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The Value and Limitations of 3D Models for Geothermal Exploration

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ABSTRACT

Three-dimensional models are increasingly used to explore for and develop geothermal energy resources. Such models can help visualize spatial relationships in complex, multi-component 3D geoscience datasets. In addition, 3D models can provide a captivating visual to help communicate with non-technical stakeholders about significant features of a geothermal system. However, there are also important limitations to 3D models. For example, all 3D models of the subsurface, particularly those built in the early stages of exploration, contain large unknown portions and high uncertainty. In addition, quantification and communication of uncertainty in 3D models is difficult and is usually not attempted. This can result in an unfortunate impression among decision-makers that an attractive and colorful 3D model construct implies that we understand more about the subsurface than we actually do. Poor decisions can follow. A central factor in this problem is the practice of constructing a single 3D model in support of decisions. We recommend instead an approach which involves multiple working hypotheses and multiple 3D models. As certain aspects of the models are tested with new data, the uncertainty declines and the differences between the models may decrease. For such a multi-model approach to be viable, the resource team must have the capability to construct 3D models with ease, quickly, and at an affordable cost. In this paper, we provide an overview of the various types of 3D models currently used in geothermal exploration, describe some software tools that are available to facilitate 3D model construction, and discuss the value and limitations of visualizing and modelling data in 3D.

1. INTRODUCTION

Exploration for subsurface natural resources commonly involves creation of a three dimensional (3D) depiction of what may lie underground. For more than three decades, the oil and gas sector has taken advantage of 3D seismic technology to build 3D models of the subsurface that are crucial to targeting hydrocarbon reservoirs (Cartwright & Huuse, 2005). Similarly, the mineral exploration sector combines 3D modelling of various geophysical datasets with downhole logs from dozens of drillholes to build 3D models that help delineate ore bodies (e.g. Perrouty et al., 2014). By comparison, the geothermal sector has been relatively slow to adopt 3D exploration strategies for a variety of reasons which include: sparse subsurface data for building a 3D model, lack of adequate training in 3D exploration, and few software tools available to easily and cost-effectively build 3D models. Use of 3D models in the geothermal sector, however, is growing.

Visualization of geoscience data in 3D space is important for several reasons. First, a 3D model construct helps interpreters better understand the 3D spatial relationships between different types of subsurface data (e.g. geological, geophysical, and well data). Indeed, in some cases, the 3D nature of the subsurface makes it difficult to adequately depict geologic relationships on a 2D cross-section. Second, 3D models can be particularly useful for defining proposed well targets, where multiple, forked targets are attempted in a single well including targets off a 2D section. Third, since creation of a 3D model involves attempting to fill an entire 3D exploration volume with information, the 3D model construction exercise helps interpreters understand and appreciate how much of the volume is unknown. Lastly, when communicating with a non-technical audience, 3D models are sometimes more effective than maps and cross-sections for relaying overall concepts about a geothermal system.

Construction of 3D models, however, does have limitations. For example, uncertainty can be difficult to quantify and communicate in 3D models. Additionally, at the early stages of exploration, construction of multiple geoscience models is vital to facilitate testing of multiple exploration hypotheses. Unfortunately, some software tools for building 3D models are elaborate, not designed for geothermal, difficult to use, and quite expensive. If 3D model construction is onerous, multiple models are not likely to be built. Instead, only a single model might be constructed. Such an approach does not adequately describe resource drilling risk, which makes the risk difficult to manage. 3D modelling should be performed with rigor and skepticism because attractive and colorful 3D models can sometimes give the impression that we know more about the subsurface than we actually do.

This paper provides a brief overview of the different types of models and uncertainty encountered in geothermal exploration. We also list 3D software tools available which are currently in use by geothermal practitioners to give readers an idea of the options that have been tried by others. The paper concludes with a discussion of the benefits of constructing a model in 3D as well as cautionary words regarding the limits of 3D models in geothermal exploration.

