Proceedings, 7th African Rift Geothermal Conference
Kigali, Rwanda 31st October – 2nd November 2018

An integrated Leapfrog/TOUGH2 workflow for a geothermal production modelling

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Keywords

Geothermal Modelling Workflow, Leapfrog, TOUGH2

ABSTRACT

Modelling software provides essential tools for the development and management of geothermal systems. Geological modelling software is important for understanding geothermal systems, developing consistent conceptual models and presenting meaningful information about their behaviour. Reservoir modelling software is used to support a wide range of activities including power production predictions, makeup well scheduling, well testing and resource assessment. Both geological models and reservoir models evolve throughout the lifecycle of a geothermal project and they provide the most added value when they are consistent and well maintained.

SEEQUENT Limited and the Geothermal Institute at the University of Auckland have jointly developed a new geothermal modelling workflow using the 3D geological modelling software Leapfrog® and the industry standard reservoir modelling software TOUGH2. The new workflow ensures consistency between geological models and reservoir models and provides tools for automatically generating reservoir model parameters. This not only allows reservoir modelling to begin at the early stages of a project but also streamlines the process of using new field data to update the conceptual model and transferring those changes to the reservoir model. Leapfrog's powerful 3D visualisation tools are also used to make high quality presentations of both field data and reservoir modelling results.

1. Introduction

Models that can be used to explain and predict the behaviour of geothermal systems have become essential tools in geothermal industry. The two most commonly used models are conceptual models and numerical reservoir models. Conceptual models gather and synthesise all the available data into a coherent representation of the system and its behaviour (O'Sullivan & O'Sullivan, 2016, O'Sullivan et al., 2001). Numerical reservoir models are calibrated using available data and then used to provide predictions about the future behaviour of the system. The two types of models are interdependent because a good reservoir model uses the conceptual model as its basis and results obtained from reservoir models are often used to inform and refine conceptual models. Neither type of model is static and over time both evolve as more data are acquired and more calibration is carried out.

The development of Leapfrog by the New Zealand based software developer Seequent Limited in collaboration with key players of the New Zealand geothermal community provided a step change in the way that conceptual models can be developed and maintained. Leapfrog's integrated environment allows field-wide, multidisciplinary data to be directly visualised, compared and modelled and it is now used widely for geothermal projects (Alcaraz et al., 2010, 2011, 2015; Milicich et al., 2010; Massiot et al., 2011; Newson et al., 2012; Pearson et al., 2012).

The industry standard geothermal reservoir simulator is TOUGH2 (Pruess et al., 1999) and progress has also been made on tools for preparing TOUGH2 models and visualising their output. Most importantly the PyTOUGH libraries were developed which can be used for handling all aspects of model development, simulation control and diverse output for complex geothermal reservoir models (Croucher, 2011, 2015; Wellmann *et al.*, 2012). Another useful tool to create and manage numerical reservoir models is TIM (Yeh *et al*., 2013). TIM is an intuitive graphical interface based on PyTOUGH that provides the opportunity to create TOUGH2 models, visualising their input parameters and output results but also directly modify the parameters of the simulation. Several other graphical interfaces have been developed for TOUGH2 including MULGRAPH (O'Sullivan & Bullivant, 1995), Petrasim (Yamamoto, 2008), TOUGHGIS (Berry *et al*., 2014), and TOUGH2Viewer (Bonduá *et al*., 2012).

Despite the advances in handling TOUGH2 models, there has been slow progress towards an integrated workflow which combines both conceptual model and reservoir model development. This is somewhat surprising as the workflow of developing a conceptual model followed by a numerical reservoir model with subsequent iteration between the two has been standard practice for some time (O'Sullivan *et al*., 2001). Both Newson *et al.* (2012) and Pearson *et al.* (2012) imported TOUGH2 model results into the Leapfrog environment and Newson *et al.* made some advances in generating TOUGH2 model inputs using Leapfrog. However a truly coupled workflow was not achieved.

The aim of this project is to present a new geothermal modelling workflow which couples the conceptual model tightly with the reservoir model. The workflow is presented in Figure 1 which shows Leapfrog Geothermal linking the multidisciplinary data together to form the conceptual model. Leapfrog also can be combined with PyTOUGH scripts and TIM to provide the two-way integration with the TOUGH2 models (Natural State, Production History and Future Scenarios).

