

INTRODUCING THE VOLSUNG GEOTHERMAL SIMULATOR: FEATURES AND APPLICATIONS

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Keywords: *Volsung, modelling, TOUGH2, wellbore, surface network, simulation*

ABSTRACT

In this paper we describe features and applications of the Volsung Geothermal Reservoir Simulator software package. Volsung includes a reservoir simulator, a wellbore model, a surface network simulator and a 3D graphical user interface (GUI) for building models, running simulations and visualizing model outputs. It is designed to make it easier to use numerical models in the decision process for managing geothermal fields. Volsung reduces model development times, simplifies the modelling process and enables sophisticated simulations designed to meet the modern day needs of geothermal operators. This paper describes features of Volsung that underlie these improvements, including: grid generation, conceptual model implementation, coupled wellbore and surface network simulations, data visualization, calibration to microgravity, modelling tracers (including salt and non-condensable gas), automatic steady-state detection, modelling faults and remote simulation with GPUs. These features and planned future developments are discussed in the context of how to get better value from geothermal reservoir modelling efforts.

1. INTRODUCTION

Volsung is a new software package for geothermal reservoir modelling. In a companion paper to this New Zealand Geothermal Workshop, we present a detailed description of the underlying reservoir simulation code including validation and benchmark speed testing (Franz et al., 2019). In this paper we present features and applications of the broader software package. The package has been designed to enable greater use of reservoir models to support geothermal developments. Volsung does this by making it faster to run models and easier to build and maintain models. Furthermore, it links the reservoir model to a wellbore and surface network model to provide fully coupled simulations that account for the main physics of interest.

2. VOLSUNG FEATURES

2.1 CONCEPTUAL MODEL IMPLEMENTATION

A key feature of Volsung is that the conceptual model is implemented independent of any particular grid. This makes it simpler to refine and regrid models as needed for particular applications.

Conceptual model features in the model are created in the graphical user interface (GUI) as 3D shapes. An example of this is shown in Figures 1 and 2 where you can see the conceptual model elements such as model regions and faults along with well tracks implemented without any reference to a particular grid structure. The 3D shapes that define model

regions and boundary conditions can be built as points, lines, polygons and surfaces; alternatively, they can be imported from geographic information system (GIS) shapefiles or other 3D data formats such as exported Leapfrog¹ or VTK² files. This means users have the flexibility to develop conceptual models completely from within Volsung or they can work with conceptual models in other GIS or earth modelling software and import them into Volsung.

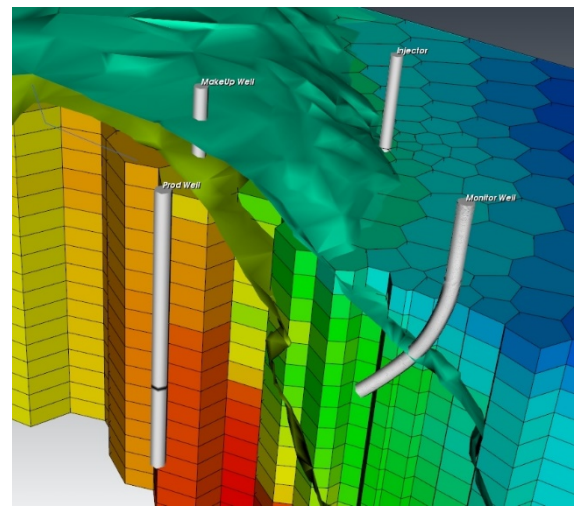


Figure 1: Model visualisation showing cells coloured by temperature, temperature isosurfaces and well-tracks.

Properties of model regions can also be entered via the GUI. To keep the conceptual model independent of any particular grid, permeability is entered as tensor components using three principle spatial components along with options for rotation. When a particular grid is generated, the appropriate permeability is calculated by projecting the tensor onto each connection vector between grid block centres. This means grids can be rotated while maintaining the original orientation of the permeability anisotropy. A range of relative permeability and capillary pressure functions can also be set from the GUI and these are associated with individual rock types. As such, it is possible to have different relative permeabilities or capillary pressures within different lithological units.

Boundary conditions (fixed state or source/sink terms) can be located in space using 3D shapes or they can be placed along model grid boundaries by convenient helper functions. Furthermore, hot plates and atmospheric conditions are conveniently implemented in Volsung as standard features.