2. MODEL TYPES

Models of the subsurface come in many different types depending on the data available as well as the specific expertise of the model-maker. In short, geologists tend to make geological models and geophysicists commonly make geophysical models. The greatest interpretational value, however, is gained when multiple geoscience datasets/models can be visualized together and co-interpreted in the same 3D environment. An example of even more advanced and integrated 3D modelling involves 3D geophysical inversion modelling, explicitly constrained by 3D geological models (e.g. Fullagar and Pears, 2007; Fullagar et al., 2008). Here, we characterize several different types of geoscience models that are used in geothermal exploration.

2.1 Digital Elevation Models

Surface topography can be visualized in 3D as a digital elevation model (DEM). We mention this here because a DEM is: 1) a type of 3D model of the Earth, 2) high quality topographic data is commonly available, 3) several software tools are available to construct a DEM in 3D, and 4) a DEM can be useful for visualizing details of the land surface and for interpreting geologic structure. Quite often, a geologic map is overlain on a DEM to gain insight about geological relationships. Although attractive visually and a good starting point, a DEM on its own usually does not say anything direct about the subsurface.

2.2 2D and 3D Geological Models

Two dimensional geologic cross-sections are the most common type of geological model. They include information such as topography, rock type, and lithologic contacts, as well as structural information such as the dip of beds and faults. Construction of 2D cross-sections is aided by downhole geologic log data obtained from wells that lie along or near the section. In areas with relatively simple geology, a 2D geologic cross-section may be sufficient to accurately depict the subsurface. However, for areas with geology that does vary in three dimensions, a 3D geologic model is a more accurate and appropriate representation. Multiple 2D geologic cross-sections that are all geo-referenced together in 3D space may serve as a robust 3D geologic model that is sufficient for the purpose of an exploration project. However, the space between cross-sections will be empty and proposed well targets heading into these areas may not refer to a specific subsurface interpretation. Construction of a solid 3D geological model fills the space between cross-sections by interpolating from section-to-section until a 3D model is generated, composed of 3D volumes of different rock units separated by 3D fault surfaces and 3D lithologic contacts. In short, 3D geologic models represent a full interpretation of what rock types are located where, and the 3D structural relationships between rock units.

2.3 Geophysical Models

3D geophysical models depict the 3D distribution of physical rock properties in the subsurface. Examples of rock properties portrayed in geophysical models include: electrical resistivity (i.e. the inverse of conductivity), density, and magnetic susceptibility. 3D geophysical models are derived from geophysical survey measurements made at the land surface. Specialized, computationally-intensive software algorithms are used to calculate 3D geophysical models of the subsurface from the surface geophysical data (a discussion of which is beyond the scope of this paper). The most common 3D geophysical model used in geothermal exploration is a resistivity model that is derived from magnetotelluric (MT) survey data. 3D density and magnetization models of the subsurface can also be constructed from gravity and magnetic survey data, respectively. 3D geophysical models are particularly valuable because they can provide information about the subsurface in areas where there is little to no drilling data. It is important to note, however, that 3D geophysical models must be interpreted with caution. In short, geophysical data processing and modelling can, at times, generate artifacts (i.e. false results) that appear quite real when displayed in beautiful colors or show results that include significant ambiguity. The most accurate 3D geophysical models are those which are constrained by and/or in agreement with direct geological and/or rock property measurements.

2.4 Integrated 3D Model Visualization

As mentioned earlier, significant improvements in our understanding of the subsurface can be attained by combining all of the geoscience data and models into a common, geo-referenced 3D environment. In such an environment, the different geoscience data streams can be co-interpreted to better understand subsurface relationships and test exploration hypotheses. Ultimately, a 3D representation of the subsurface must be able to explain all of the geoscience measurements.

