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APPLICATION OF 3D MODELLING AND VISUALIZATION SOFTWARE TO RESERVOIR SIMULATION: LEAPFROG GEOTHERMAL AND TOUGH2

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ABSTRACT

Reservoir modeling is a multidisciplinary task aimed at consolidating diverse, and complex, geosciences information, reservoir production, and injection history into a robust numerical model of the system. The resulting model is used for resource management and to assess resource sustainability for a number of development scenarios. The Wairakei-Tauhara and Ohaaki geothermal systems (New Zealand) are operated by Contact Energy Ltd, and have been modeled extensively over past decades using the expertise of University of Auckland Department of Engineering Science. The advent of faster computers and a greater quantity and variety of data has allowed significant improvements in the resolution of these models.

One consequence of the increased modeling resolution is that the assignment of reservoir parameters to a numerical model has become increasingly challenging. This has led to a collaborative effort between Contact Energy Ltd and ARANZ Geo Ltd, to improve both the visualization and creation of reservoir models. The software, available commercially as Leapfrog Geothermal, includes the import and visualization of TOUGH2 input files, and assigning reservoir model parameters based on geological attributes from a 3D geological model.

This collaboration is providing an opportunity for geoscientists, and reservoir engineers to integrate geothermal data into a common visualization platform. Case studies from Wairakei and Ohaaki are discussed.

BACKGROUND

TOUGH2

Geothermal reservoir simulation is used to test the conceptual models of systems, investigate system sensitivity, and predict system response to production scenarios. The widely used TOUGH2 geothermal reservoir simulator (Pruess, 2004), receives its input from a text file, which can be more than 100,000 lines of precisely formatted text. Hence most TOUGH2 modelers use some form of computer-aided pre-processing.

TOUGH2 output is similarly in the form of a large text file. Because the output describes the spatial distribution of data, and often the change of conditions over time as well, the output requires post-processing in order to interpret the modeling results.

Pre- and post-processing graphical user interfaces (GUIs) have been written for TOUGH2, such as MULGRAPH (O'Sullivan and Bullivant, 1995) and PetraSim (Yamamoto, 2008). While these GUIs allow relatively quick and error-free set-up of models, they do not have advanced geological modeling and visualization capacity, and they also limit the user's access to the simulator's advanced features, for instance by constraining the model grid structure.

One of the difficulties faced in the creation of a GUI is that research institutions have in many cases developed local variants of TOUGH2, including the implementation of different solvers, thermodynamics modules, boundary condition implementations, and representation of sources and sinks, including geothermal production and injection wells.

Another approach is to use scripts in various programming languages. A recent addition to the arsenal of the reservoir modeler has been the creation of PyTOUGH (Croucher, 2011). PyTOUGH is a library of Python scripts which enables the user to potentially control all aspects of TOUGH2 simulations, from grid creation, file editing, to sets of model runs with varying parameters, and post-processing. PyTOUGH has the flexibility to process variants of TOUGH2, however it still requires a familiarity with object-oriented programming and the Python syntax.

Ultimately, the principal difficulty faced by all these approaches is that the conceptual model which forms the basis of the modeling system is often obscured in the implementation details. The design of TOUGH2 input files is not associated with the data it is representing. This hinders communication between reservoir modelers and geologists, and also the documentation and maintenance of models.

LEAPFROG Geothermal software

Leapfrog Geothermal modeling software has been developed to model and visualize geothermal systems in three dimensions. The models are based on mathematical interpolation functions, and this provides a grid free representation of the geological structure and numerical quantities such as temperature and pressure. The technology was originally developed for the mining industry (Cowan et al 2002) but recently the technology has been adapted for the geothermal industry (Milicich 2010).

The mathematical functions underpinning the models are computed using radial basis function interpolation. This approach has can be shown to be equivalent to solving the dual Kriging problem in geostatistics (Chiles and Delfiner 1999). The principal advantage of this approach is the resolution of meshes and grids used to represent components of the geothermal system are not fixed; they can be calculated as the isosurfaces or point evaluations of the underlying mathematical functions at arbitrary resolution.

