Utilizing a Comprehensive 3D Model to Understand, Maintain, and Expand the Soda Lake Geothermal Resource, Nevada USA

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ABSTRACT

Increasing power generation at the Soda Lake geothermal power plant requires thorough understanding of the well field and reservoir structure. A three dimensional drill-hole and geologic model was created, incorporating data from temperature surveys, wireline geophysical logs, mudlogs, narratives indicating suspected fault and fracture zones, and numerous technical papers. Once all information was compiled, it was used with other geospatial data to create a drill-hole project in Geosoft's Target software, with wells oriented in 3D space, and a variety of down-hole data displayed in both 2D and 3D. CSAMT and seismic profiles were dropped into the 3D model, where they could be viewed in conjunction with other data. For the first time, geoscientists could visualize the subsurface locations of all wells with respect to each other, geology, geophysics, and the temperature anomaly. The result was dozens of data layers that could be toggled on and off and rotated in space. This model was then imported into the Oasis Montaj project, where it was combined with geophysical data to offer a more comprehensive view of the Soda Lake geothermal field. Cross-sections, fence diagrams, and strip logs were easily produced and updated in Target via user-defined templates. Slices of 3D objects such as temperature voxels and geologic surfaces were also displayed in 2D cross sections.

This model has made a valuable contribution to the overall understanding of the Soda Lake geothermal system. As a result, the team has implemented changes leading to increased production at Soda Lake. Two wells that had initially failed as producers were revisited after using the 3D model to study them in the context of their surroundings. One is now hooked into the plant as a producer, while the other is currently undergoing injection testing, with initial tests indicating improvement. An older well was also revisited, and flow tests dramatically demonstrated that a steam cap had developed beneath the well. The 3D model was used in conjunction with geophysical data to study the steam cap, and Magma now has plans for direct use of the steam. In addition, the first of several potential new wells has been targeted and is due to spud in June, 2010.

Introduction

The extensional Basin and Range Province, covering most of Nevada and surrounding areas of the Western United States, is well-known for hosting numerous geothermal systems. The Soda Lake geothermal field is less than 20km southwest of the Carson Sink, and approximately 100km east of Reno, NV (see Figure 1).

The two binary power plants at the Soda Lake power facility have a combined gross installed capacity of 23.1MW, with an estimated net capacity of approximately 16MW. However, annual

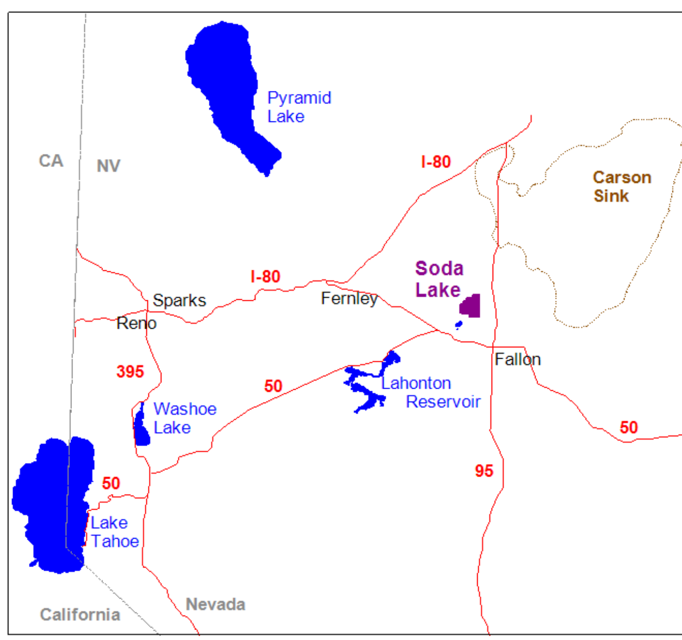

Figure 1. Location of Soda Lake geothermal power facility.

output currently averages only 8MW. When Magma Energy (US) Corp. acquired the Soda Lake Power Plant from Constellation Energy in 2008, the decision was made to first restore the plant to nameplate capacity, then further increase power production by drilling more wells, possibly stepping out beyond the currently known field. A prerequisite to these goals was a thorough understanding of the location and extent of the reservoir, as well as the geologic and structural controls on the individual aquifers. This knowledge would also contribute to better management of the cooling trend of the geothermal field following more than twenty years of production and injection.