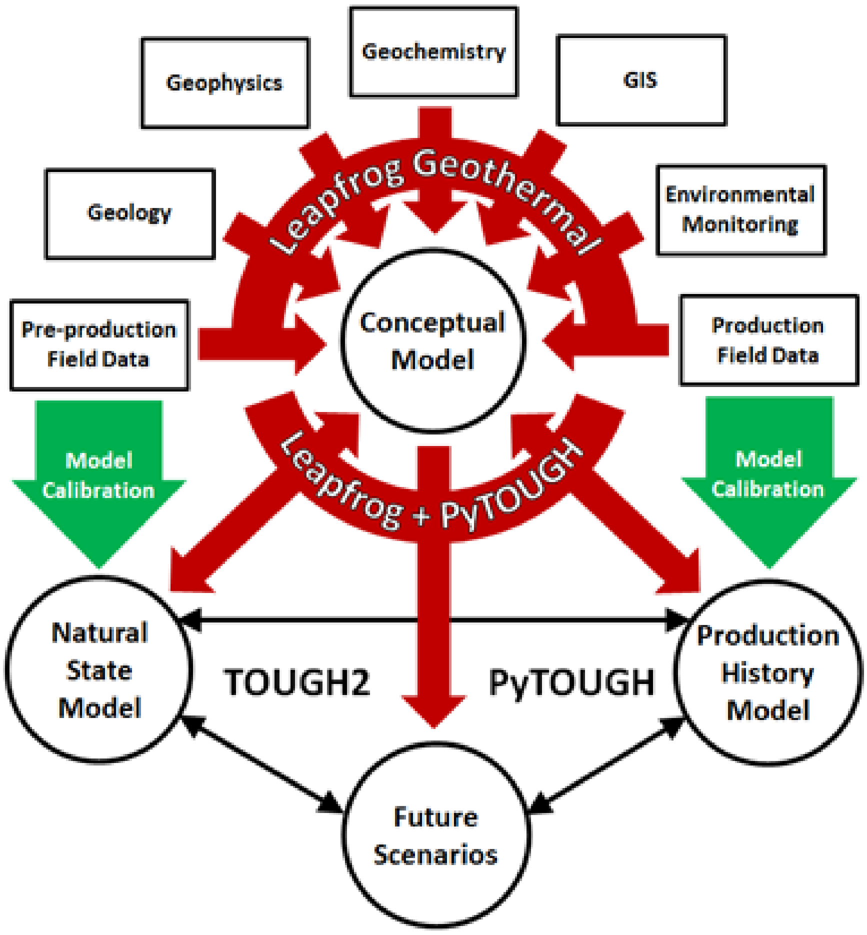


Figure 1: A new geothermal modelling workflow using Leapfrog, TOUGH2 and PyTOUGH.

Using this workflow to achieve a tight coupling between the conceptual model and the reservoir model adds value to the geothermal modelling process in several important ways:

- It ensures that the structures of the conceptual model and the reservoir model are consistent and clearly documented
- Meaningful, consistent 3D visualisation can be presented for both of the models
- It streamlines the process of using new data to update the conceptual model and can transfer those changes directly to the reservoir model
- It significantly reduces the effort required to set up a reservoir model which allows them to be developed earlier and by less experienced reservoir modellers
- It enables experts from a range of disciplines to interact and communicate using a single source of information that includes all available field data and reservoir modelling results

The following sections demonstrate the new work flow by first presenting the conceptual model representation, then describing the creation of the TOUGH2 model from the conceptual model and finally discussing the presentation of the results based on a calibrated TOUGH2 model. The data used in the example comes from a real geothermal system but it has been simplified and augmented with synthetic data for demonstration purposes.

2. Conceptual model representation

A conventional plan view of the conceptual model is presented in Figure 2. It shows that the system is volcanically hosted and that the major faults play important roles as both conduits and barriers to flow. The topography is also important with surface features associated with the outflow of the system occurring at low elevations and steam heated features occurring at high elevations. The cross-sections shown in Figure 3 show the geological model and interpreted temperature contours determined from the downhole measurements and surface observations. These show that upflows are occurring at the intersection of Faults A and S and also up Fault D. Temperatures above 200°C are mostly restricted to the tertiary volcanics and mesozoic basement units. Alteration has been identified in the wells and the location of the clay cap has been inferred using data from a Magneto-Telluric (MT) survey. The survey can provide contours of conductivity at various depths which can be used to define a 3D volume in Leapfrog as shown in Figure 4. The interpreted clay cap can then be easily included in the cross-sections shown in Figure 3.

While the plots presented in Figure 2 and Figure 3 give a good description of the system, Leapfrog enables much more powerful visualisations of the conceptual model to be generated. An example is presented in Figure 5 showing the temperature iso-surfaces and mesozoic basement topography.

