GRC Transactions, Vol. 42, 2018

Adding a 4th Dimension to 3D Geomodeling – Using Numerical Simulation

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Keywords

3D, geologic model, numerical simulation, natural state, exploration, resource potential, reservoir management, conceptual model, resource estimates, geomodelling

ABSTRACT

Technological advances have made data interpretation possible that was not possible in the past, and in the process have rendered the conceived concepts from previous technologies invalid. Natural state modeling is one technology that has made such advances. It is now possible to easily and accurately render geologic, structural, geophysical, geochemical and mineralogical information in manipulatable 3D software platforms, creating a more meaningful representations of geothermal reservoirs and detailed conceptual models. Additionally, there have been advancements in the understanding of the correlation of these types data with temperature. Therefore, even with limited direct data (e.g. temperature surveys from wells), more accurate 3D temperature maps and surfaces can be developed over a larger area in a new geothermal field, with a combination of direct and indirect data, much earlier in the exploration process. A more robust analysis through numerical modeling is possible, if the elements of the conceptual model are captured.

Using a numerical simulator, every assumption used in building the conceptual model separately is tested within the context of a physical system to verify that the model is internally consistent and conforms to the laws of physics. Numerical modeling includes the fourth dimension, of time, as the field starts from nothing and must develop in the model. Understanding what forces led to a particular temperature value at a particular location, beyond the static measurement at that location, allows for holistic understanding of a dynamic system. Results of the natural state modeling force changes to the conceptual model to allow the temperature to develop through time, into the current temperature configuration. The results can also alter the expected temperature distribution to a larger, smaller or different shape. The numerical simulation becomes part of the geological modeling effort in an iterative process where the combined effort is greater than the sum of its parts.

1. Introduction

In early numerical modeling (early 1980's) there were no natural state models, which is a stabilized model of the geothermal system prior to exploitation. Starting conditions in most early models were not stable, so the natural state model was developed as a method to produce a stable steady-state model prior to completing a production history match. The natural state model is now considered the starting point for the model of the working geothermal field and is completed as standard practice. At first, the natural state model consisted of creating an initial state and running the model for a few hundred years from this point until it reached a state of pressure equilibrium, but normally this time was too short for heat transfer to stabilize. The shorter run time was primarily due to the slow performance of computing machines from that time, the best of which had far less power than today's mobile phones. Running the models for more than a few hundred years was time and cost prohibitive. As computing migrated to PCs, costs came down, and performance increased by orders of magnitude, it followed that natural state run times lengthened and are now routinely run for model periods of hundreds of thousands to a million years. Natural state models assure stable starting conditions that match the actual distributions of pressure and temperature for the next steps in modeling the working field. For the most part, stable steady-state initial models are created for developed fields that have a history of production over some time. The models are created in preparation for a pressure history match to the field conditions as measured through time. A good natural state model is a requirement for a quality history matched numerical model for use in reservoir management.

In the past, natural state modeling was considered a sub-set of numerical modeling that included history matching and forecasting. Accurate forecasting required calibration, which came from the match of pressure and enthalpy responses calculated within the model to those measured in the working field. Over time, natural state modeling has gone from non-existent, to short runs of pressure stabilization, to longer run times that included temperature stabilization, then running through the full placement of the heat envelope, and now with temperature projections that take into account geoscience and geochemistry using only a limited number of wells, or in some cases, not even needing wells. In the process, natural state modeling has evolved not only to be a part of the overall field simulation, but also into a separate form of modeling that adds tremendous value in its own right, in a field development time frame, well before conventional numerical modelling is possible. Now numerical modelling can be an effective tool even before a production history is established, in early development and exploration phases.

2. Traditional Numerical Modeling

Forecasting the extent and productive capacity of geothermal reservoirs has evolved, from volumetric calculations, to decline curve analysis, radial flow theory, and then to lumped-parameter models. Early lumped-parameter models were based on energy and mass balance equations in a single 'tank' with pressure dependent storage capacity and recharge; no geology was included. As modeling evolved into modern distributed-parameter or multi-tank models, the importance of the geology started to emerge, but still in early modeling, the number of blocks and layers were limited, and geologic features could not be included with any accuracy.

These early methods and models began with obtaining a match between the model results and actual output of the field during its history, so that some confidence could be obtained from the subsequent forecasting output of the model. This began like a decline curve equation, but with many more polynomials and added complexity. Note that it is possible for a curve to be matched using many and various types of equations. Numerical modeling became focused on fitting the curve, and very accurate curve fits are now possible, although not unique. As computing power continues to increase, more modeling blocks and additional features such as complex equations of state and wellbore modeling can be added and the virtual equation gets to a higher order, creating a match and forecast that is more precise for the curve or situation being matched. Once a field match has been accomplished, accurate forecasts can be made, along with the determination of future field production issues and their timing. For financing purposes this matched numerical model is adequate and is used extensively.