Along with the Soda Lake Power Plant, Magma also took possession of paper files dating back to the early 1970s, including those for over 100 slim holes, temperature gradient holes, stratigraphic test holes, production and injection wells, and directional re-drills. Sources included the USGS, Chevron, and Phillips petroleum, all of which had done exploration work in the area. Some individual well files contained detailed information regarding drilling and mud logging, multiple temperature surveys, and geophysical wireline logs. Others had very few details, providing only hand-written temperature surveys with narrative descriptions for well locations. The first priority was to collect all this information into a single comprehensive database, as these data had not previously been synthesized and examined together. From the database, a 3D model of the entire field was then generated using Geosoft's Target software. This software was chosen partially because the company was already employing Geosoft's Oasis Montaj software to process geophysical data, so there would be no incompatibility issues. Although the software was designed for use in mineral exploration, its drill-hole capabilities and versatility in displaying numerous types of data make it a high-quality tool for the geothermal industry as well.

Database Creation

A complete list of wells and their locations and depths allows drilling and mud logging data to be associated with locations in space. Unfortunately, several of the wells had missing or contradictory coordinate and depth information from different sources, requiring further research. Following months of thorough investigation and digital transcription of historic data, 90 of the 104 wells drilled prior to 2009 were located in space. All location data were hand entered into an Excel workbook along with directional survey information, mud-logging and drilling data. All original temperature surveys were entered into the database. Wireline geophysical logs were also available for approximately two dozen wells. Most of these logs were in paper form, with no accompanying digital data, so the paper logs were scanned and sent to LogDigi, LLC, in Houston Texas. The logs were digitized and returned as LAS files that were then incorporated into the database.

Mapping Products Produced from Database

Plan Maps

The first items produced in Target were plan maps showing the best known locations for all wells, with surface traces of all directional wells. With the exception of its 3D capabilities, Target's interface is similar to many GIS programs. The program is compatible with several of these GIS software packages, and can utilize ESRI shape files, MapInfo tab files, and even AutoCAD drawing files. ArcGIS mxd's can be opened from within Target, and individual layers can be dragged from the mxd and dropped into Target 2D or 3D maps. Consequently, the initial maps were easily built within Target using layers from previously existing maps. By adding geophysical data such as LIDAR, resistivity, and magnetic anomalies, plan maps were used extensively to study the steam cap that was discovered to have developed beneath a former producer (41-33).

3D Model and Maps

Once drill-hole data was imported into the Target databases, the creation of the 3D model began. Using DEMs as topography grids, all surface layers (plant outlines, roads, aerial images survey boundaries, etc.) were draped over topography. Down-hole data were then displayed in a variety of ways. Target can display interval data as rock code patterns, bar graphs, text bands, or numeric bands. Point data can be displayed as profiles, line graphs, printed text or structural tics (disks or rings) oriented in accordance with strikes and dips of structural data. Each of these visualization methods was tested, using a variety of parameters, in order to determine the best way to display individual data types. In some cases, the same data were displayed differently in two or three different layers, so they could be visualized in combination with other data in a manner that facilitates interpretation. Because only two types of data can be displayed in a single map-run, multiple iterations of the same map were run, each with different information. Layers from individual maps were then dragged and dropped into a single Master 3D model, which now holds several dozen layers of information that can be toggled on and off individually. From the 3D view of this map, it was also possible to create geologic contact surfaces based upon the stratum as listed in the database. Unfortunately, because of inconsistencies in mud-logging and highly variable gridding parameters, these surfaces were initially unreliable at best. Refinement of the contacts will be discussed in the strip log portion of this paper.

As previously mentioned, 2D and 3D geophysical data for the Soda Lake area was processed using Geosoft's Oasis Montaj software, then brought into the Target 3D model. Even the temperature grid was created in OM. Because wells and therefore temperature data are more plentiful at shallow depths, the deeper portion of the field was gridded separately, using different parameters from the shallow portion. The two 3D grids ('voxels') were then merged to create the best possible temperature model for the field. From this voxel, 3D temperature contours (isosurfaces) were created at desired values. In Figure 3, those surfaces demonstrate that one of the directionally drilled wells (41B-33) had approached the hottest portion of the field only to drill beyond and away from it at depth. This well is now undergoing injection testing in the hopes that it might either be used as an injector at depth, or that the injection will increase the permeability in the higher zone, thereby making the well a viable producer..

