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MODELING THE OHAAKI GEOTHERMAL STSYEM

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ABSTRACT

The Ohaaki geothermal system lies within the Taupo Volcanic Zone (TVZ) in the North Island of New Zealand. Since the early 1980s, a series of numerical models of the Ohaaki geothermal system have been developed at the University of Auckland in collaboration with Contact Energy and its predecessors. The simulator used is AUTOUGH2 (adapted from TOUGH2) and the extra capabilities of this simulator, plus the use of PyTOUGH (a library of Python scripts), have been invaluable.

Natural state simulations are used to compare the model results to the temperature data for the pre-exploitation state of the reservoir. Then production history simulations are carried out, and model results for pressure, temperature, CO_2 flow, and enthalpy are compared to data from the well testing period, the recovery period, and the production period.

Maintenance and improvement of the model is part of an ongoing effort to represent the Ohaaki system more accurately, enabling the model to be utilized as a tool for reservoir management and to predict the future behavior of the resource under various scenarios.

THE OHAAKI SYSTEM

The Ohaaki geothermal system lies on the eastern margin of the Taupo Volcanic Zone (TVZ). The Waikato River bisects the system, dividing it into the West and East Bank areas (see Figure 1). There are two separate upflow zones for each of the East and West Banks. Ohaaki (along with the other systems within the TVZ) is a high-temperature liquid-dominated hydrothermal convective system. The driving force of such a system is convection of water driven by density differences. Heat and mass are transported through the permeable rock of the reservoir by convection of water and steam. Ohaaki has a base temperature in excess of 300ºC and a large gas (CO_2) content. More information on the system can be found in Hedenquist (1990).

The basement of the Ohaaki system is a pre-volcanic greywacke, which down-faults to the north-west. This is overlain by a volcano-clastic sequence interspersed with dacitic and rhyolitic volcanic domes and flows, with complex permeability and porosity distributions. The two main production reservoirs are the Wairoa formation at depths of 400 to 1200 m field wide, and the Tahorakuri formation on the West Bank below depths of 1500 m. Details on the structure and stratigraphy of the field are outlined in Wood et al. (2001) and Rae et al. (2007).

OHAAKI POWER STATION

Drilling commenced at Ohaaki in 1965, with a total of 44 wells drilled between 1966 and 1984. There was an extended period of well testing and recovery up to 1988, when the Ohaaki Geothermal Power station was commissioned [Lee and Bacon (2000), Clotworthy et al. (1995)]. There are now over 65 wells drilled in the area.

The plant commissioned in 1988 was 116 MW_e and during the first 5 years of production, generation was maintained at ~100 MW_e. In 1993, the available steam began to decline. A deep drilling program was undertaken in 1995, which identified high temperatures and permeability in the deep volcanic formations underlying the West Bank [Lee and Bacon (2000)]. This was relatively successful; however, steam supply continued to decline. A second deep drilling program also focused on the West Bank was undertaken in 2005–2007 (Rae et al., 2007), allowing generation output to be maintained at about 60MW_e.

RESERVOIR MODEL

Grid structure

Over time, a deeper understanding of the reservoir has been developed based on data gathered by various geoscience techniques and from deeper drilling. Also over time, computational power has increased, and so it has been possible to make the reservoir model more and more refined. Earlier grid structures for the Ohaaki model have been described in Blakely et al. (1983), Newson and O'Sullivan (2001), Zarrouk et al. (2004), and Zarrouk and O'Sullivan (2006). The reservoir model discussed here is the "2011" model described in Clearwater et al. (2011).

The size of the model grid is chosen to include as much area as is needed for recharge to the system, and as much depth as is feasible in terms of the limitations of the equation of state for H_2O/CO_2 available in TOUGH2. The deepest well drilled at Ohaaki reaches a depth of almost 2.6 km, and the base of the model is set at 3 km depth.