With the addition of a large numbers of model blocks and continuing increases in computing power, a different level of numerical modeling is available for reservoir management. While a non-unique match is adequate for a simple forecast, if changes are contemplated such as from a major expansion, a new injection strategy, water augmentation, or other major change, the ‘equation’ obtained by the history match may not be valid after the change, and the forecast will not be valid either. In order for the model to be used for reservoir management, the solution must be constrained using detailed inputs from the field data. The more constraints added to the model, the more distinct and therefore accurate, and flexible, the solution becomes. To obtain results useful for reservoir management, more detail is required, for example feed zones must be accounted for individually, as do well production, outflow, recharge zones, geologic zones, and rock types. A strong natural state model is also required; every input to the model must fit what is known and be logically correct. In a field management model no numerical ‘tricks’ can be used to generate a match. In this version of the numerical model, the conceptual model of the resource that includes the geologic information is as important of an input as the production data and must be honored. The information from the conceptual model of the resource is captured in individual model blocks using the parameters of permeability in three directions, density, porosity, specific heat, and wet heat conductivity. The geologic model must be included in the setup of the numerical model and they must be reconciled through the modeling in a back and forth process.

In completing a model to this level of detail, it is not only possible to improve management of the existing field, but the model can be used to discover additional reservoir areas or to extend the current production area. For example, a recent model completed for the Momotombo field in Nicaragua, which has been on production since 1983, revealed that there is pressure support coming from the northwest edge of the field (Kaspereit et. al. 2016). On inspection, the source of the pressure support was interpreted to be northwest to southeast along a major fault into the northwest side of the field (yellow arrow, Figure 1). This identified the most advantageous location for make-up wells, injection relocation in weaker areas, as well as expansion potential.

In the above example, input from individual wells at the edge of the field were shown to have higher pressure support than was sustained in the initial model configuration. The conclusion was that there was additional reservoir or recharge coming from that edge. This type of realization can direct exploration outside of the working field. The numerical model defines the potential size of a new area, and the geologic inputs (i.e. recognition of a major fault conduit) define the shape and location of support coming from those new areas.

In developing the reservoir simulation mesh, the authors were required to revisit the accepted conceptual model of the Momotombo field, and this was done directly in numerical model, using the production data from the working field and older exploration results from reports and plan maps denoting faults. No 3D geologic or conceptual model was available to inform the numerical model. But finding these particularities reveals the power of capturing the geologic model as closely as possible in the numerical model parameters.

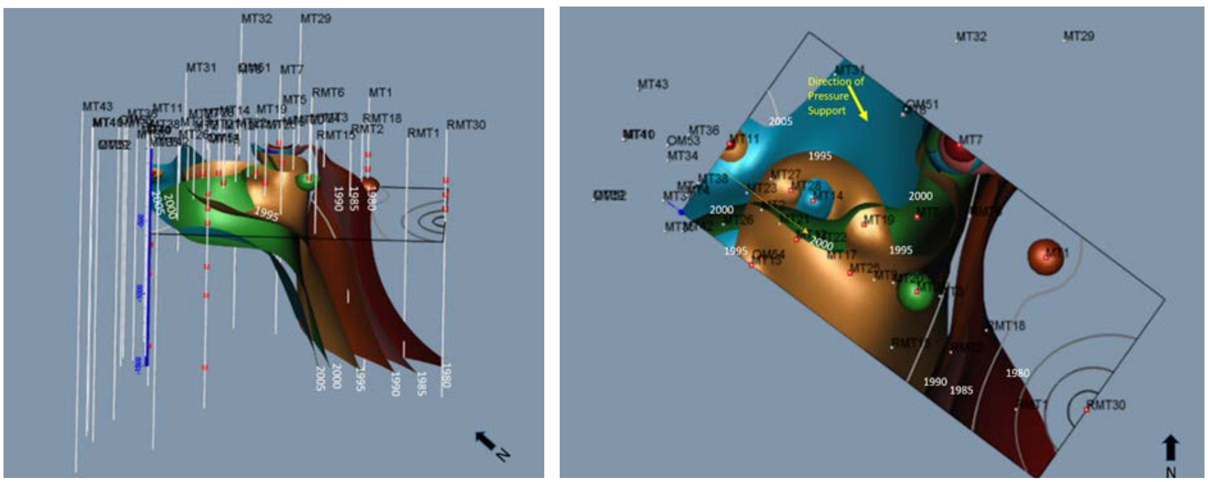

Figure 1. Cross-sectional view (left) to the northeast (model north), showing the 205°C isotherm migrating from southeast to northwest through time as an influx of cooler meteoric water occurred. Each 205°C isotherm surface represents a data set collected every five years, from the period 1980-2005. Plan view (right) of 205°C isotherms for 1980-2005 (every 5 years), showing localized resistance to northeast migration of cooler meteoric water influx, likely caused by hot fluid recharge from the area north of MT-31 in the 1995 surface, indicated by the yellow arrow (from Kaspereit et. al. 2016

3. Conceptual Model Integration

3D geologic modeling software is now commonly used to visualize, verify, and develop the conceptual model of geothermal systems. With the growth of this type of modeling, the geology and other elements of the conceptual resource models have become digitally accurate and can be used to constrain the numerical model further than previously possible, enhancing the interplay with the numerical model. Some software allows a direct interface between the two, although currently only one way, from the geologic model into the numerical model. This interplay has enhanced the reservoir management and expansion potential in existing fields.