Displaying voxels and surfaces in 3D gives geoscientists the opportunity to examine many features of the well field in a multitude of ways. Voxels and surfaces can be clipped in real time, slicing through the model from any direction. Clipping can also be done by value in order to cut away the cooler parts of the field. This clipping feature was often used to slice through the voxel and look at the data in relation to the actual well locations (see Figure 5).

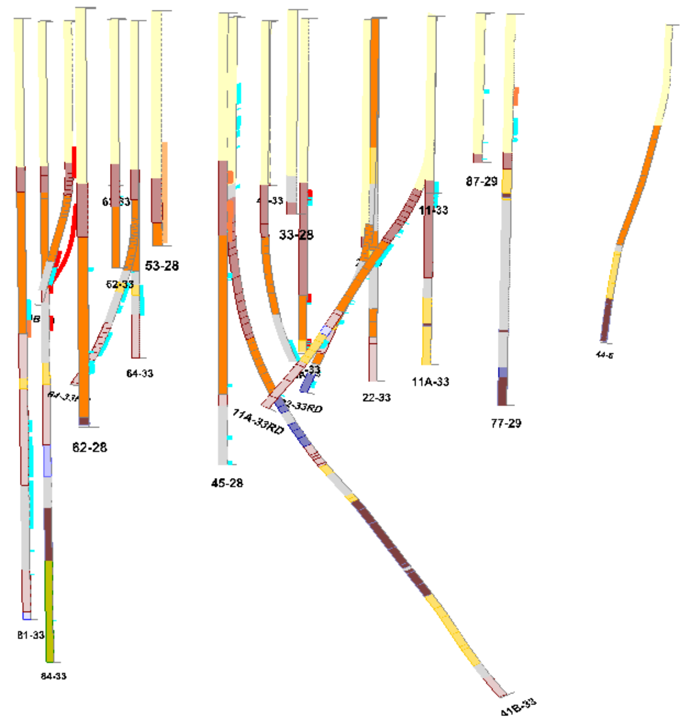

Figure 2. Wells showing lithology, production intervals (in red) and lost circulation zones (in cyan).

From the 3D viewer, the model can be rotated in space, and the user may zoom in or out to examine various parts of the field in more detail. Incorporating CSAMT profiles, seismic profiles, and old hand-drawn cross-sections as slices in the 3D space makes comparison with other data easy. The ability to toggle all layers on and off makes the model a valuable tool to look at a variety of geologic, structural, and drilling data. By displaying all of the wells with their geology, we can see how the positions the wells relate to each other and to the overall geology (see Figure 2). We can easily detect wells for which the geologic strata vary significantly with respect to the rest of the field, requiring a closer look. Two wells near the center of the Soda Lake field show no indication of intersecting the upper basalt layer encountered in every other part of the field, so the 3D model is being used to examine the geology and determine whether these wells might have been drilled through the footwall of a normal extensional fault that may have partially displaced the basalt away from the drilled area. When the layers for lost circulation zones and slotted production intervals are turned on, the model can be rotated until these zones align into planes that may also represent faults or other structures at depth. Using the same model with different layers turned on, the exploration team was able to study the temperature distribution in depth. In Figure 3, isosurfaces were created from the temperature voxel and compared with the areas of old seismic studies where the shots exploded prematurely due to these increased temperatures at the surface. Obviously, the uses for the 3D model are limited only by the data that go into creating it.

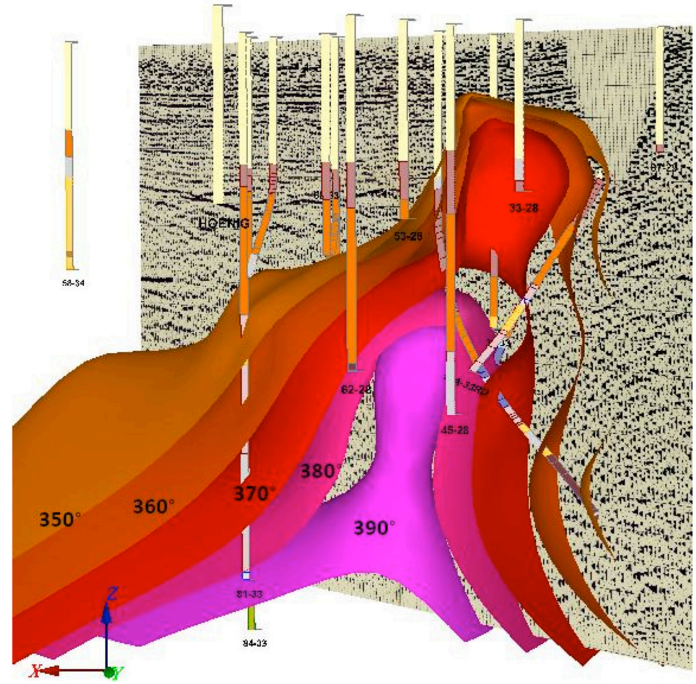

Figure 3. Concentric thermal isosurfaces are clipped to expose internal structure of the system.