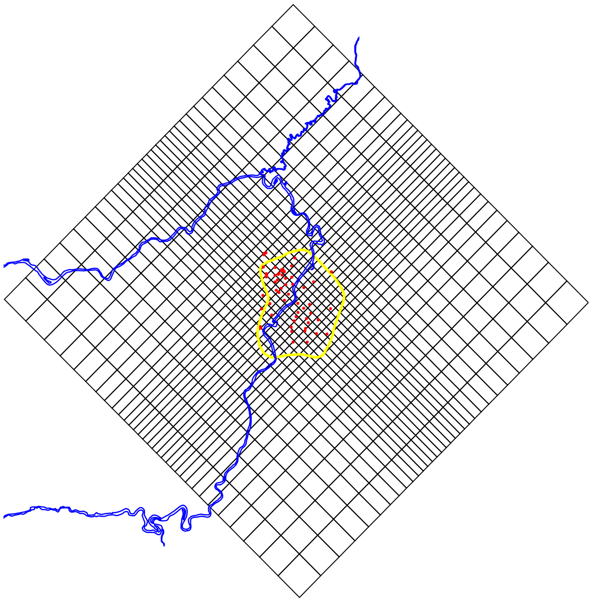

Figure 1. Plan view of the Ohaaki reservoir model grid. The blue line is the Waikato River, the yellow line the resistivity boundary, and the red dots show well-head locations.

The grid has been rotated so that columns align with the dominant faulting direction – NW-SE. The model consists of 23 layers, each with 992 elements, plus one atmosphere block, leading to a total number of elements of 22817. The grid is roughly a square covering 16 km by 15 km. Figure 1 shows a plan view of the model grid.

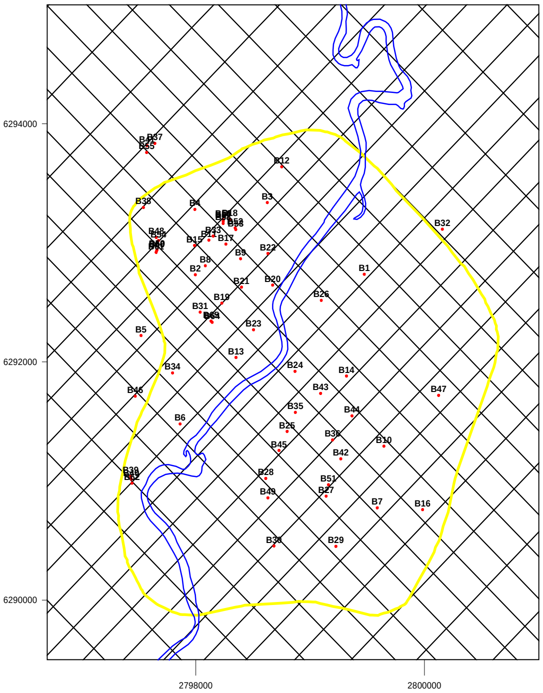

Figure 2. Close up of the model grid. The yellow line is the resistivity boundary, the red dots show well-head locations and the blue line is the Waikato River. The West bank lies on the North-West side of the river, the East bank on the South-East side.

The greatest refinement of the grid occurs within the reservoir resistivity boundary. The aim is to allow each well to be placed in a separate block and to avoid 5-sided blocks or connections that are not orthogonal. The gradual expansion of block size goes from 250 m by 250 m in the central borefield, to 1 km by 1 km at the outer boundary of the model. A close-up view of the grid is shown in Figure 2.

The layer structure of the model is shown in Figure 3. The top four layers are 100 m thick. There is then a refinement down to a layer of 20 m to give a good resolution of the Ohaaki Rhyolite, which acts as a fluid pathway. After that, the layers increase again to a maximum thickness of 250 m.

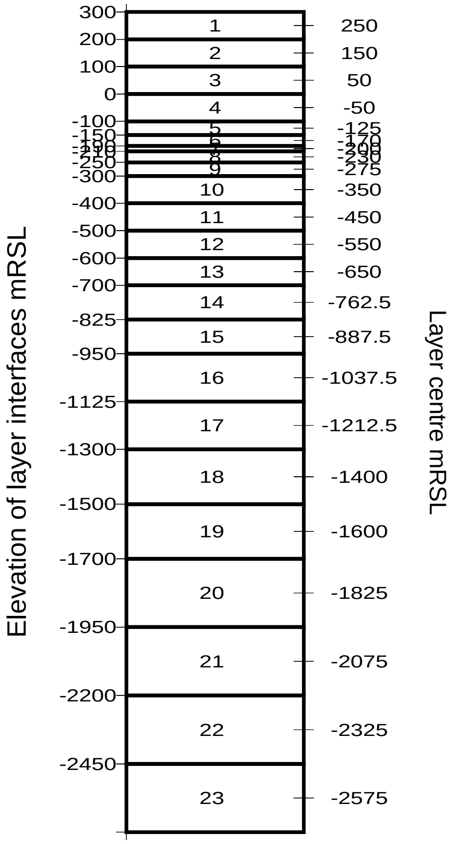

Figure 3. Vertical layer structure and layer names.