There are two basic forms of models. Firstly, there are discrete models which describe quantities that occur in discontinuous units such as geology and alteration. Secondly there are continuous models that describe numeric quantities such as temperature, pressure, contaminant levels etc.

The discrete models are formed by a chronological combination of stratigraphic surfaces. These surfaces are modeled based on lithologic contact information from drill holes, which is supplemented by lines and point data drawn by a geologist. Since there are almost never sufficient direct measurements the geological interpretation added by the geologist forms a critical component in the creation of the geological model. However, it is possible to make several different interpretations and combine these independently with the quantitative measurements. This allows several possible scenarios to be actively compared and allows for models suitable for drillhole planning and reservoir management to be developed side by side from common data.

The continuous models take a similar approach to combining measured and interpreted measurements. Traditionally, temperature models have been interpreted by hand from the observed data, because there are usually insufficient measurements to produce isosurfaces that are not significantly influenced by the sampling regime. Allowing the user to combine interpretation with measured data is a practical way of approaching this problem.

An important feature of the software is that interpretation and measured data are maintained separately, allowing the quantitative data to be updated automatically when new measurements come to hand and the interpretation to be changed when appropriately (Cowan et al, 2004).

The data that can be imported and used in Leapfrog Geothermal, is not restricted to point data, but includes well logs, feed location and relative strength of the feed, structural orientation, and GIS data. Current developments in interoperability are focused on the direct import of the geophysical data sets of particular relevance to geothermal systems such as magnetotelluric data.

THE CONCEPTUAL MODEL

A conceptual model is a key component in a Leapfrog project. This is a grid free representation of all the quantities in the physical world that are used to describe the geothermal system. This includes the geology, alteration, temperature, pressure etc. It is crucial that this is maintained independently of the simulator used to compute the mass and energy balance equations, in order to allow the free exchange of information between all geoscientists involved in the modeling of the geothermal system.

Using mathematical functions to describe the conceptual model allows the easy translation of the best available data into a form appropriate for the end user. By keeping the conceptual model separate from the specialized tools used by the different practitioners in the industry (geologists, geophysicists, reservoir modelers, GIS specialists) it becomes readily accessible to all scientists and engineers associated with the geothermal field.

TOUGH2 AND LEAPFROG

Development of the Leapfrog TOUGH2 capability is proceeding as a collaboration between ARANZ, Contact Energy, and the University of Auckland, Department of Engineering Science Geothermal Group.

It was apparent at an early stage that it would require a considerable length of time to automate the generation of the input files to a level that would allow users to design or potentially access the entire content of TOUGH2 input files. In recognition of the practical needs of reservoir modelers an evolutionary approach to the translation of the conceptual model into TOUGH2 simulation files was taken. This approach leverages existing technology such as PyTOUGH where appropriate and focuses on progressively replacing the hand generated and scripting interfaces to TOUGH2.

An example of this approach was the decision to maintain compatibility with the MULGRAPH grid definition. TOUGH2 utilizes an integrated finite difference method (finite volume) to solve the governing equations. As such the input file describes the computational grid by connection distances and block volumes rather than in a Cartesian co-ordinate system (other than the direction relative to gravity). Most models require some defined co-ordinate system in order to view the modeling files in context. MULGRAPH uses a separate 'grid' file which allows for pre and post processing of TOUGH2 files, and associates an input file with map grid co-ordinates. Leapfrog has the capability to import and display MULGRAPH grid files, to query the blocks by on-screen selection. While Leapfrog will soon have the capability to generate TOUGH2 grids, it was considered necessary to keep this MULGRAPH compatibility during the development phase for the software.

The first version of the TOUGH2 interface released commercially in 2011 allowed the user to import and visualize TOUGH2 input files. Although limited in scope, this allowed the user to compare the reservoir model directly with the existing geological models that had been developed to assist with field management and target future geothermal wells.