Cross Sections

Geologists need cross sections to fully understand any geologic area, and Soda Lake is no exception. Fortunately, all of the data that was imported to create the 3D model could also be used to automate the creation of cross sections incorporating voxel slices, isosurfaces, and scanned seismic or other sections (see Figure 4). While some geologists were initially reluctant to utilize digital technology (having hand-drawn their cross-sections for decades), the ability to automate certain aspects of the creation of these sections was found to be extremely helpful. By using software that places drill holes accurately in space and shows the exact depths of certain types of rocks or alteration, the time it takes to create multiple iterations of cross sections by hand was freed up. Consequently, geoscientists were able to spend a more time on data interpretation and drawing in contacts, hypothesized faults, and other structures. Again, templates for the cross sections were created in order to streamline the process of creating multiple sections with the same parameters. Up to eight data types can be displayed in a single run of a cross section; so fewer iterations were necessary in order to build a group of cross-sections with many layers of data. Although the sections were generally printed with only a few layers of data turned on, the convenience of having more layers available digitally allowed for enhanced brainstorming sessions between geoscientists. For example, if the team was examining a paper cross-section, and they suspected that a localized geophysical anomaly might be caused by silicification of sediments, they could turn to the same map displayed on the computer screen and toggle on additional data layers, like those indicating secondary quartz or silicic alteration, thus aiding them in their interpretation. In Figure 4, we see a section created along a seismic survey line, with the seismic profile and a semi-transparent slice from a temperature voxel forming the background. Any lay-

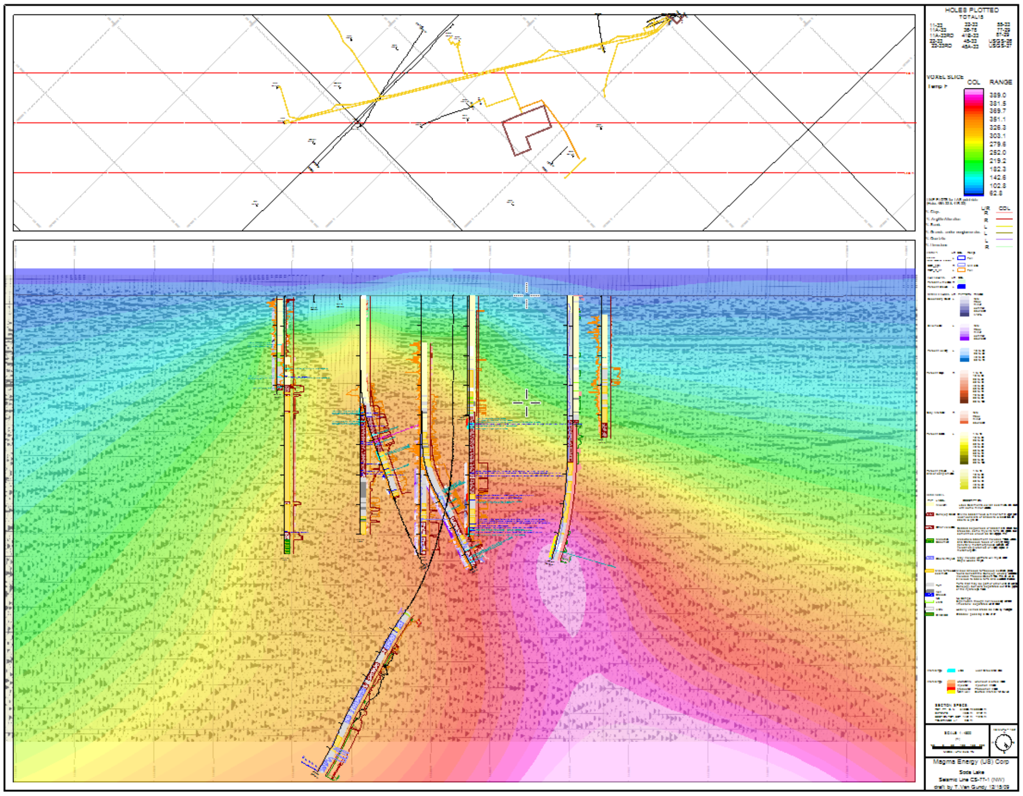

Figure 4. Plant outlines (brown) and piping (yellow) shown in the upper plan view help the reader orient this angled section in space.