A brief search of the literature revealed some recent examples of integrated 3D geoscience modelling efforts in the geothermal sector. The examples found are from Nevada (Jolie et al., 2015; Siler et al., 2016a; Siler et al., 2016b; Siler et al., 2016c; Witter et al., 2016a), Alaska (Witter et al., 2016b), California (Cumming and Mackie, 2007; Hartline et al., 2015; Newman et al. 2008; Peacock et al., 2016), Washington State (Witter et al. 2017), the Caribbean (Ryan et al 2013), Germany (Bar and Sasso, 2014; Luschen et al., 2014), Indonesia (Nusantara et al., 2017), Japan (Humphrey et al., 2017; Wulaningsih et al., 2017), Kenya (Kandie et al., 2016; Mibei et al., 2016), and New Zealand (Heise et al., 2008; Massiot et al., 2011; Alcaraz et al., 2012; Bertrand et al., 2013; Alcaraz et al., 2015). Each of these studies may have a more geological or geophysical focus. However, all of them attempted to integrate multiple streams of geoscience information for interpretation of a geothermal system in a 3D environment.

It is important to remember that 2D cross-sections and 2D plan maps (from a specific depth horizon) are essentially vertical and horizontal slices of the three-dimensional Earth. In some cases, 2D sections are created in isolation with no larger 3D model present. While in other cases, a 3D model of the subsurface has already been generated and the 3D model is visualized by extracting 2D slices (vertical or horizontal) from the 3D model.

2.5 Reservoir Models

An important part of geothermal resource development is 3D modelling of heat and fluid flow in the subsurface to forecast the performance of a geothermal reservoir over time. Commonly referred to as a "numerical model" or "reservoir model" these models use temperature and flow data from wells along with subsurface porosity/permeability information to construct a 3D depiction of the time-dependent flow of heat and fluids through the geothermal system. This type of 3D modelling is performed towards the end of the exploration stage after production & injection wells have been drilled and tested. Specialized reservoir engineering software is necessary to conduct the calculations required for accurate reservoir modelling (e.g. TOUGH2, FeFlow, TETRAD). A discussion of reservoir modelling is outside the scope of this paper. However, it is important to point out that reservoir modelling is likely to be more successful and accurate if the reservoir modelling effort is informed by integrated 3D geoscience modelling described in this paper.

3. 3D MODEL UNCERTAINTY

A key challenge in natural resource exploration is the inaccessibility of the subsurface. Cartographers have unimpeded access when making a city road map thanks to air photos, satellite images, or simply driving all the roads. Geothermalists do not have that luxury when mapping the subsurface and are forced to create models which represent our educated best guesses of what lies beneath. Any model of the subsurface, therefore, contains different regions for which we have different levels of uncertainty such as: 1) regions of high confidence where direct measurements are available, 2) regions of medium confidence that lie in close proximity to or between areas where there are direct measurements, 3) regions of medium confidence where the subsurface has been inferred using indirect measurements and/or geo-scientific principles, 4) regions of low confidence in areas that lie far from measured data where it is difficult to make geologically sound inferences (Table 1). To further complicate matters, the uncertainty level in each region is also strongly affected by data quality. For example, if data quality is poor in one portion of a geothermal prospect, the confidence level goes down in that area. This general characterization of model uncertainty based on data density and quality may seem obvious; however, it is almost never included in a qualitative, quantitative, or visual manner in geoscience models. A brief review of the geothermal literature found two examples (Bradys geothermal area; Siler et al., 2016c and the Fallon FORGE project; Siler et al., 2016b) in which uncertainty in a 3D model is depicted and quantified. To better communicate risk and uncertainty at a geothermal prospect, new and better techniques for spatial characterization of confidence levels in 3D models need to be developed.