¹ <http://www.leapfrog3d.com/products/leapfrog-geothermal>

² <https://vtk.org/>

Wells in the model are defined as well tracks using spatial coordinates and feedzone elevations.

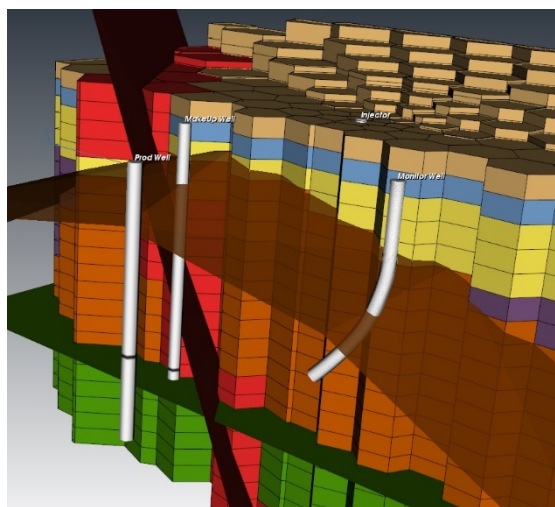


Figure 2: Conceptual model in Volsung showing well-tracks and surfaces defining model regions and faults. One can see two conceptual layers (brown and green) which act as surfaces for filling the model with lithological units. The dark red slanted surface represents a fault, which overrides the lithological unit choice made by the layers.

Because all aspects of the conceptual model including model regions, boundary conditions, rock properties and well feedzone locations are defined independent of the grid it is a straightforward process to refine and alter the model grid so it is fit for the particular application of the reservoir model.

2.2 Grid Generation

Currently Volsung allows for three different types of grids: radial, tartan (recti-linear) and Voronoi. In each case the grid is defined via a dialog window and then saved as a grid file. Different grids can be selected, used, updated, swapped out and stored for later use as the user sees fit. Grids can be developed in local coordinate systems and then transformed into global coordinates to make it easier to combine with information from other coordinate systems such as well tracks and surface topography.

Radial and tartan grids do not require any further explanation here. The Voronoi grid generation is achieved by a triangle force relaxation method (Persson & Strang, 2004) followed by Delaunay triangulation and Voronoi cell identification. The Voronoi cells can be easily refined around well tracks and other points of interest. Because the permeability is defined independent of the grid and projected onto individual connections it is possible to include anisotropic permeability in Voronoi grids (see, e.g., Arnaldsson et al. (2014)).

Model ground surface can be entered as a set of spatial coordinates so that grids with ground surface elevation can be developed that have a top layer with blocks of varying height to match the ground surface or blocks can be removed from the model if they protrude above ground surface elevation.

2.3 Coupled Wellbore and Surface Network Simulation

A key feature of the Volsung system is that flow from the reservoir model can be coupled to a wellbore model. The

standard approach when simulating production from a well is to extract a certain amount of mass from a reservoir model block coincident with a well's feedzone. However, unless the thermodynamic conditions at the model block are fed through a calibrated wellbore model there is no guarantee that the feedzone could produce the amount of fluid being asked of it. This motivates the requirement for some type of check that conditions at the feedzone are sufficient to produce and this functionality is often included in simulators such as the well-on-deliverability option in TOUGH2 (Pruess et al., 1999). An additional complication arises when a well has multiple feedzones. If a well has one feed in a deep liquid zone and another feed in a shallow steam zone these two zones may evolve differently during a forecast scenario and the relative contribution from each feedzone may change drastically. If this process is not modelled properly, then forecasts can become inconsistent with physical behaviour.

Another motivator for the coupled wellbore simulation approach is so reservoir modellers can provide more useful answers through to operators. Typically, a manager or plant operator will want forecasts of fuel (geothermal liquid and/or steam) availability at plant operating pressures or make-up well requirements. This is very difficult to answer accurately with a reservoir model that only forecasts reservoir conditions. Coupling a wellbore model to the reservoir model enables wellhead deliverability curves for mass flow and enthalpy to be calculated from reservoir conditions. These deliverability curves can then be linked to power plant requirements via a surface network model. This has the advantage that the full feedback loop between reservoir conditions, fuel availability, plant requirements and injection load is accounted for. The reservoir model can then be used to forecast power generation and make-up well requirements.