Boundary Conditions

Due to the large area of the model (and also from observing pressure changes at the boundary blocks), the model is thought to be large enough to capture all pressure changes created within the borefield and within the whole of the hydrothermal convective regime, and so all side boundaries are treated as closed. This is also a reasonable approximation for Ohaaki, because of the high CO_2 content and large boiling zone. The pressure changes in the reservoir get buffered by the expansion and contraction of the boiling zone, and hence do not spread to the edges of the model.

The top layer of the model follows the surface of the water table. The temperature and pressure of this top layer are fixed at atmospheric conditions – a temperature of 10°C, pressure of 1bar. This is a suitable approximation if the water table does not vary too much during production, and lies at a shallow depth. Over the bottom boundary mass, heat and CO_2 are injected. These are varied as calibration proceeds.

A background conductive heat flux of 120 mW/m² is used— typical of the values found throughout the TVZ. This heat flux is increased in blocks close to the main reservoir, representing the greater heat flow anomaly associated with Ohaaki. The mass inflow at the base of the model represents the upwelling fluid near the base of the convective plume which has not been captured within the model. The CO_2 is injected at an average mass fraction of 2.5%— which is representative of the amounts found in wells at Ohaaki.

A summary of the total heat, mass, and CO_2 injected into the base of the model is shown in Table 1. The total amount of carbon dioxide injected gives an average flowing mass fraction of 2.5%. A total heat input of 119 MW is applied to the model, which is close to the natural heat flow of around 100 MW (Allis, 1980), but as there is large uncertainty around this value, the model is reasonable.

Table 1. Total flow into the base of the model.

	Enthalpy (kJ/kg)	**Temperature (°C)**	**Total**
Mass	1430	314.4	68.32 kg/s
Heat	-	-	39.64 MW
CO_2	1430	310.51	1.7 kg/s

Populating grid blocks

Geoscience data is invaluable in helping to decide what rock properties should be assigned to each element in the model. Recent collaboration with ARANZ and GNS Science and the use of the LEAPFROG geological modeling software has introduced an automated way of extracting the geological model rocktypes and applying them to the elements in our TOUGH2 model. New TOUGH2 simulation input files can be created within the software and results can be visualised (e.g. Newson et al. (2012)).

The LEAPFROG software is a three-dimensional geological mapping package that allows a new integration between modeling and earth science. Reservoir modelers can view a compilation of different geological, geophysical and geochemical data to compare and relate back to the reservoir model. A MULGRAPH [O'Sullivan and Bullivant (1995)] grid and TOUGH2 input file can be loaded and any rock parameter visualized, and the geological model can be integrated into the reservoir model—geological lithologies can be exported on to TOUGH2 grids.

Simulator

The simulator used for this model is AUTOUGH2. This is a local version of TOUGH2.2 developed at the University of Auckland. Details of the development of this simulator can be found in Yeh et al. (2012). The main improvements compared to TOUGH2.2, in a geothermal reservoir modeling context, are the inclusion of all EOS modules in a single executable, increased allowable numbers of blocks and connections, and the inclusion of new well types for production and future scenario simulations. EOS2 is the fluid property module used, first because Ohaaki is a gas-rich reservoir, and second because no EOS module is available in TOUGH2 for handling the interaction of air, water and CO_2 at the temperatures encountered in the reservoir. The coefficient used for Henry's law is the original version developed by O'Sullivan et al. (1985), and is a slightly different correlation to that used in TOUGH2.

For the steady-state simulation, the GENER types used are those in the original TOUGH2-MASS, HEAT and COM2 (CO_2). However for production and future scenarios, we have had to implement new GENER types in order to represent the complicated production and reinjection requirements.

NATURAL STATE MODELING

Implementation

To get initial conditions for the Ohaaki reservoir model, a natural state simulation must be performed first. This is to try and reproduce the conditions of the reservoir before any production or drilling occurred. The TOUGH2 model is set to run to a large time step, usually 1.0E+15 seconds is deemed to be large enough, until all primary variables have stopped changing and the simulation is in a steady state. Permeability and deep inflows are then adjusted iteratively until the model matches the observed temperature distributions.