The current system has progressed to the stage where users can automatically create the TOUGH2 input files and then subsequently hand-edit these files when required. The permeabilities are defined in real world coordinates and then translated to the TOUGH2 grids.

It is now also possible to set the initial conditions for a simulation. The efficiency of finding a numerical solution to non-linear differential equations depends critically on the choice of initial conditions, and the direct generation and documentation of these represents a significant advance.

Processing TOUGH2 output is the next step in developing the Leapfrog –TOUGH2 interface. The examples shown in this paper have utilized the capability of Leapfrog to read imported datasets. Modeling results are processed outside of Leapfrog then imported as csv files as columns of x, y, z, 'value', where x, y, z are the Cartesian co-ordinates of the block center, and 'value' is temperature or vapour saturation. Leapfrog can then compute and display isosurfaces for 'value'.

EXAMPLES

Alum Lakes model (Wairakei)

This model (Newson, 2009) represents a 2D vertical slice through part of the Wairakei system, and was designed in order to test the influence of reservoir pressure drawdown on surface features. In the context of this paper it is used as an example of how a model grid, the TOUGH2 input files (Figure 1), and output files in the form of processed modeling results (Figure 2), can be viewed in Leapfrog.

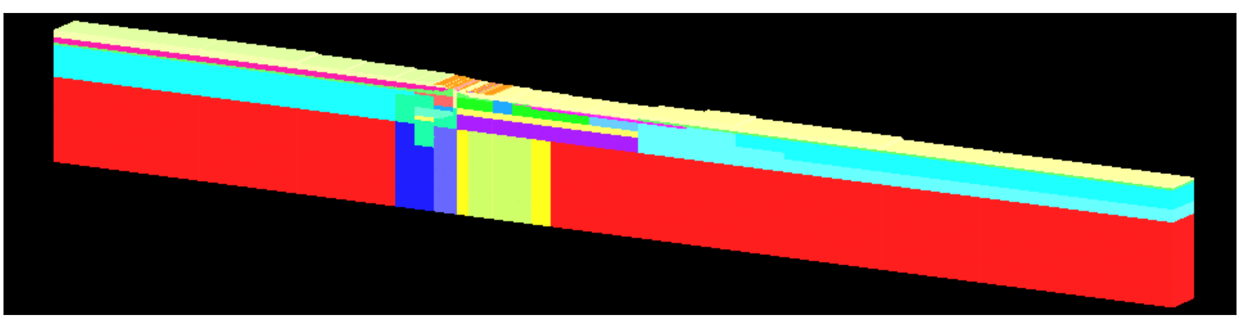

Figure 1: Alum Lakes model – TOUGH2 input rock domains.

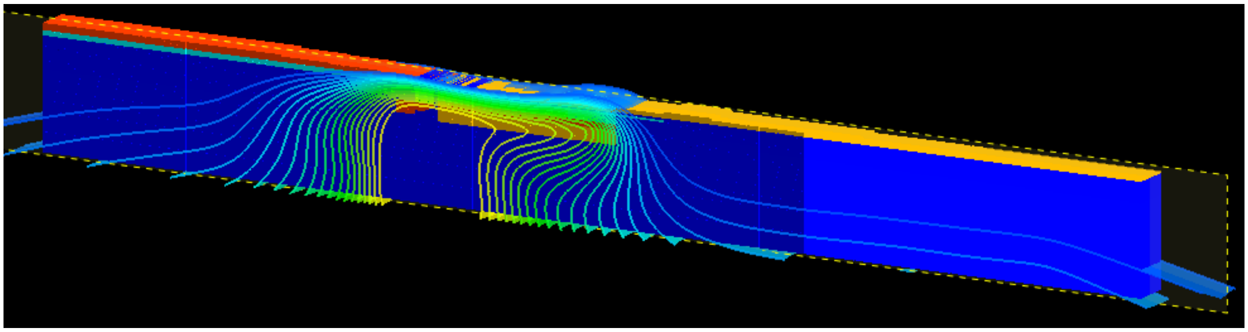

Figure 2: Alum Lakes model: Horizontal permeability structure (model input) and steady-state isotherms (model output). The isotherms relate a horizontal flow of hot water in the reservoir to the high horizontal permeability shown in yellow.