ers existing in a plan map may be dragged and dropped into the plan view of a section map, where the midline and width of the section corridor are shown in red.

Strip Logs

Strip logs were created to give geologists a more thorough understanding of individual wells. By designing a template with lithology, alteration, structure (if any), drilling data, lost circulation zones, and slotted intervals, an entire batch of logs could be run simultaneously simply by selecting the desired wells. There was concern about the accuracy of the original lithologic contacts between units, since logging was done as percentages of rock types from chips, carried out by multiple geologists from several different companies, and assigning depths to contacts was therefore a subjective process. Consequently, geophysical wireline logs were digitized, brought into the project, and displayed on strip logs alongside geology. *These* strip logs couldn't be created by a simple template, however. Because, the wells were logged by a variety of vendors with different tools, the scales for particular profiles often varied wildly. A template was used to begin each strip log, then profiles of individual curves were examined within the Target database, and high and low values were used to refine parameters for the creation of each individual strip log. While this process was initially time-consuming, with practice it was simplified and became routine. Resistivity curves presented another challenge, with scales preventing them from being displayed in a manner that showed any fine details. Although Target does not offer the option to plot curves on a logarithmic scale, the channel math function allows the user to apply a variety of mathematical operations to any numeric data channel, so the logs of the curves were often calculated and displayed next to the original curves in order to bring out the detailed character, as shown in Figure 5.

Once the strip logs with the wireline geophysical log data were created, the geoscientists could look at the logs side by side on the same scales and pick out individual units in the thick volcanic packages by correlating geophysical signatures across holes, and adjusting contacts accordingly. These new contacts were then fed back into the model. The original lithology was not deleted, as it sometimes showed finer detail, despite the contacts being subjective. Old and new strata could now be displayed side-by-side (See Figure 5). Using this method, geologists have identified many units having similar characteristics and consistent thicknesses in the eastern part of the field. Continuing this work will allow them to build a full stratigraphic column, more detailed than the generalized one, which was aided by the strip logs as already described. This process also highlighted the fact that geology in the western part of the field is very different

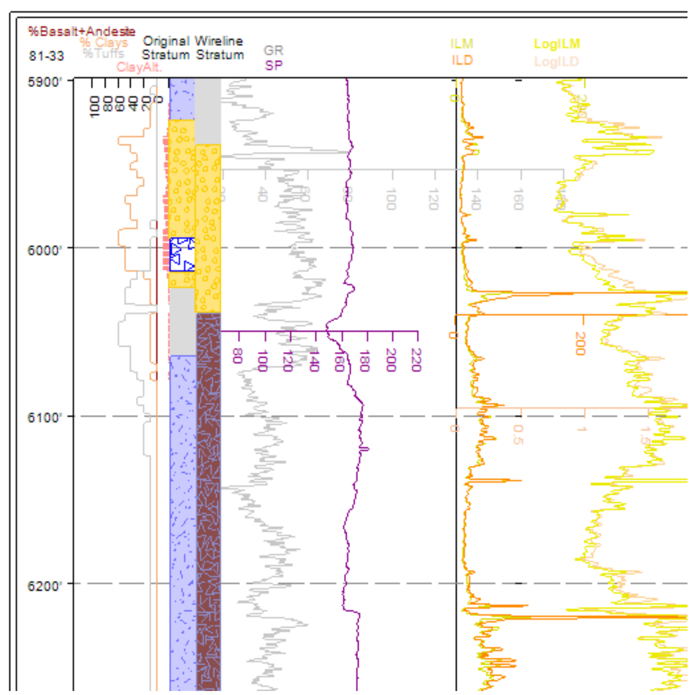

Figure 5. Original strata (left) and geophysical curves were used to refine contacts and create the new strata (right).

from that in the east. For example, in some places the upper basalt layer is four times thicker than it is in the east, while in other places it is missing entirely. These differences have led to further work, in which the cuttings from all wells will be examined by hand, and several via thin section over the next two years.