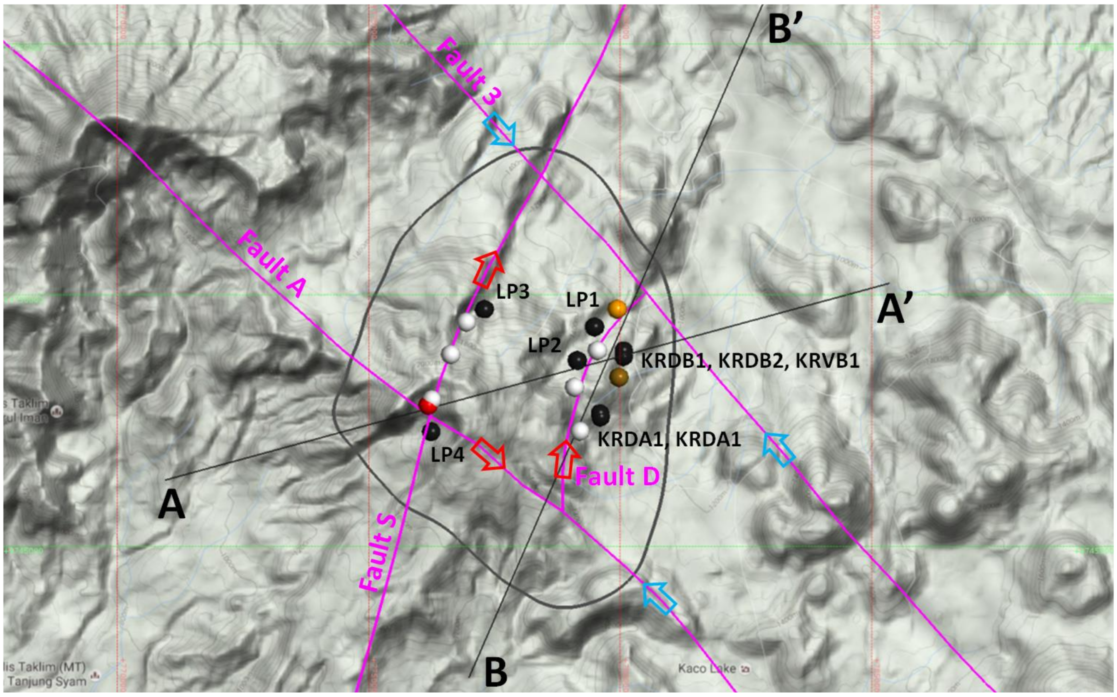
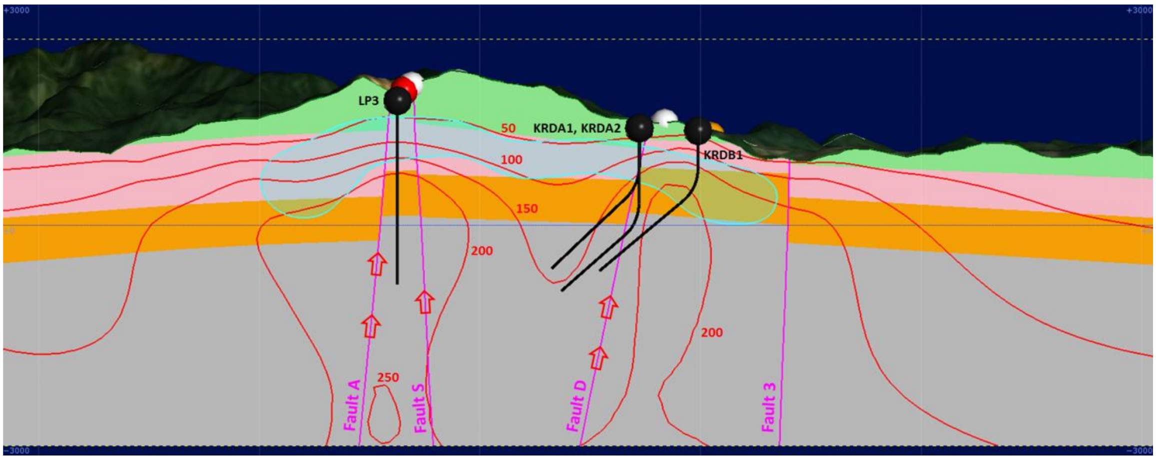
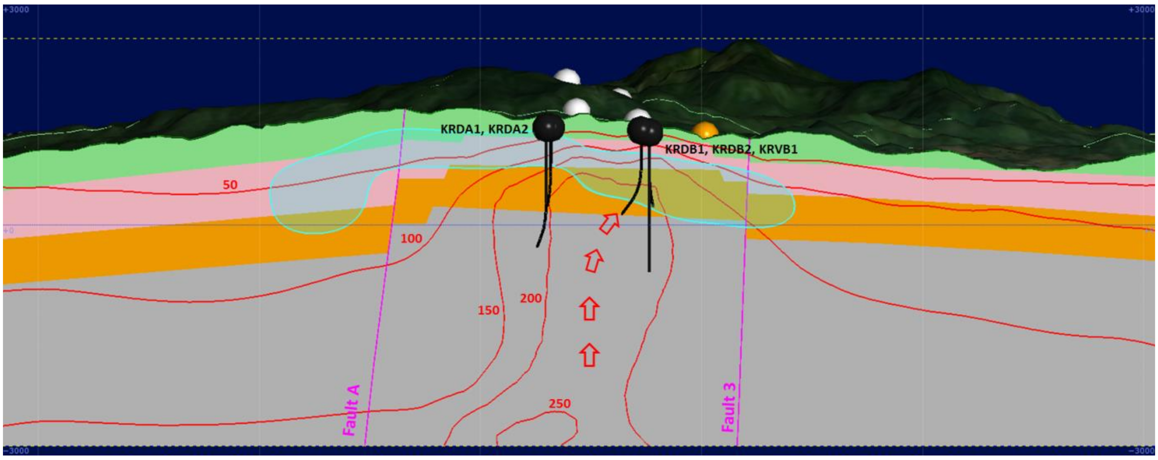


Figure 2: Plan view of the system with topography shown. Main faults indicated in magenta, resistivity boundary in dark grey and well pad locations in black with well names given. Locations of surface features and the cross-sections in Figure 3 are shown. Hot and cold fluid flow also indicated.

a) Section AA’



b) Section BB’



Upper Quarternary Volcanics | Terciary Volcanics

Mid Quarternary Volcanics | Mesozoic Basement

Figure 3: Cross-sections through the conceptual model of the system. Geology, faults (magenta) and clay cap (light blue shading) indicated. Wells close to the cross-sections, surface features, temperature contours and direction of the upflows are included.