Tauhara model (Wairakei)

The grid for this model was created using PyTOUGH and imported into Leapfrog, where the rock domains were assigned from the Leapfrog geological model (Figure 3). In this case, permeability is strongly related to rock type, and the permeability domains were assigned directly from the geological model. The model grid structure is a regular rectangular 15 m x 10 m x 10 m blocks. The model represents a vertical 2D slice, and hence is only one column (10 m) deep. The top surface is stepped, representing the water table.

Because this is part of a larger system, the model boundary conditions have to represent the interface between the modeled volume and the larger system, and will have a large influence on the model output. It is very useful to have a visual indicator of a specified boundary condition. The example shown here is the bottom boundary temperature, which is calculated as smooth function of distance from ends of model, and imported into Leapfrog as discrete values for each grid column. The colour of the points is proportional to temperature value.

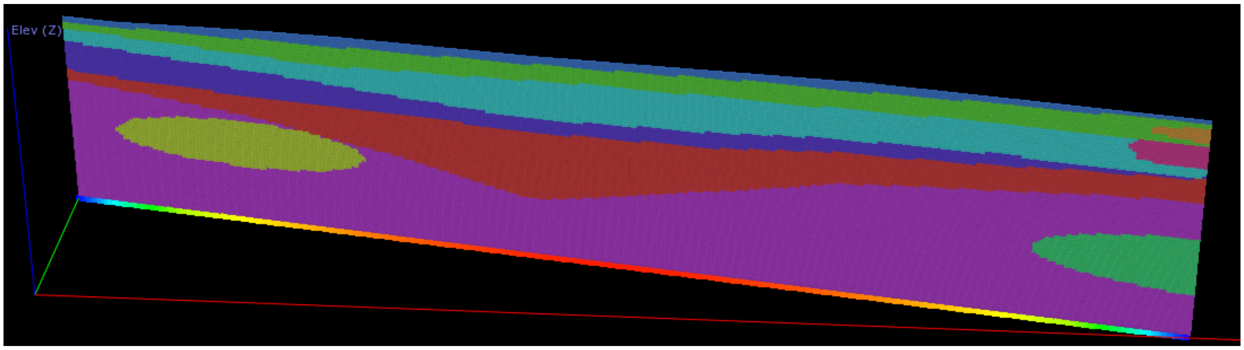

Figure 3: Model permeability domain assigned from the Leapfrog geological model. The conceptual temperature boundary condition at the base of the model is shown as a colour scale.

Ohaaki model

The Ohaaki reservoir model (Clearwater, and O'Sullivan, 2011) is used for reservoir management by Contact Energy. The first version of the model was developed in the late 1980s and since then has been more-or-less continually updated, refined, and recalibrated as more geological and reservoir information has become available. One consequence of this long history of development is a complex permeability structure has been developed to match the available field data. The model matches the field data and predicts future reservoir behavior well. One downside of this complex structure is that it is difficult to perform computer assisted calibration (inverse modelling). Current work on the model includes utilizing Leapfrog Geothermal to visualize and compare the existing permeability structure the conceptual model. The goal is to identify potential areas for simplification and improvement in order that more use can be made of inverse modeling techniques. This will allow the existing numerical model and hence its predictive performance to be further improved.

While there is capability in Leapfrog to implement a total over-ride of the existing model permeability structure with the relatively simple structure of the geological model, this is not an option because the model performs well, and the re-calibration would be extremely time consuming.

Visual comparison of modeling input data, simulator results (output data), and measured field data are required for model calibration. Three examples of data visualization using Leapfrog are described below.

Visualization of model two-phase zone and isotherms (temperature isosurfaces) show that boiling is occurring in approximately vertical cylindrical zones in the Ohaaki model (Figure 4), which spread out laterally in a trumpet-shape only in the shallow system, coinciding with the most elevated isotherms.