The concept of coupling a reservoir model to a wellbore model has been previously investigated by other authors (e.g. Hadgu et al. (1995), Bhat et al. (2005), Butler et al. (2009), Ayala (2010), Gudmundsdottir (2012), Nandanwar & Anderson (2014), Franz (2016), and Matsumoto (2018)). The key to successfully coupling these simulators is by having a robust wellbore simulator which can reliably find solutions under a wide range of thermodynamic conditions; if an exact solution cannot be found, then sensible model simplifications or adjustments are needed since it is impractical to halt a simulation and manually fix wellbore model issues. It has hence been our main motivation to develop a combined reservoir, wellbore and surface simulator as part of a single robust package in order to ensure that the different (reservoir, wellbore and surface) simulators can easily exchange data and are built on the same set of internally consistent tools and thermodynamic functions.

Objects currently available in the surface network include wells, unions, valves, splitters, injectors, heat exchangers, separators and a power plant model. An example surface network model is shown in Figure 3. Objects are placed into the surface network in an editor. Every object has input and output ports which can be connected to each other to form the network topology; each port provides a unique flow rate consisting of mass rate, dry energy/electrical rate, enthalpy, component mass-fractions and pressure. Depending on its type an object calculates an output port response to its input port conditions. Some objects offer free parameters - for example mass rates for throttling a producing well - to the

surface simulator. Others, like power plants, also provide an objective function to indicate a mismatch to a desired state.

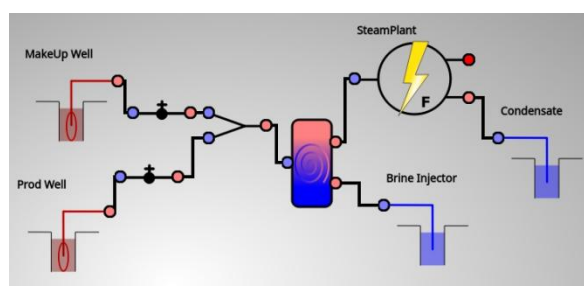


Figure 3: Surface network in Volsung showing two production wells connected to a separator. The brine flows to one injector and the steam goes a steam plant; condensate is re-injected via another well

The solution for the surface network system is found iteratively. A basic iteration propagates a trial solution from upstream objects (e.g. producing wells) to downstream objects; each downstream object can then determine its current solution. Once all downstream objects have calculated their states the direction is turned around and pressure change suggestions are propagated upstream. If after such a basic iteration the pressures in the objects are not matched, then the state is declared invalid. If a state is valid its objective function is calculated by using a weighted least squares approach. In the current version of Volsung the objective function is defined as the weighted sum of squared mismatches between the desired and modelled power output for each power plant. In this manner, minimising the objective function modifies production well flow rates in a realistic and physically plausible manner to obtain a solution whereby plants generate at their specified generation rates.

In the scenario mode, a simulated annealing type optimization algorithm is used to vary free parameters and minimize the objective function until its global optimum has been found. The algorithm for this process is a Temperature Parallel Simulated Annealing with Adaptive Neighbourhood (TPSAAN) algorithm (Miki et al., 2002). The simulation is started by creating parallel clones of the surface network; each clone then works on a fixed simulated annealing temperature and tries to optimize the objective function. At intervals, the clones exchange their solutions; better solutions move towards colder temperatures and vice versa. This results in a broad probing of the parameter space yet fast convergence on a good solution. Since the clones can be run in parallel, this method performs very well.

The surface network model has several modes available to run production history and forecast simulations. During production history well flow is specified in flow rate tables for each well and typically the surface network does not take control of the simulation. During forecasting some or all wells can be adjusted to meet plant demands and predefined make-up wells can be turned on automatically if desired. An example simulation is shown in Figure 4. In this scenario two wells are connected to a power plant with a target generation of 1.15 MW. In the scenario without make-up wells the plant has a plateau over which it can generate its target value and then from the year 2021 generation declines because the well is unable to provide sufficient steam at the plant's operating pressure. In the scenario with a make-up well a new make-up well is automatically turned on at this time and both wells are throttled to meet the generation target.