4. Natural State Modeling

As the 3D geologic models and numerical modeling together were used to improve the traditional reservoir simulation (completed after there is a production history to match), it followed that they should be combined early in the modeling effort, at the natural state stage. First at the traditional level, the synergy was very apparent, as shown in the Momotombo example given above. The 3D geologic/conceptual model before drilling includes temperature surfaces created from measured temperatures at the surface, from shallow TG wells or shallow temperature surveys, or inferred from fluid chemistry of hot springs, or interpreted using geophysical information as proxy for temperature. Other information within a 3D geologic/conceptual model includes estimated aquifer depths, rock types, geologic structures, alteration patterns, and geophysical interpretations. The conceptual model will also include interpreted flow patterns, which can be verified within the numerical simulation. Magnetotelluric (MT) surveys providing rock resistivity information are a common tool, providing information on the location, potential size and even temperature of the underlying reservoir. The intent of a natural state model traditionally was to provide a stable initial model from which to commence the numerical modeling of the working field. But with the advent of advanced 3D representations from exploration information, it is possible to make conclusions about the resource through numerical modeling even with no production information. The numerical model adds the physical constraint of time, improving the interpretation. All physical constraints must be honored in a dynamic numerical model, as opposed to within a static geologic model. Therefore the natural state model is a way to verify assumptions made in construction of the conceptual model. Once the conceptual model and numerical model are combined digitally, correlations with temperature can be made with geophysical data within areas with wells and temperature extended to areas were only geophysical data exists. This has led to the use of natural state modeling with 3D geomodeling for use in exploration.

While pre-production models are obviously less accurate than a full numerical model from a working field, they provide the opportunity in the exploration stage to run a forecast to determine possible reserves, which is likely more accurate than a volumetric calculation or power density commonly used at this stage. The reserves estimate acquired through reservoir stimulation can be used with the statistical methods commonly used to analyze potential reserves such as Monte Carlo analysis.

In a large prospect with many hot springs, the authors used natural state modeling to determine if separate resource areas had formed from a single source, two, or many. The name and location of this prospect are currently confidential, but numerical simulation during development drilling, prior to production assisted in the determination of the development strategy. Using the physical constraints on pressures and temperatures, plus limited surface geology and an MT interpretation within a 3D geologic modeling platform GOCAD, the shape of the resource and temperatures were interpreted.

The numerical simulation revealed that in order to create the resistivity pattern seen in the interpreted MT data, a different flow pattern was needed than was proposed in the initial conceptual model of the resource. The 3D geologic model that was used included surface geology including mapped geologic structures and subsurface resistivity patterns from the MT data. A conceptual model of the resource was applied to begin production drilling. At the time of numerical simulation, there was some temperature and pressure data available from the first wells drilled in the field. From this it was possible to confirm a correlation between the drilling results (rock type, alteration, temperature) and resistivity. In the numerical modeling the resistivity isosurfaces from the MT interpretation were used to approximate the temperature isosurfaces for the resource. It was found that an overly high flow rate was needed to have the temperature distribution measured at the hot springs if the original conceptual model was honored. From this realization, a more plausible flow distribution became apparent. With only one pad drilled, the natural state modeling was able to determine the more likely upflow area and this led to the targeting of highly productive wells early in the drilling.

The natural state model revealed that a temperature rollover present in the original conceptual model was not possible because the amount of cold fluid necessary to create the rollover as proposed was not available. This change led to targeting of successful wells in the deeper reservoir.

Using the 3D geologic model, the natural state model also showed that a part of the area that was originally interpreted to be reservoir from the MT interpretation alone was actually a low temperature outflow, which changed the proposed development size, layout, and proposed injection strategy.

The natural state model can be used to better target wells that to prove or disprove hypotheses made in the static conceptual or geologic model. This process can reduce the number of delimitation wells needed.

5. Conclusion

Geologic and conceptual modeling in 3D software platforms has greatly improved our visual understanding of geothermal reservoirs. It has allowed spatial comparisons and correlations to be done and extended our interpretations further from hard data, allowing exploration to procced with greater certainty. As is true for all models, and in particularly early ones, assumptions must be made. By adding numerical modeling to the exploration workflow, a 4^{th} dimension of time is added, which allows the placement of the heat to be accounted for and adding additional constraints to the model while testing assumptions. The numerical process itself, based on physical laws, forces consistency with physics and all the resource assumptions made in the conceptual model. The result obtained in interaction of the two modeling methods, is greater than the sum of the parts, forcing a unique answer during the exploration process, and getting to the desired development faster, more efficient, and with lower risk. This greatly reduces exploration costs and the development cycle time. As the field progresses into the exploitation phase, the synergy continues and allows for even better reservoir management capable models over the life of the field. There are limited published examples of using reservoir simulation in this manner, mostly due to the confidential nature of exploration. However, the potential of this method is great and should be considered in early field development.

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