Temperature Results

Comparison of the model result with data for a well on the West Bank can be seen in Figure 4. There is a temperature inversion at 0 mRL, which is due to the Ohaaki Rhyolite formation allowing cold groundwater to seep into the main reservoir. Early wells drilled on the West Bank feed from the Intermediate reservoir, about 400–1200 m depth. Newer West Bank wells are feeding from levels between 1600 and 2400 m deep. The model shows a reasonable match to the field temperatures in this area.

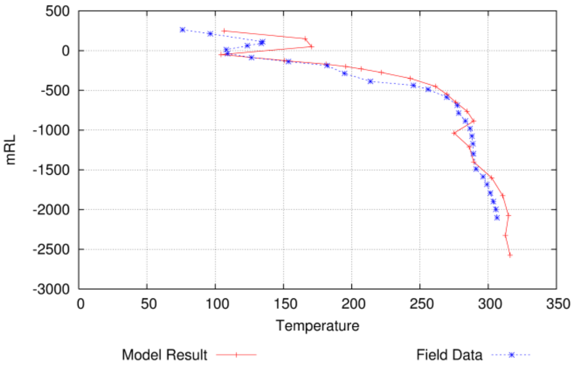

Figure 4. Temperature profile for a typical West Bank well.

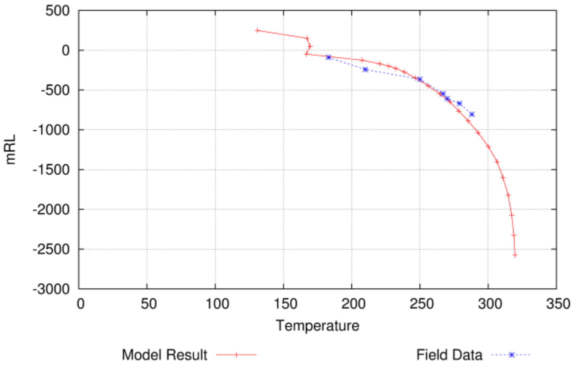

Figure 5. Temperature profile for a typical East Bank well.

Model results for a typical well on the East Bank are shown in Figure 5. East Bank wells all produce from volcanic formations between 500 and 1200 m deep. No significant permeability has been found any deeper, and so most new drilling is focused deep on the West Bank. Field data for the East Bank is more limited than for the West, but the model is showing a good match to the data.

PRODUCTION HISTORY MODELING

Implementation

To simulate the production history, we locate the coordinates within the reservoir model pertaining to each of the feed zones for each well. Each block containing a feed zone location is then assigned a time-dependent mass production rate (using a MASS generator), taken from measured field data. This sounds simple, but there has been considerable difficulty in extracting this field data.

Due to the limitations of accurately measuring two-phase flow at the time of commissioning the power plant, a continuous record of production data from individual wells at Ohaaki is not available. Instead, the total combined mass and total production enthalpy data (for each group of wells connected to each separator) is recorded.

For each well, the operating well-head pressure is recorded regularly, along with the status of the well (whether it is on production, on bleed, closed, reinjecting, etc.). The number of days per week that the well is on production is recorded, and thus the proportion of each week that each well is open is available. Individual wells are output tested every six months, and these tests provide characteristic curves for each well, from which it is possible to derive a flow rate given the measured wellhead pressure. These tests also provide information on the proportion of total flow each well is providing to the separator

From the calculated flow rate and the open times for each well, we can calculate a weekly mass flow, by multiplying the mass flow per week by the proportion of open time. These proportions are used to calculate weekly flows for each well to be used in the model as the time-dependent mass flow rate.

For multi-feed wells, the production is further broken down by assigning a proportion of the total flow rate to each feed.

Neither of these two procedures (obtaining continuous records of well by well production using occasional output test data to assign separator flows to individual wells, and assigning set proportions to multi-feed wells) is entirely satisfactory. The well characteristic curves and proportion of the contribution from each well to the separator vary from one output test to the next, and the enthalpy response of the model is quite sensitive to flow rate. So this approach to creating production rates may lead to incorrect model enthalpies.

Entering the injection data into the model is much simpler and more accurate: continuous injection rates for each injection well are provided. These are implemented as MASS just like production, but with a negative generation rate. One hundred percent of remaining separated geothermal water (SGW) is reinjected at Ohaaki, 30% of the condensate is reinjected, and the rest is lost to the atmosphere through the large natural draft cooling tower.

The period simulated is from 1966 until 2010. This encompasses early well testing, a recovery period, and commencement and continuation of the power station production.