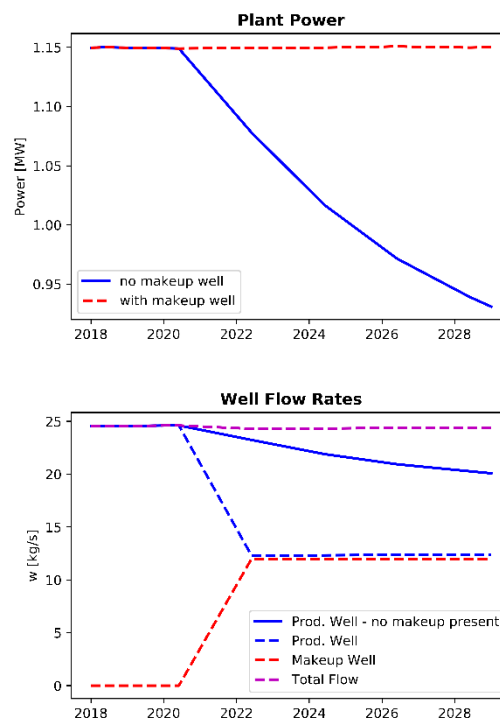


Figure 4: Simulation results for a surface network example: power generated by the plant (top) and fluid produced by the wells (bottom) versus time in years. Without a make-up well the production well cannot adequately supply the plant and power generation tails off (solid line). If the plant is allowed to bring a make-up well online then it can maintain its generation target; the production fluid required is distributed over the two available wells (dashed lines).

Options for modelling wells in Volsung include fixed mass-fraction wells, wellbore coupled wells and pumped wells.

2.3.1 Fixed mass-fraction wells

For fixed mass-fraction wells, mass is simply extracted from the gridblock coincident with the wells feedzone(s); each feedzone is allocated a fixed fraction of the total flow at the wellhead. Importantly, the well still requires a well track and feedzone elevations; this ensures that the specification of the well is independent of any particular grid.

2.3.2 Wellbore coupled wells

Wellbore coupled wells make use of the wellbore model described in Section 2.4. Thermodynamic conditions of the gridblocks at model feedzones are passed to the wellbore model to model the flow up the well and calculate wellhead fuel availability information. When the appropriate flow from the well has been determined by the surface network simulator, fluid is extracted from the well's feedzones consistent with feedzone contributions as determined by the wellbore model. The GUI can be used to display and plot wellhead deliverability curves and wellbore thermodynamic conditions for each print or output time of the simulation.

2.3.3. Pumped wells

Including pumped wells in Volsung enables systems to be analysed where the enthalpy and pressure in the reservoir is insufficient to support flow to surface without pump support. Each pumped well is specified with a desired flow rate,

specified wellhead pressure, pump maximum flow rate, pump differential pressure and pump efficiency. Fluid flow from a reservoir model block into a well feedzone is modelled by taking into account the thermodynamic conditions in the reservoir block, the block size and the productive index of the well's feedzone. A check is made to see if the pressure at the feedzone plus the differential pressure applied by the pump is sufficient to enable production at the desired rate.

2.4 Wellbore Model

Volsung's wellbore simulator features as a fully integrated simulator between the reservoir and surface models and also as a standalone GUI called Gudrun which can be used to model individual wells without the need to run a fully coupled simulation.

The wellbore simulator is based on solving the ordinary differential equations for mass and heat along a wellbore (e.g. Hasan & Kabir (2002)). The time integration is carried out using either a simple Euler or a more advanced Runge-Kutta (4th order) method. Fluid is exchanged at feedzones only; linear and quadratic (Forchheimer) draw equations are supported.

The wellbore flow-path configuration offers the feature to have time-dependent segments present; this is of interest in running coupled simulation since it avoids having to create two or more separate well representations if the wellbore flow-path has changed, for example by sleeving the well. It also offers the possibility to add to the simulation known variations in wellbore diameter due to scaling or cleanouts.

The wellbore simulator can be run using pure water, H₂O and non-condensable gas (NCG), or H₂O and salt equations of state (EOS); in the latter case, currently salt precipitation does not lead to wellbore scaling but this effect could be included in a later version. Inclusion of another EOS with H₂O, salt and NCG is planned.

Pressure drop correlations available in the wellbore simulator include homogeneous (Hasan & Kabir, 2002), Duns and Ros (1963), Hasan & Kabir (2010) and Hagedorn & Brown (1965). Further correlations similar to the ones used for GWELL/GWNAFL/HOLA such as Chisholm-Orkiszewski and Chisholm-Armand have been implemented for comparison purposes with the GWELL family of wellbore simulators (Aunzo et al., 1991). Lastly, the wellbore simulator includes the Orkiszewski (1967) pressure drop correlations but we found them to be unsatisfactory for practical use due to numerical issues leading to discontinuities in model output. The Gudrun GUI also features import mechanisms for wellbore models from the GWELL and Simgwel (Marquez et al., 2015) wellbore simulators.