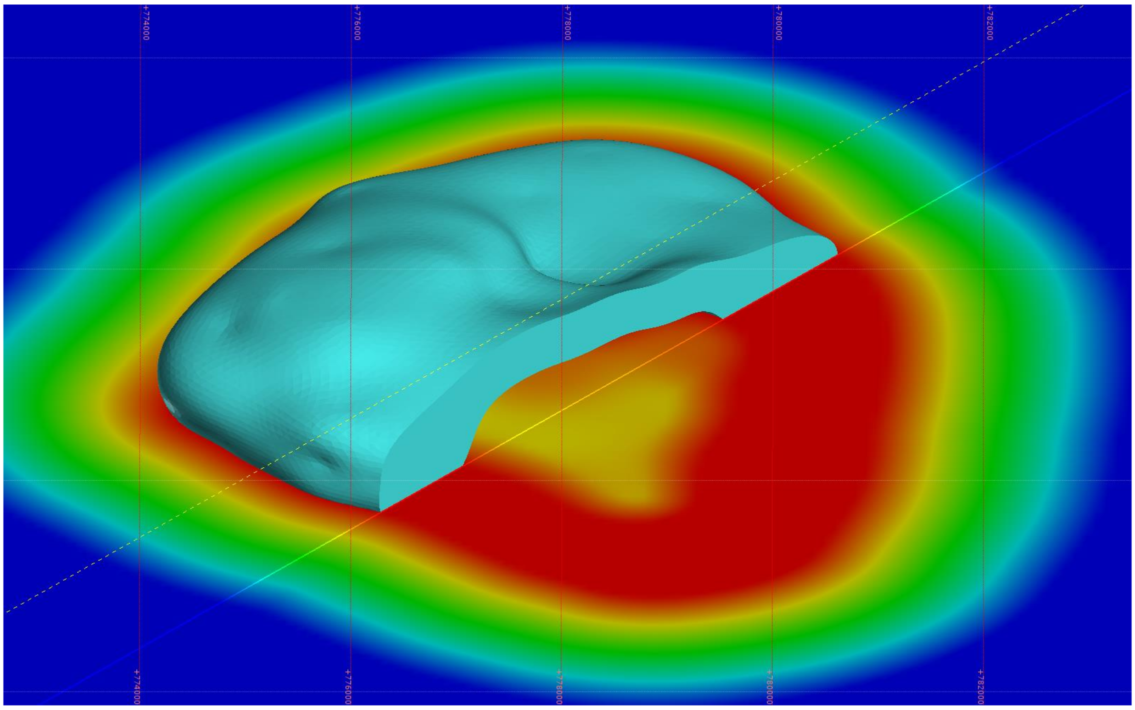


Figure 4: Estimated conductivity at 300 masl from Magneto-Telluric (MT) survey with 3D interpreted clay cap shown in light blue.

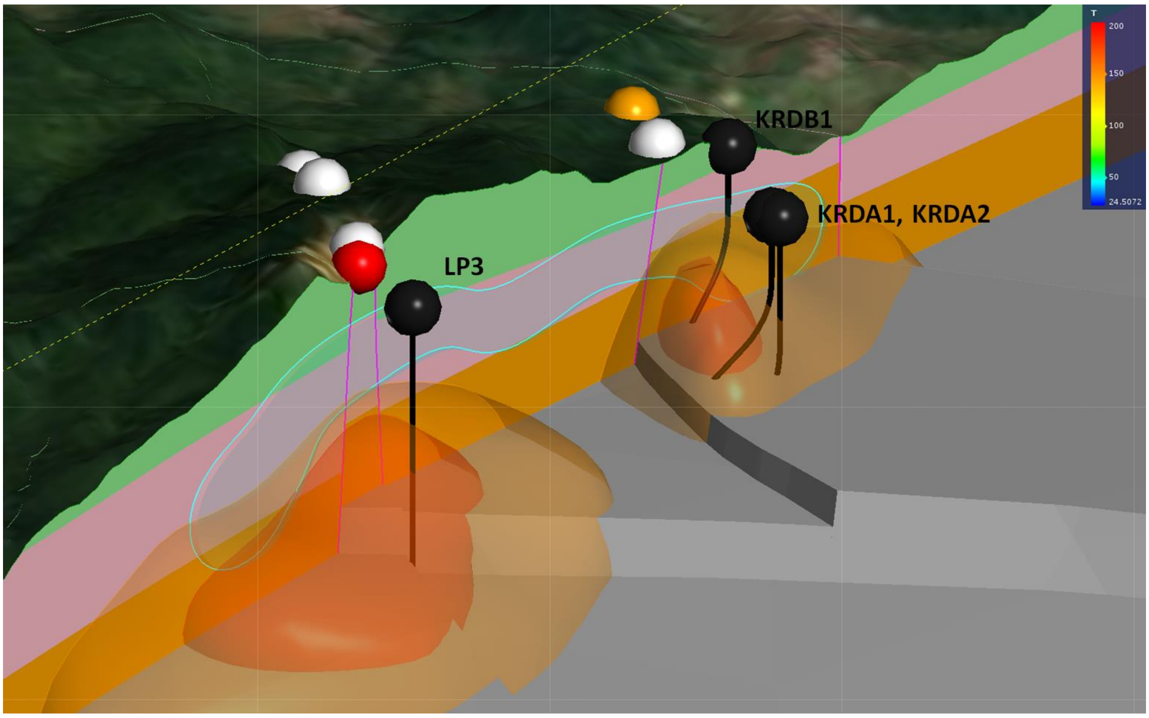


Figure 5: Conceptual model along cross-section AA' shown in 3D with temperature iso-surfaces and mesozoic basement topography.

3. TOUGH2 model generation

Once the conceptual model has been developed, Leapfrog can be used to directly generate the TOUGH2 model input file. Figure 6 shows the TOUGH2 model that has been generated with the topography mapped accurately on to the grid and the geological units automatically assigned. The Leapfrog functionality which creates the TOUGH2 model allows the grid to be rotated so that it can be orientated to align with the faults. It also allows irregular grid spacing which enables a more highly refined grid to be used near the wells and in the centre of the system. Recently, the option of creating an unstructured TOUGH2 grid has been added and enables the representation of more complex structures.

Leapfrog allows the user to select the geological model that will be used to create the TOUGH2 model. This means that the full range of methods within Leapfrog for including faults and alteration zones in geological model can also inform the TOUGH2 model. Also because Leapfrog's geological model dynamically adjusts as new data are added, subsequent TOUGH2 models will automatically inherit those changes. Figure 7 shows the system's faults overlaid upon the TOUGH2 model with its bottom left half removed to expose the fault blocks which have been coloured magenta. Once these blocks have been identified, automated PyTOUGH scripts, or a manual selection of blocks in TIM, can be used to assign different properties to them in the TOUGH2 model. This allows high levels of heterogeneity in the TOUGH2 model as faulted blocks within the same geological unit can have different properties. The properties can also be anisotropic and for the example presented here faulted blocks tend to be conductive along the strike of the fault but act as barriers across the fault. The same treatment is given to altered geological units and the representation of the clay cap in the TOUGH2 model is shown in Figure 8.