Leapfrog can visualize the relationship of model input with output, for instance Figure 5 shows a cross section with vertical permeability (from the input file) and the iso-saturation surfaces (model natural state output). This clearly shows a positive correspondence between high vertical permeability and shallow boiling.

System-wide comparison between the model and field data is crucial for model calibration, and presentation of results. Two sets of 3D temperature data are shown in Figure 6; the model output is shown as solid colour (volumes in 3D) and the interpreted temperatures from field data are shown as lines (surfaces in 3D). Spatial variation can be seen by stepping through successive cross sections at user-specified intervals.

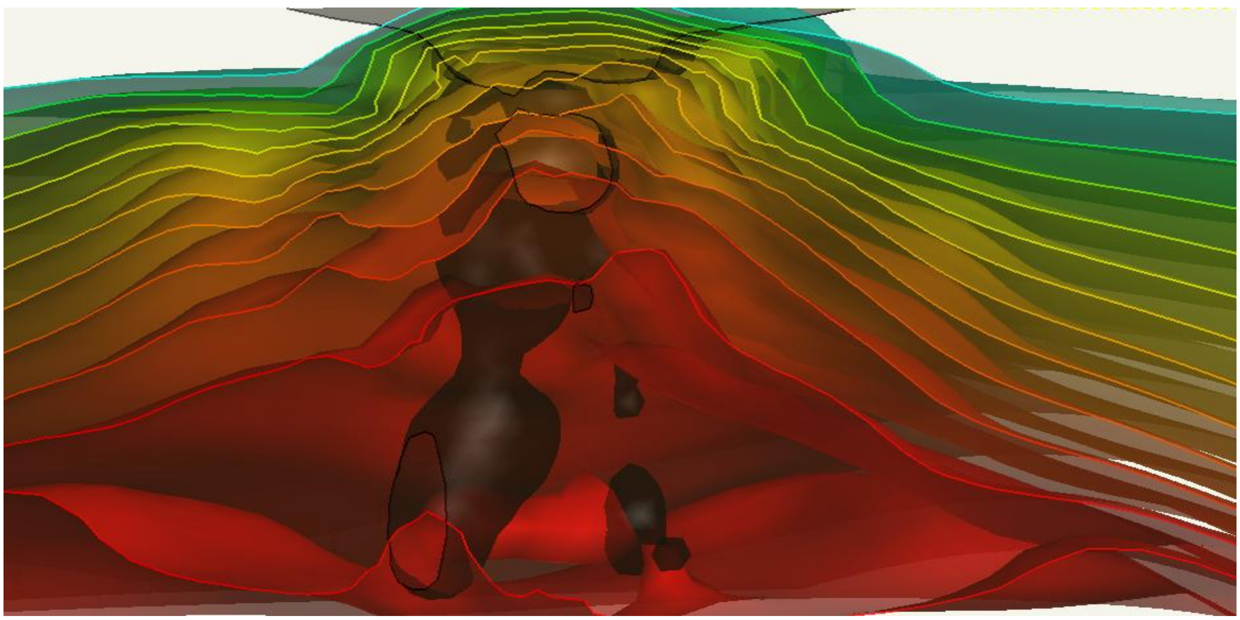

Figure 4: Two-phase zone (enclosed by the black surface) and temperature (two sets of model output data).

