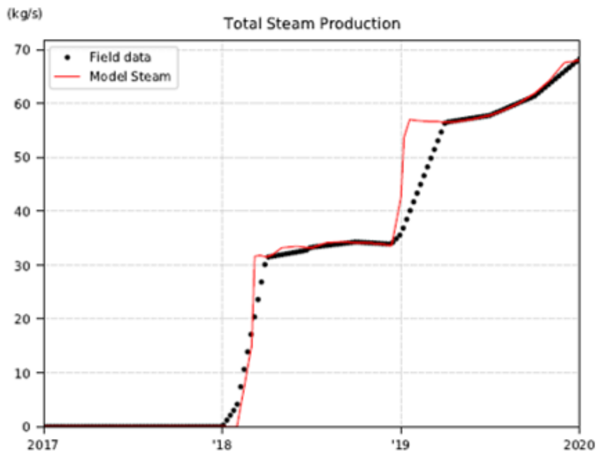

Figure 8: Total Steam production in the production history.

3.4 Future scenarios

Whereas the production history model is driven by the measured actual production mass flow data from the wells, the future scenario uses a deliverability option, which requires a productivity index (PI) for each feedzone in the wells. With this deliverability model, the feedzone discharge is proportional to the pressure above a cut-off pressure. In addition, a maximum flow rate can be set. Following the exercise purpose and time allocated, the calibration of the productivity indices can be performed automatically or manually in order to forecast the feedzone behaviour of the existing wells for the future scenario.

Two production make-up wells and one additional reinjection well are available to set up a future scenario strategy. The feedzones information, the performances of the initial nine wells and the reservoir characterisitics , can help the users to choose their scenario.. By using the spreadsheets, the user can easily define multiple production and reinjection plans with different well options (current and make-up wells). Various future production objectives can be tested such as obtaining the best optimised steam flow rate from the geothermal field or sustain the pressure decline in the reservoir. The future scenario runs right after the production history and simulates 5 years of production, until 2025.

Comparison of the scenarios in terms of pressure response, brine and steam flows, and fluid enthalpy can be made. Using the optimal scenario, sensitivity estimates are made by testing both 2*PIs and 0.5*PIs for the new make-up wells. Figure 9 shows the total steam flow and estimated power production from two proposed scenarios: 002 (one new production well with one new reinjection well starting the 01/01/2020), and 003 (two new production wells with one new reinjection well starting the 01/01/2021). The implementation of a second production well and starting the production one year later show a significant increase of power production for the future scenario.

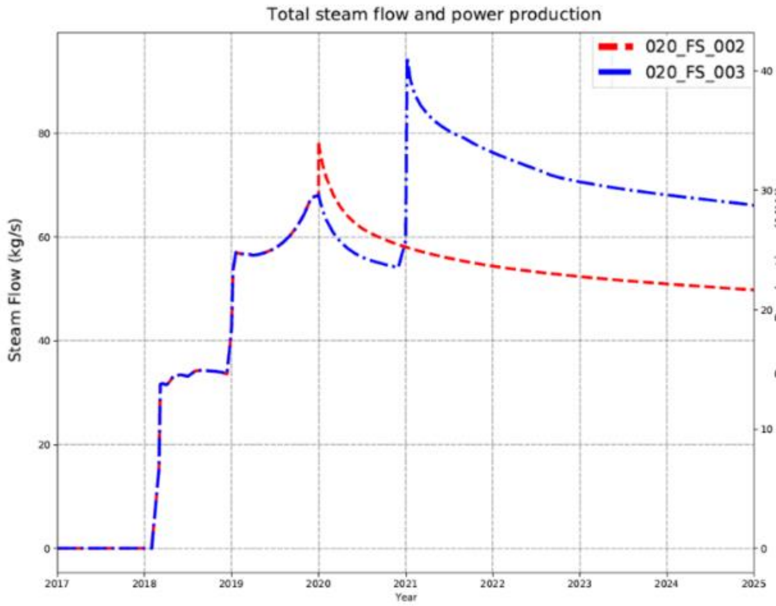

Figure 9: Total steam and power production from two scenarios.