Several different wellbore simulation modes are available. The most common ones allow the modeller to simulate single wellbore conditions—for example when comparing to PTS (pressure, temperature and spinner) surveys—or more complex modes for determining the wellhead characteristics (deliverability/injectivity curves) and searches based on them. A deliverability curve is a plot of production rate versus wellhead pressure and a search in this context might be to find the wellhead pressure for a given flow rate. Numerical stability in these searches was a paramount design criterion; the wellbore simulator aims to make sensible

choices if it can't find a solution. For example, weak feedzones below prolific feedzones can lead to situations where no wellbore integration is successful. These weak feedzones can be automatically eliminated to enable a solution to be found. This behaviour is optional and appropriate warnings are given.

An example output from the wellbore model standalone GUI Gudrun is shown in Figure 5.



Figure 5: The Gudrun standalone GUI for the Volsung wellbore simulator. The screenshot depicts a deliverability curve on the right and a deviated well with its casing configuration and feedzone locations displayed in 3D on the left.

2.5 Data Visualisation

Good data visualisation is key to understanding and communicating model results. Volsung makes use of the VTK platform to visualise model results in a 3D model viewer window. Model cells can be coloured by lithology, state or any thermodynamic property. Users can step through standard views of model layers or use tools provided to cut and slice the model view in 3D. Using the visualisation tools provided, it is very easy to get a comprehensive understanding of the distribution of temperature, pressure, saturation and other conditions in the reservoir model.

It is also possible to view isosurfaces of model thermodynamics as shown in Figures 1 and 6 and flow vectors as shown in Figure 6.

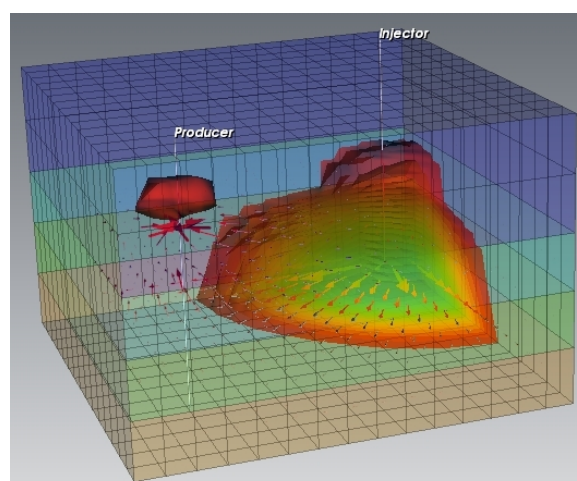


Figure 6: Volsung model visualisation showing flow vectors and isosurfaces of temperature.

A slider bar enables users to move the model display through time. Double clicking on an individual cell brings up that cell's current properties and options for plotting cell

properties (thermodynamic properties, fluxes and sources/sinks) over time.

The in-built data visualisation in Volsung is a comprehensive package for viewing, exploring and communicating model results. Another requirement for most modellers is an easy way of routinely generating plots of model results such as calibrated natural-state temperatures or pressure and enthalpy data matches. Volsung provides this functionality via a Python library that enables high quality plots to be generated via a flexible script-based approach. An example output from the Python plotting library is shown in Figure 7.

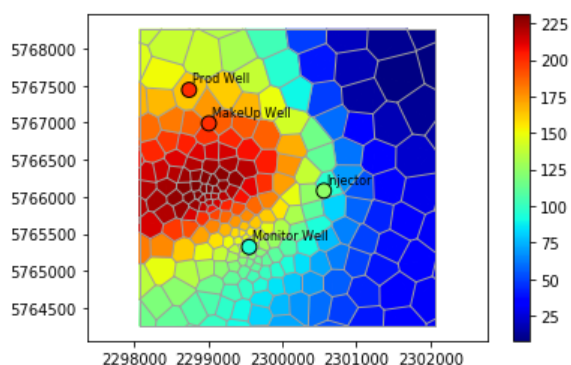


Figure 7: Data visualisation using Volsung’s Python plotting library showing a slice through the model with Voronoi cells coloured by simulated temperatures and well tracks at slice elevation coloured by field data temperatures on the same scale. This slice plot could be a useful tool to check where the reservoir model is too hot or too cold.