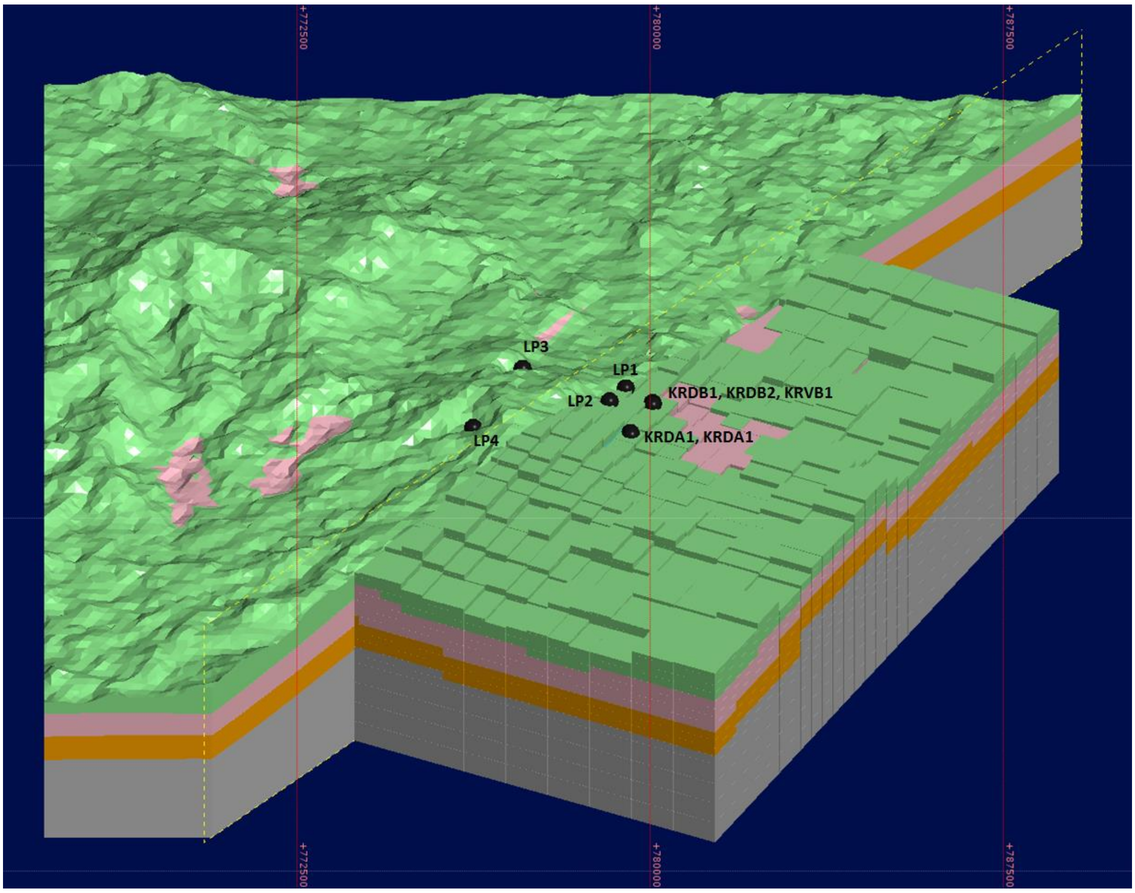


Figure 6: Leapfrog model (top left) with generated TOUGH2 model (bottom right). Well pads indicated.

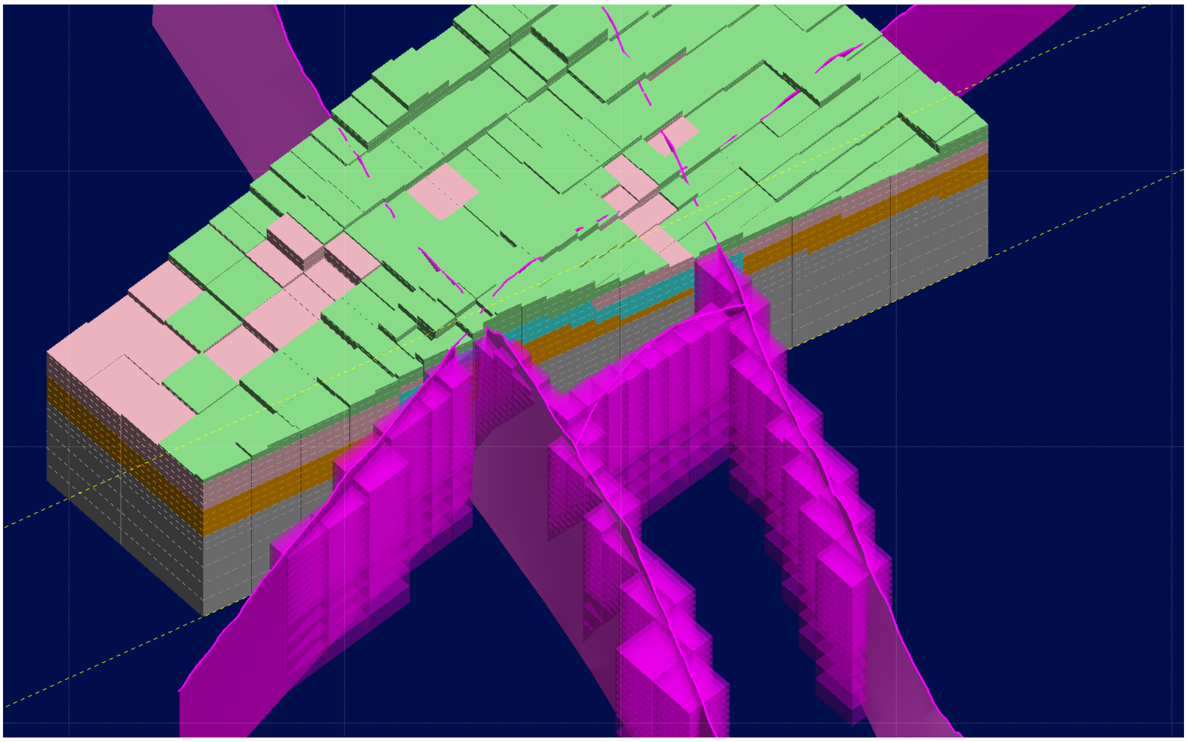


Figure 7: Representation of faults in the TOUGH2 model. Leapfrog model faults shown in magenta with the corresponding faulted TOUGH2 block shown in the cut away half of the model.