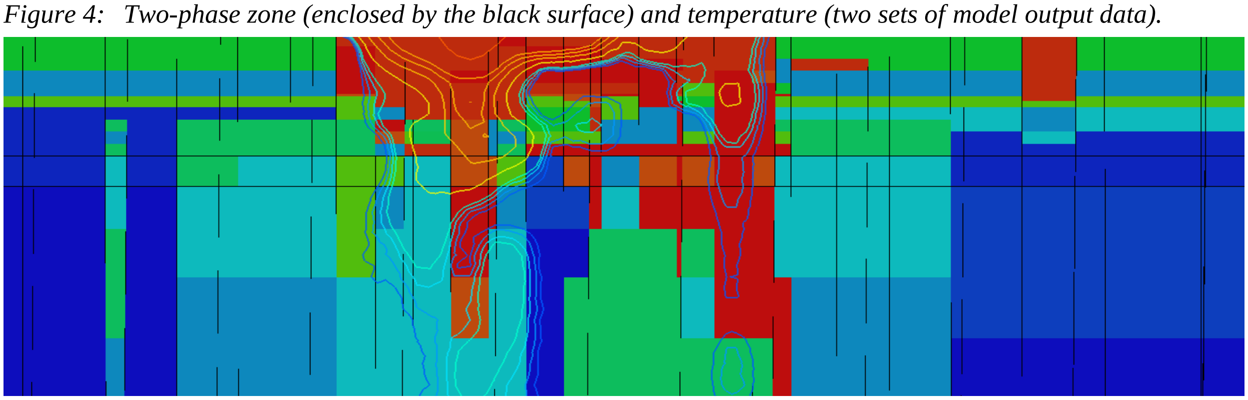

Figure 5: The model block parameter shown here is vertical permeability, with red indicating high, and blue indicating low permeability. Saturation iso-surfaces are similarly coloured, with orange indicating high steam saturation, and blue, low steam saturation. Maximum boiling appears to be related to shallow, high vertical permeability zones.

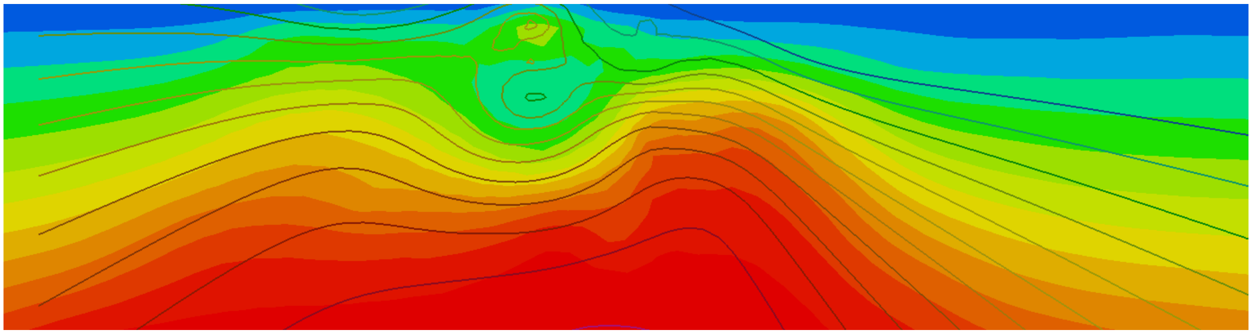

Figure 6: Isotherms on a vertical cross section. Model output is solid colour and interpreted temperatures from field data are shown as lines.

CONCLUSION AND FUTURE WORK

Capability to interface with TOUGH2 reservoir simulation software has been added to Leapfrog 3D geological modelling software, allowing processing and visualization of natural state modelling input and results.

Future work includes post processing of time-dependent model output and individual well data; conceptual modelling; grid generation and model design; and model calibration.

Current capability with TOUGH2 models is limited to the block-centered properties (primary variables) of natural state models which do not vary over time. Work is proceeding on processing flows, and primary variables which change over time.

It is intended that the geoscience and reservoir data can be used to build conceptual models of the entire system which are consistent with known and interpreted reservoir conditions, providing a much-needed integration of geoscience and reservoir data. The ability to construct reservoir models directly from these conceptual models that honour all the data will be a powerful reservoir modelling tool.

Grid generation within Leapfrog will provide choices of grid which are compatible with the conceptual model. Grids may also be easily modified and refined within the Leapfrog environment, simplifying the process of model development.

There is potential to develop inverse model calibration in Leapfrog, given that the geoscience and reservoir data used for calibration is already contained in the modelling software.

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