2.6 Microgravity

Changes in microgravity provide a useful calibration tool for reservoir models particularly when there is development or saturation of a two-phase zone. Calculation of microgravity from a reservoir model requires a summation of changes in mass in each model block scaled by the distance squared of that block to a measurement point (e.g. Franz (2013)). This is easy enough but requires some careful accounting of geometry, particularly if the blocks are subdivided into fracture and matrix subdomains as in the MINC formulation used in TOUGH2 (e.g. Pruess (1992)). In Volsung we provide this as a module in the software package so it is easy to view changes in microgravity in the GUI and to compare microgravity predicted by the model to measured data.

2.7 Tracer Simulation and Switching EOS

Equations of state (EOS) are used to calculate the thermodynamic state of model blocks given a set of primary variables. A system with pure water requires a different set of equations to a system with salt and/or non-condensable gas (NCG). Often a model is developed with one EOS but there may be some reason to convert the model to a new EOS—say to test the potential impact of NCG on the boiling conditions in the reservoir. In Volsung the model EOS can be switched by simply selecting the particular EOS from a drop-down menu. Default values for new components (e.g. salt or NCG) are then used as initial conditions and in mass fractions of source terms—these can be edited manually;

mass fractions of existing components are preserved during the transfer to a new EOS.

A similar approach can be taken for simulating tracer tests. Volsung is able to simulate all available EOS with multiple aqueous tracers and the fractions of different types of water can be used for tracking pollution plumes, fluid mixtures and tracer tests.

2.8 Natural-State Simulation Enhancements

Volsung includes several features to speed up natural state model runs. In addition to the numerical simulation enhancements described in Franz et al. (2019), Volsung also includes automatic steady-state detection and automatic switching on and off of MINC blocks.

The automatic steady-state detection monitors changes in the thermodynamic conditions of blocks over time to detect a system state close to steady state when running through the natural-state period. In the steady-state detection approach used in Volsung, the maximum change of each component throughout the model is calculated and compared to the time step. The maximum change in each component is described by

$$\max(|\Delta M^k|) / \Delta t \leq \varepsilon^k$$

where M is mass or heat, t is time, ε is the stability criterion and the superscript k denotes the particular component (water, salt, NCG for example). If three consecutive time steps are considered stable, then the system is considered to be at steady state and the time is skipped towards the production or scenario period. A user can enter three different ε^k values: a major criterion refers to the first component, i.e. water; a minor criterion is applied to all other mass components; and an energy criterion is applied to the heat component. These different criteria can be set to sensible values to reflect what a user regards as stable enough for their purposes. The steady-state detection is meant to be an auxiliary feature to help when simulations have problems reaching a large simulation time due to numerical truncation problems at large time steps.

Automatic switching on and off of MINC blocks allows a user to enter a time before which MINC blocks will be disabled and after which they will become active and initialized with thermodynamic conditions from the relevant fracture element. This can greatly speed up natural-state run times.

2.9 Remote simulation on GPUs

Volsung’s speed is enabled by solving the linear system on a GPU (Franz et al., 2019). Users who do not have a GPU on their local computer can still utilize the benefits of GPU simulations by running them remotely on either a dedicated workstation or a cloud-based environment such as Amazon Webservers³ or Google Cloud Compute Engine⁴. A user just needs to setup a GPU instance with secure shell (SSH) access and then Volsung can seamlessly pass the run files to the remote machine, run the simulation and transfer back the output files. In this way a user can work with models and

³ <https://aws.amazon.com/>

⁴ <https://cloud.google.com/compute/>

view model results on their local machine but run simulations on a remote system.

3. APPLICATIONS

At the time of writing one full field operating geothermal field model has been run using Volsung. Volsung has also been used as part of a consultancy service to assess the potential for a low enthalpy geothermal development in New Zealand and it has formed the platform for a week-long geothermal reservoir modelling course.

The full field model run using Volsung is the Tiwi geothermal field. The Tiwi field is operated by the Philippine Geothermal Production Company, Inc. (PGPC) and started commercial production in 1979. Tiwi had some two-phase regions in its natural state and developed extensive single-phase steam zones during the production phase. At the time of writing we have successfully translated the natural-state model into Volsung; work on the production history and scenario phase is currently ongoing.