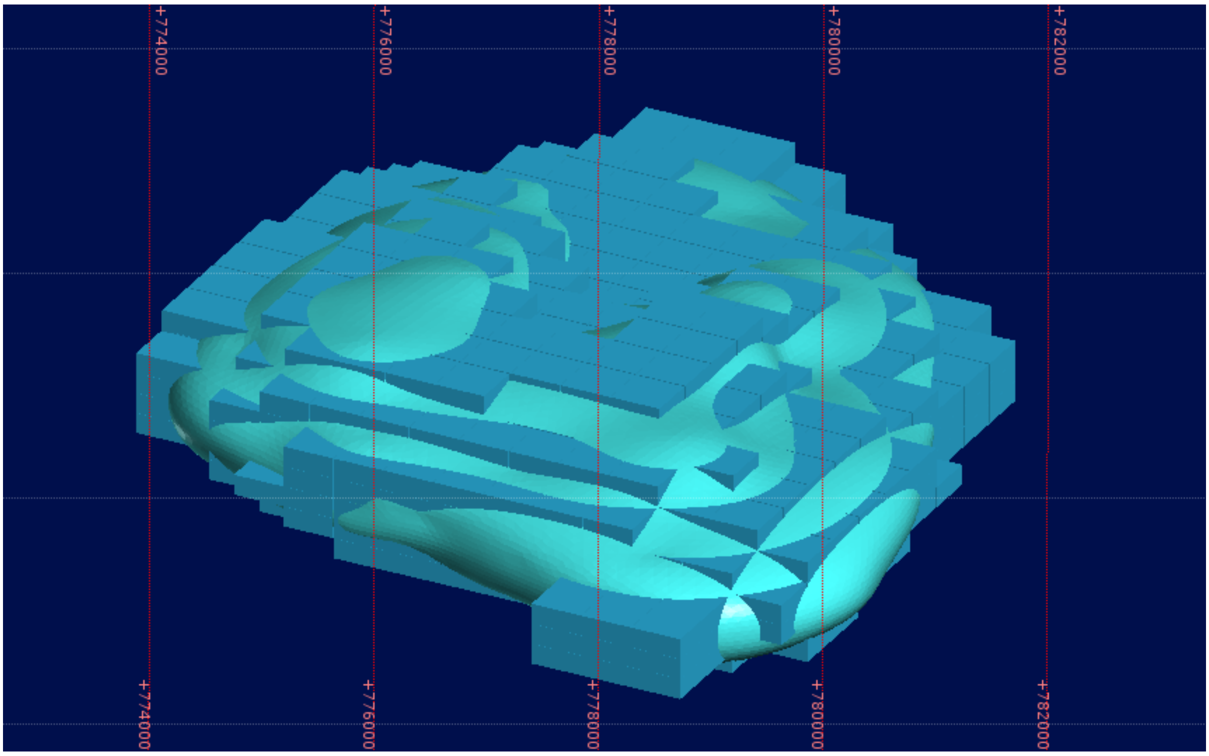


Figure 8: Representation of the clay cap in the Leapfrog model and the TOUGH2 model.

4. TOUGH2 model calibration and presentation of results

After a consistent TOUGH2 model structure has been generated using Leapfrog, PyTOUGH scripts are used to generate the model parameters. There are three important advantages in using PyTOUGH scripts for generating the model parameters. First, using scripts makes it a trivial task to regenerate model parameters for a TOUGH2 model that has had its structure updated using Leapfrog. Second, PyTOUGH scripts simplify the calibration process and are important records of the calibration history (Croucher, 2011, 2015). Finally PyTOUGH scripts significantly reduce the chance of introducing errors when assigning model parameters to complex simulations. As an alternative, without requiring scripts, TIM can be used to visualize 2D plan views or slices of reservoir parameters assigned to the blocks. It provides a powerful tool during the calibration process, by allowing manual changes of model parameters and providing a general overview of them at the same time (Figure 9).

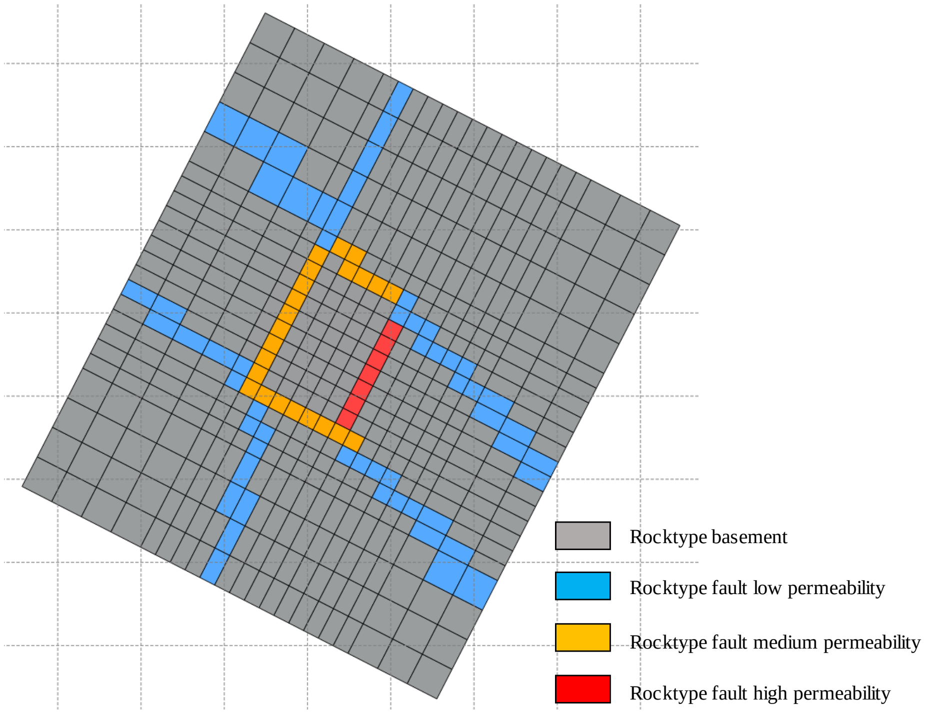


Figure 9: 2D slice showing the different rock-types at the basement of the TOUGH2 model using TIM. Rock-type parameters and locations can be manually changed within the graphical interface.