4. REPORTING

The users are able to generate standardized reports with executable Python scripts to plot the transient steam and brine flow, the transient pressure and the average enthalpy of the well (or optionally per feedzones as shown above). From the simulation results and using various visualization tools such a TIM and Leapfrog Geothermal ®, the students can produce high-quality reports with 2D or 3D plots. Figure 10 is an example of a 3D visualization produced with Leapfrog Geothermal ® after importing the results of a future scenario. It shows the 250°C isotherm and the location of the steam zone in the reservoir.

Thus, the students are able to spend a substantial time on the understanding of the key processes of modelling a geothermal reservoir rather than getting bogged down with the details of using the simulator. From our experience, rather than spending a large amount of time in setting up the inputs and plotting the results, the students are quickly immersed in the analysis of the physical effects of production and reinjection, and understanding how the model is working. In this exercise, the use of synthetic data induces no particular correct solution, which enables multiple answers that would fit the dataset. Thus, the geothermal system can be analysed globally rather than discretized into smaller local problem areas.

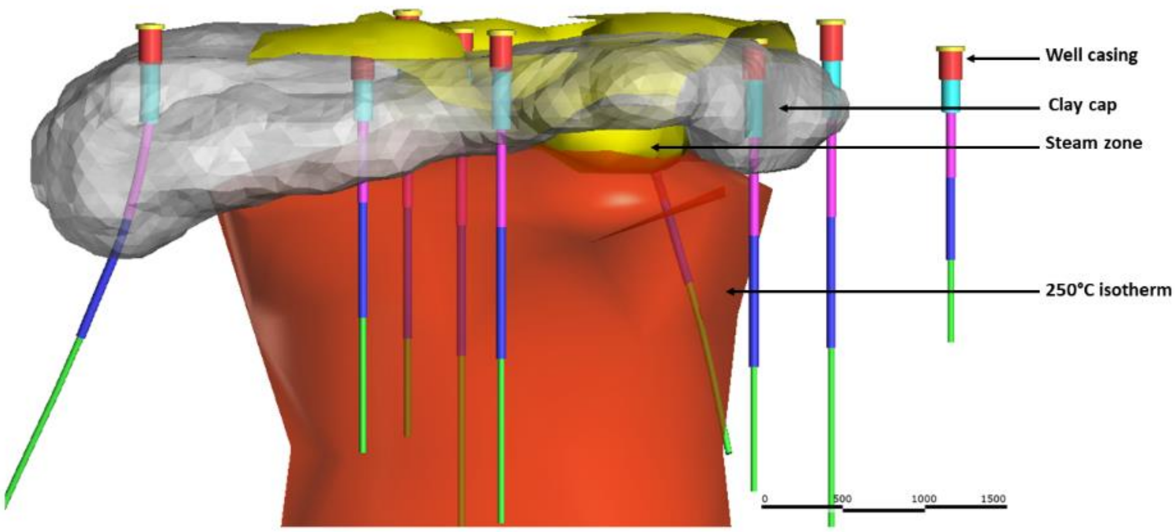

Figure 10: Example of future scenario 3D visualization in Leapfrog Geothermal ®.

5. CONCLUSION

In the context of increasing the fraction of renewable energy in the total energy mix, the geothermal industry and academics will require high-quality geothermal modellers and reservoir engineers to maintain and increase the geothermal installed capacity worldwide sustainably. We have developed a practical training workflow using a synthetic geothermal model, showing the key steps of calibration for the natural state and the production history, with fast simulations. Future scenarios can be investigated with various objectives, easily implemented with spreadsheets and Python executables.

The users are quickly able to generate standardized reports from the results at all stages of the modelling process. The wide possibilities of importing the modelling results in graphs, 2D slices or in a 3D viewer enable the modeller to obtain a complete understanding of the state-of-the-art of geothermal reservoir modelling. This training workflow provides a practical insight of a typical modelling exercise of a complex high temperature geothermal reservoir.

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