A complicating factor in the translation to Volsung was that the existing model used a modified TOUGH2 version. The key differences were that the PGPC model provided used permeabilities and porosities as 3D fields instead of discrete rock types and that it contained modified connection areas for blocking/enhancing faults.

We solved the issue of 3D field variations by first writing a customized version of PyTOUGH⁵ and then used it to analyze the TOUGH2 model and create the required number of “lithological units” to replicate the property variations. We then translated the grid into Volsung and used a file-based block association model where each grid block is associated with one of the defined lithological units; this approach works with other systems as well, for example with Leapfrog models.

The modified connection areas were also analyzed and translated into barrier representations; Volsung uses these barriers to modify permeability and heat conductivity of connections between individual blocks, which can increase model resolution to contain sub-grid features.

Once the model had been redefined in a Volsung compatible format, the necessary boundary conditions (heat and mass inflows and outflows) were also defined and we ran the natural state of the Tiwi model twice; first using initial conditions provided by PGPC, which were close to steady state, and then using a cold liquid state as the starting condition. We then compared pressure, temperature and gas saturation between the TOUGH2 and Volsung steady states by plotting the block-by-block differences in histograms; these are shown in Figure 8. Pressure differences were all smaller than ~ 0.12 bar and temperature differences were generally smaller than 0.7°C . Given the fact that Volsung uses IAPWS-97IF steam tables versus IFC-67 used by TOUGH2 the two simulators show excellent agreement (IAPWS (2007), Pruess et al. (1999)).

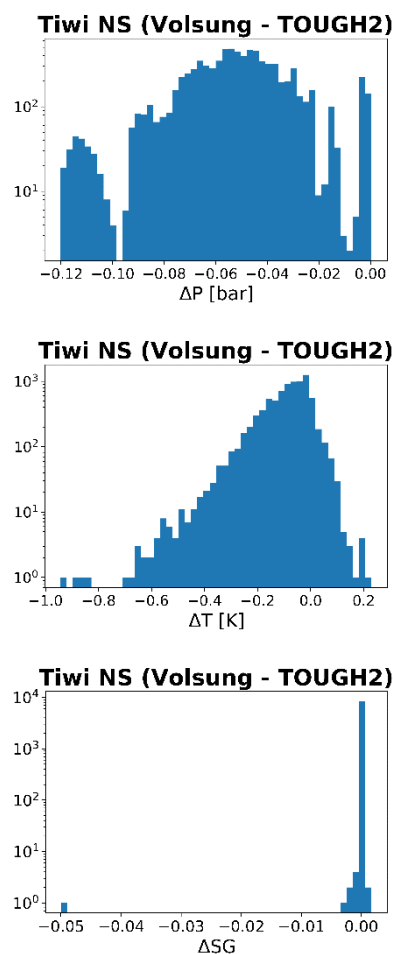


Figure 8: Histograms showing the block-by-block differences between Volsung and TOUGH2 results for the Tiwi natural-state run. From top to bottom: pressure, temperature and gas saturation differences. The -0.05 gas saturation difference in a single block is due to non-uniqueness of the solution for the Grant relative permeability curve.

Gas saturation differences were all smaller than 0.005 with the exception of a single block which showed a difference of 0.05 . Closer inspection showed that this block was located next to a region with ~ 0.05 gas saturation and had remained single phase. This behaviour is well understood in the context of a non-unique solution due to the relative permeability function used—a Grant curve with 0.05 residual saturation, i.e. the system is free to deviate by this amount.

Finally we compared the results from the cold start with the above results and only found maximum relative numerical deviations in the order of $\sim 10^{-7}$, which is close to the single precision truncation error of $\sim 10^{-8}$ for the file format in which the data is stored, i.e. the results can be seen to be nearly identical.

⁵ <https://github.com/acroucher/PyTOUGH>

4. CONCLUSIONS

Features and applications of the new Volsung reservoir modelling package have been described. Key features designed to improve the utility of geothermal reservoir models include:

1. A 3D GUI to develop conceptual model elements independent of the model grid.
2. A coupled wellbore model and surface network model capable of running real-world forecasts.
3. A 3D model viewer plus Python library for data visualisation.
4. Various features to enable faster model run times and flexible and adaptable model usage.

Volsung has been used on several projects indicating it is ready for wider uptake in the geothermal industry.

ACKNOWLEDGEMENTS

We would like to thank PGPC for allowing us to publish the results from the Tiwi model translation study.

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