Calibration of the production history is performed by comparing pressure, enthalpy, and CO_2 histories. Porosity, permeability, and adjustment to the boundary upflows is made as required. Pressure data are continually available from monitoring wells throughout the field, and well output tests performed every 6 months provide individual well data for pressure, production enthalpy, and CO_2 flow as a percentage of total flow rate.

At Ohaaki, there are very few significant surface features (vents, hot springs, etc.), and only one of them—the Ohaaki pool—is represented in the reservoir model. The Ohaaki pool at natural state discharged at a constant rate of about 10 kg/s. After early well testing and production, discharge from this pool fluctuated, then ceased. The bottom of the pool has since been cemented, blocking natural fluid flow, and the pool is now filled with runoff from other wells discharge. Because the initial flows were relatively constant, and the flow is still 10 kg/s (although artificial), a MASS generator of 10 kg/s at the depth in the reservoir that the fluid is known to come from is applied for natural state and production simulations.

Contact Energy supply heat to local timber drying companies. Prior to 1997 two-phase flow was supplied for timber drying from a well separate from the production field. The timber drying facility required a specific amount and dryness fraction. This was applied using a POWR generator (a new well type created in AUTOUGH2). In 1998, the well providing the timber plant was hooked up to the production system, and no excess steam was available to the timber drying plant. Instead, some of the SGW, rather than being re-injected, was supplied, so the fluid going to the timber drying no longer needs to be included in the reservoir model.

Results

Pressure

The model pressures during the well testing and production period show a good match to the field data, especially for most new, deeper wells on the West Bank. The model result for block eca11 is shown in Figure 6. Layer 11 in column eca has been allocated as the feed zone for this well, 750 m deep. The model follows the pressure drawdown reasonably, showing the correct trend but a bit too much drawdown.

Drawdown history from deeper-feeding West Bank wells is shown in Figure 7. The model results in this plot are taken from layer 19 (1900 m deep) in column eqe. There are two wells that feed from this block, the first being BR15 during the early well testing and production period until 1995, to which the model shows a good match. The model then shows the correct amount of drawdown until 2007 onwards, when BR60 started producing. The latest drawdown pressure match is reasonable.

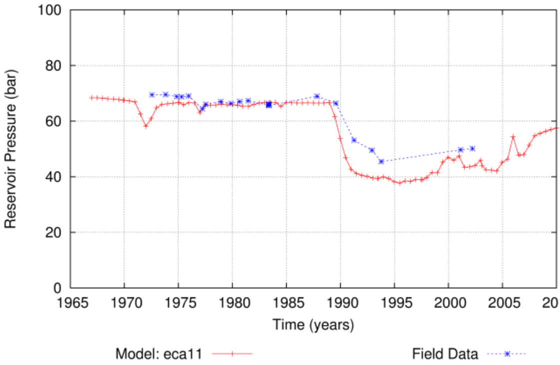

Figure 6. Pressure vs. time for a typical shallow East Bank well.

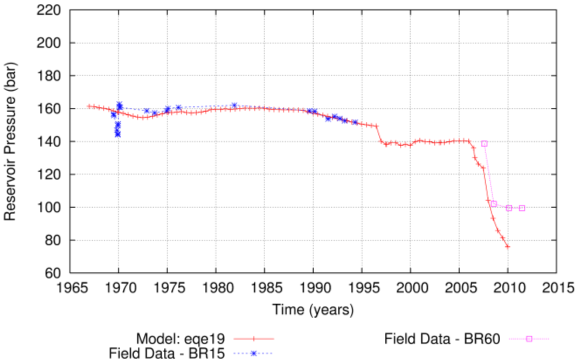

Figure 7. Pressure vs. Time for a typical deep West Bank well.

Enthalpy

The match with field data is quite varied. In general the well-by–well performance of the model match is reasonable. However, further calibration is required for some areas where not enough boiling is occurring—especially over a period over 1990 to 2000, as seen in Figure 8.

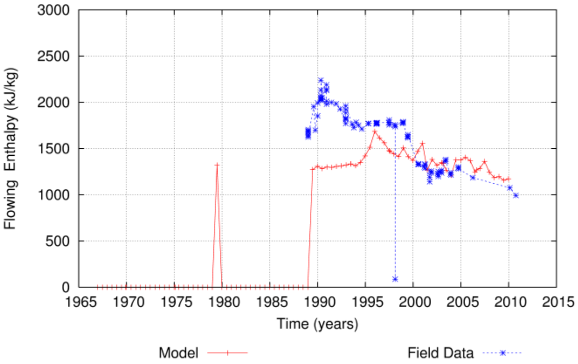

Figure 8. Enthalpy result for a typical East Bank well.