The TOUGH2 model calibration process is carried out outside of the integrated Leapfrog environment. The development of the numerical TOUGH2 model consists of three interdependent steps and follows an iterative process. The first step is the development of the natural state model, based on the parameters given by the conceptual model (e.g. permeability structure). It gives a representation of the reservoir temperature and pressure distribution before any production has occurred. Different parameters, such as permeabilities, heat and mass inputs or rainwater recharge are adjusted until a good match between the field data and models results is obtained. The next stage is the development of the production history model, starting from the parameters and results carried over from the natural state model. At this stage the past production and injection in the field is included in the model. Here, permeabilities and porosity are adjusted to match output data from wells such as pressure and enthalpy histories or temperature and pressure evolution. Any adjustment of parameters requires the natural state model to be run again in order to get a new consistent set of initial conditions for the production history model. Finally, once the model is well calibrated, simulations of future scenarios can be used to investigate the future reservoir response to various development strategies.

The full range of diagnostic plots such as downhole temperatures (examples given in Figure 10), pressure transients or slice and plan views can be generated using PyTOUGH, TIM or other TOUGH2 output processing tools. Leapfrog is able to offer extra insight during calibration by displaying model results in 3D. Figure 11 shows the error between the TOUGH2 model downhole temperatures and the measured data. This type of plot can help reservoir modellers to identify model zones where the calibration is poor, using information from several wells simultaneously. The results in Figure 11 show that for this particular version of the model the shallow temperatures around wells KRVB1, KRDB1 and KRDB2 are too cold while the upflow of high temperatures up the fault to LP3 and LP4 is too strong.

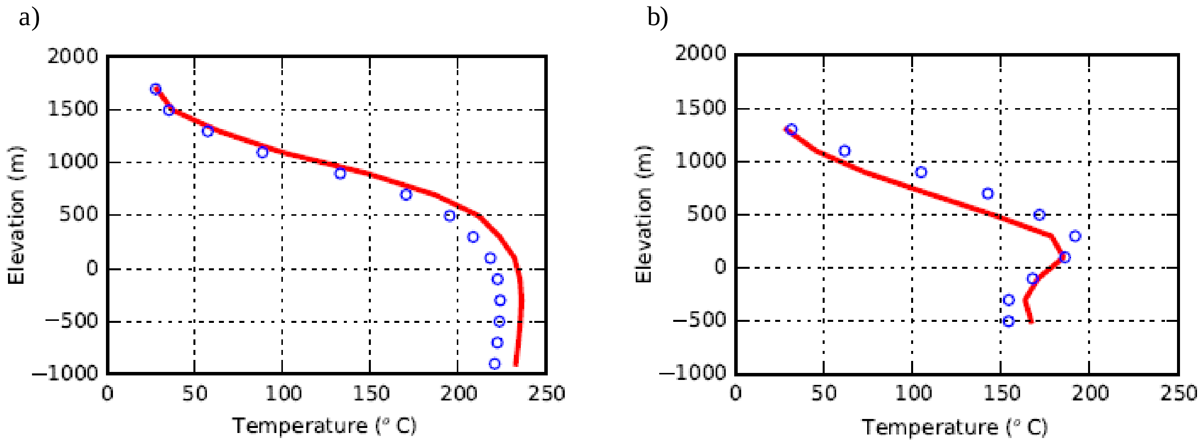


Figure 10: Examples of modelled (red) downhole temperature for wells (a) LP3 and (b) KRDA1 during the calibration process. Field measurements are shown as blue symbols.