Drill-Hole & Geologic Model Feeds Back into Geophysical Model

Not only were the geophysical grids created in Oasis Montaj used in the Target drill hole project, but the drill hole project was also used in Oasis Montaj. Each time it was updated and refreshed, the 3D map was simply packed and saved to the server; from there it could then be opened in Oasis Montaj and added to the geophysicist's 3D model. Thus the entire modeling process became iterative, with each piece feeding back into the overall understanding and interpretation of every other piece. In Figure 6, the contoured surface represents the elevation at which the modeled MT resistivity increases with depth from low, shallow values of 1 to 4 ohm-meters (associated with overlying sediments), to values greater than 5 ohm-meters (associated with the top of basalts). Underlying the basalt is a thick sequence of volcanics with resistivities of 5 to 10 ohm-meters, which hosts the main thermal resource above 350° F (shown here as a wireframe surface). The entire model is shown here against a background voxel of resistivity data from MT.

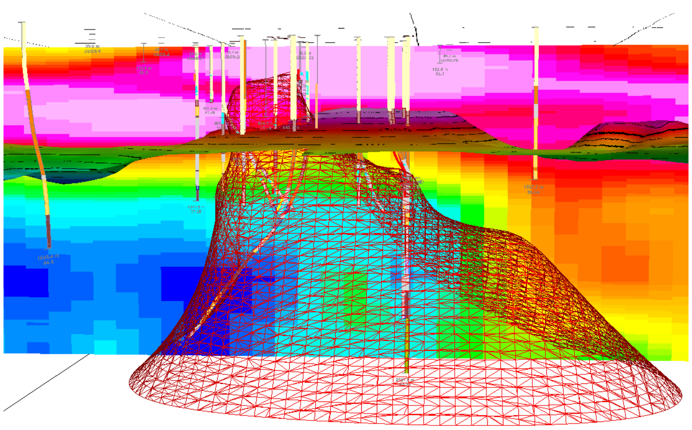

Figure 6. Wells and geology displayed with resistivity and temperature data.

Results

By studying the 3D model in conjunction with geophysical data, Magma's exploration team has been able to examine the Soda Lake geothermal field in greater detail than ever before. The first priority was to determine what changes to existing wells could increase current production levels. Two wells were drilled as producers in 2009, but both were thought to be failures. 45-A-33 could not sustain an acceptable flow rate, and 41B-33 drilled through a high temperature shallow zone with lost circulation, but was cased and drilled deeper, with no additional high temperatures or permeability zones encountered at depth. Visualizing the field in 3D helped demonstrate that both of these wells could still have potential and should therefore be re-examined. The liner for 45A-33 was pulled and three deflagration shots performed. This well now produces 650 gallons per minute at 383.5°F. At the time of this writing, 41B-33 is undergoing injection testing, with initial tests indicating a three-fold increase in injectivity. The model also indicated that shut-in former producer, 41-33, should be given a second look. The team was pleasantly surprised when a January flow test dramatically demonstrated that a steam cap had developed beneath the well. LIDAR and microgravity data incorporated into the 3D model have contributed to the understanding of the location of the steam cap as well as how and where injected fluids are cooling the field. Although the steam cap isn't quite large enough to produce from, a plan for direct use is being developed, and it is expected to ultimately contribute to the net power production at Soda Lake. The thermal anomaly is also better defined, allowing the team to target future wells with a higher likelihood of success. Now, the second phase for increasing power production has begun. With the aid of the entire 3D model (including geology and geophysics), the team has selected several new drilling targets, both within and beyond the main field. The first of these (25A-33) has already been permitted and drilling is about to commence. These various changes to the existing field as well as the targeting of future wells were all directly or indirectly influenced by the deeper understanding of the geology and resource afforded by the 3D model.

The construction and interpretation of the 3D model is an ongoing process, which will continue to be refined. Working with the new strip logs and studying the bore-hole cuttings will provide more detailed lithology, leading to the building of better geology voxels and contact surfaces. A 3D seismic study being partially funded by the DOE should indicate the locations of faults and other geologic structures, which will be brought back into the model and contribute to still better geologic modeling. Refinement of the temperature model is ongoing, as is the accumulation of water chemistry data (which has yet to be added to the model). Future work may even include using other software to interface with Target.

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