Enthalpy data is quite variable from well to well—the East Bank wells tend to have an initial increase in enthalpy followed by a slow decline, whereas the West Bank wells start out at a lower enthalpy that stays constant or increases over time.

CO_2 percent mass fraction

The model results for carbon dioxide content over time are very mixed in quality. For some wells, the model match is very poor, but often this is associated with a mismatch in enthalpy which can hopefully be improved by further calibration. For other wells, the match is very good, as seen in Figure 9. Overall trends and magnitudes averaged field wide are reasonable.

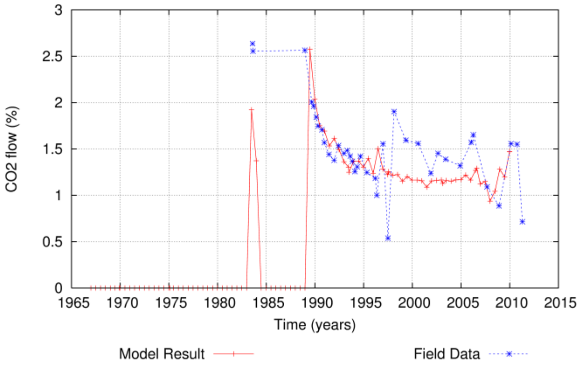

Figure 9. The CO_2 vs. Time for a typical West Bank well.

FUTURE SCENARIO MODELING

The Ohaaki reservoir model is currently being used as a tool for reservoir management. Various drilling/production/injection scenarios are carried out with the model, over both short and long-term time scales, to get an understanding of how the reservoir may behave in the future.

Implementation

The final conditions from the history-matching simulation are used as initial conditions. All boundary conditions remain the same as for production and natural state conditions. Future scenarios for Ohaaki may contain existing wells, new make-up wells, or a combination of the two. The production requirements may be restrictions on steam or mass take or both from different areas of the field. The reinjection requirements can be complex combinations also. Make-up wells are added or removed over time to meet the mass and steam requirements. Wells are run on deliverability, so each well needs a cut off pressure and a productivity index (PI). The PI is easily automatically obtained for existing wells by using DELG, a mass type in AUTOUGH2 (Yeh et al., 2012). PI for make-up wells is determined from similar existing wells PI's. Cut-off pressures are obtained using a well bore simulator.

CALIBRATION

Aside from the field data extraction difficulty outlined earlier in this paper, another particular problem has been found when trying to calibrate the Ohaaki reservoir model. This difficulty appears to be particularly severe for models with a CO_2/water equation of state, but could be due to the interaction of any liquid and gas phases, since it has also been seen on layers near the unsaturated zone when using an air/water model.

In some cases, a small change in the permeability structure resulted in a particular model block needing to change from a two-phase state to compressed hot water. In the Ohaaki model, the high CO_2 content can often make this phase change difficult, and the natural state simulation takes a very large number of time steps to complete. Or, the time step may get so small that the simulation may never reach completion.

Unfortunately, this problem makes it difficult to use the inverse modeling code iTOUGH2 (Finsterle, 1993) to assist with model calibration, and makes it hard to determine the sensitivities of the model to variation in parameter values. This is where PyTOUGH [Croucher (2011)] has been invaluable—Python scripts can be used in conjunction with inverse modeling software, such as PEST (Doherty, 2000), to ensure that only a true steady-state simulation is reached before any parameter changes are made. PyTOUGH also enables automation of the calibration process. A script can be used so that if a block is holding up the simulation, the gas saturation or another property of that block and its neighbors can be checked. Then, depending on what is holding up the simulation, we can push the saturation to either single phase or two-phase in the INCON file, or alter permeability in the TOUGH2 input file. This can all be performed without the user having to intervene.

FUTURE WORK

The current refinement of the shallow layers in the model (100 m thick) is too large to accurately capture shallow pressure transients, and having the top surface as the water table constrains the table level to be unrealistically fixed. Shallow pressure changes can be very important in a geothermal context, to look at any consequences of fluid extraction such as ground deformation. The model is currently being refined in the shallow layers, and the top layer's elevation updated to reflect the surface topography rather than the water table. To continue having CO_2 in the model will mean having an unsaturated zone filled with CO_2 rather than air.

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