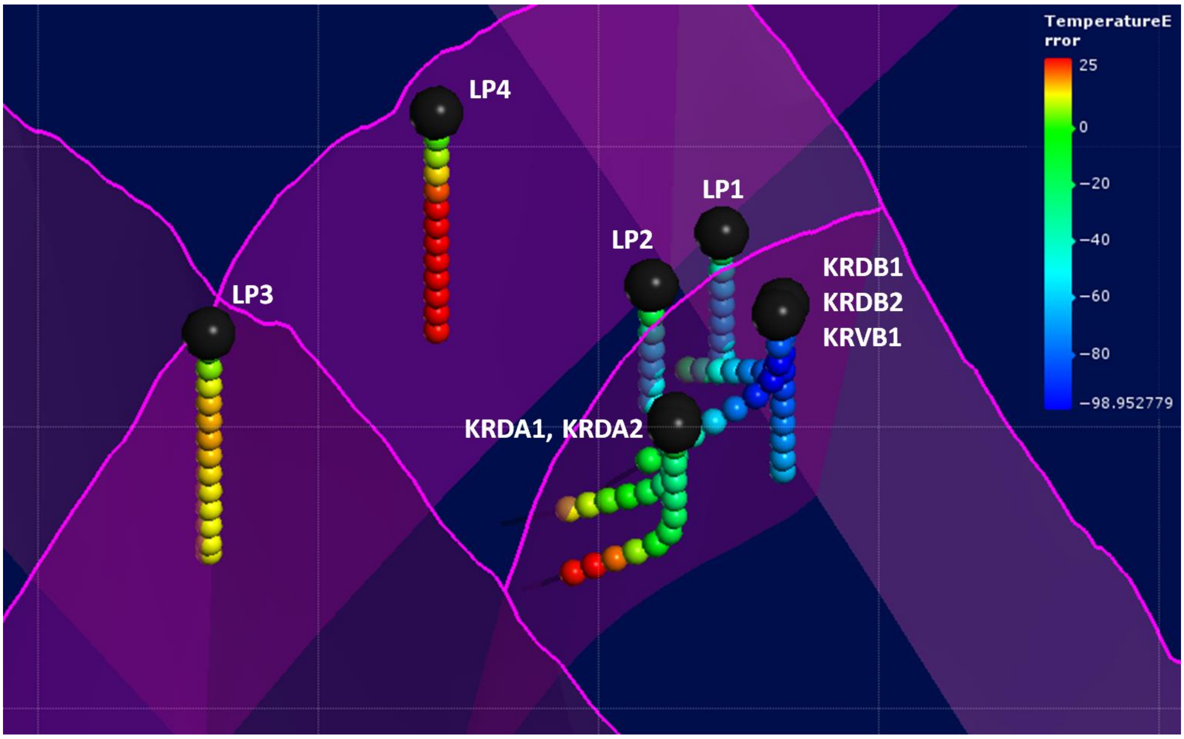


Figure 11: Example of using Leapfrog to make a 3D visualisation of errors in modelled downhole temperatures.

When a model has been satisfactorily calibrated to the field data a range of plots are typically prepared which present the model predictions of important aspects of the system. These are usually in the form of time histories plots, downhole plots and 2D contour plots. Using the workflow presented here, TOUGH2 results consistent with the conceptual model can be imported back into Leapfrog using PyTOUGH and then visualised in 3D. Powerful presentations can be made that combine data from a wide range of sources with the TOUGH2 model results to help understand system behaviour and support management decisions. Often stakeholders will be more confident interpreting reservoir model results when presented along with familiar data and the conceptual model. An example of the power of 3D visualisation of TOUGH2 results is shown in Figure 12. It captures the development of a steam zone at the top of the 200°C iso-surface after 10 years of production. The steam zone forms within the fault and lies almost entirely within the tertiary volcanics geological unit.

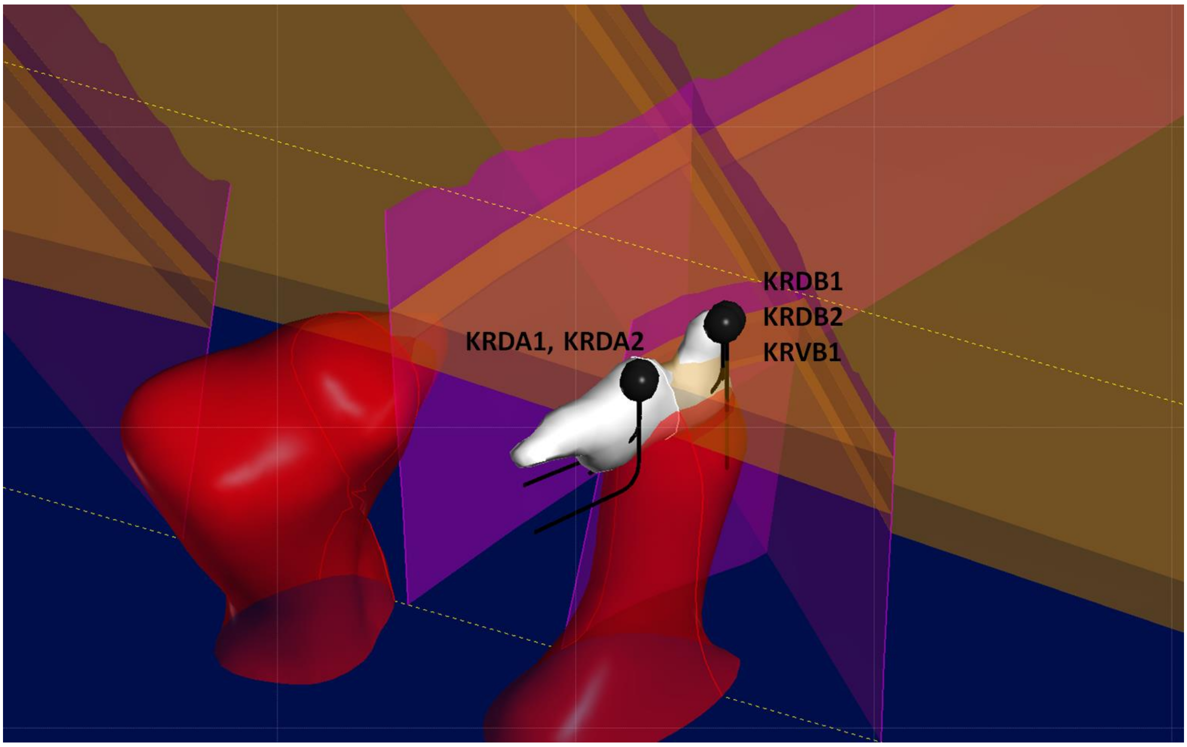


Figure 12: Example of using Leapfrog to make a 3D visualisation of the evolution of a steam zone (white) during production. The production wells, 200°C iso-surface, faults (magenta) and the tertiary volcanics geological unit are included.

Conclusion

A new workflow for geothermal modelling has been presented. It uses Leapfrog Geothermal to ensure that the structures of the conceptual model and the reservoir model are consistent and clearly documented. Leapfrog's dynamic updating of the geological model streamlines the process of using new data to update the conceptual model and it can be used to transfer those changes directly to the reservoir model. The effort required to set up a reservoir model is greatly reduced by using Leapfrog to generate the TOUGH2 model structure. Then by applying modular, reusable PyTOUGH scripts or by processing the model within TIM allows good control of the numerical model parameters during the calibration process, thus allowing good understanding of the reservoir behaviour and providing confidence in model predictions.

This means that reservoir models can be developed earlier in the geothermal project cycle and by less experienced reservoir modellers. Meaningful, consistent 3D visualisation can be presented for both of the models by importing TOUGH2 model results back into Leapfrog. The workflow enables experts from a range of disciplines to interact and communicate using a single source of information that includes all available field data and reservoir modelling results. These significant benefits allow more value to be extracted from geothermal modelling process and more robust management decisions to be made.

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