Model Region	Uncertainty Level	Types of data/models	Examples
Areas where direct measurements are available	High confidence	Well data; geologic map	1) Temperature measured in the well at 1000 m depth is 150 °C 2) Rock type mapped at the surface is limestone
Areas in close proximity to or between direct measurements	Medium confidence	Near or between well data; shallow subsurface under a surface geologic map	1) Interpolated subsurface temperatures between wells 2) Shallow extrapolation of a fault surface to depth based upon strike & dip angle of the fault mapped at the surface
Areas where indirect information is gained about the subsurface	Medium confidence	Geophysical models of the subsurface derived from surface geophysical data; geothermometry data from a hot springs water sample	1) Infer the depth to top of granite basement rock based upon depth-to-basement modelling of gravity data 2) Infer location of an impermeable clay cap based upon resistivity modelling of magnetotelluric data 3) Geothermometry results suggest the geothermal reservoir is 170 °C but at an unknown depth
Areas inferred from geoscientific principles	Medium confidence	Geologic cross-sections or 3D geology models	1) Stratigraphic layers vertically offset from each other in adjacent wells suggest a fault lies between 2) Stratigraphic layers extrapolated laterally have constant thickness
Areas far from measured data	Low confidence	None	1) Educated guess of what could be in the subsurface without any supporting evidence

Table 1. Summary of the different regions (found in any subsurface model) which have high, medium, and low confidence. The quality of data in each region further affects the level of uncertainty.

In practice, expression of 3D interpretation uncertainty should focus on permeability. Permeability is the most important parameter in a geothermal system since it controls both the distribution of available energy and the rate at which it can be extracted. In addition, permeability has a strong influence on the energy density (e.g. temperature) of the resource. Permeability is also the most uncertain parameter and can vary by many orders of magnitude with low end permeability providing containment and high end permeability supporting flow. Significant uncertainties in other interpreted parameters such as subsurface rock distributions, heat source, or fluid chemistry are important, in part, because of their impact on permeability interpretation. Expression of permeability uncertainty is not quantitative in exploration 3D model sets, but rather, is usually expressed visually by showing different versions of the impact of permeability on temperature contours and flow patterns. Interpretation of these patterns is supported by the distribution of genetic factors such as fault irregularities, rock contrasts, and mineralization as suggested by geologic and geophysical data. In many cases, the variety of exploration stage 3D models in a prospect primarily highlight the variation in permeability as expressed in flows and temperatures, leaving the other background characteristics the same across the model set. These permeability patterns are the key to well target and design decisions.

4. MODELING METHODS

There are a variety of software tools available for visually integrating multiple geoscience datasets for the purpose of co-interpretation in 3D (Table 2). Some of the most sophisticated software tools have been around for decades and were originally developed for the oil and gas industry (e.g. GOCAD, Petrel, Earth Vision). Only one 3D software package has been specifically customized for use in the geothermal energy sector (Leapfrog Geothermal). In most cases, increasing software sophistication results in a higher software price tag. However, some 3D software tools are free (Sketch Up Make, Blender, Paraview, Geoscience Analyst). One of the key factors which differentiates some of the free software tools from their non-free counterparts is the ability to visualize vs. the ability to build in 3D. For example, some software packages allow you to view a 3D resistivity model, 3D well traces, and a 3D DEM in a common environment, but it is not possible to build a 3D interpreted fault surface to add to the model. Other software tools do allow construction of 3D surfaces and volumes that result in a more comprehensive 3D model. The software options listed in Table 2 each have their own advantages and disadvantages, the details of which are outside the scope of this paper. Snapshots of different 3D geoscience models, built with the different software tools, are displayed in Figures 1-8. The figures are merely an array of examples from the literature and in no way depict what each software can and cannot do. The web addresses of each software are listed in Table 2 so the reader can obtain more information.

Software Tool	Visualize in 3D	Build in 3D	Relative Cost	Reference
Sketch Up Make	Yes	Yes (with limits)	Free	https://www.sketchup.com/
Sketch Up Pro	Yes	Yes	Low	https://www.sketchup.com/
Blender	Yes	Yes	Free	https://www.blender.org/
Paraview	Yes	Difficult	Free	https://www.paraview.org/
Rhino3D	Yes	Yes	Low	https://www.rhino3d.com/
RockWorks	Yes	Yes	Medium	https://www.rockware.com/
Leapfrog Geothermal	Yes	Yes	High	http://www.leapfrog3d.com/
Petrel	Yes	Yes	High	https://www.software.slb.com/products/petrel
GOCAD	Yes	Yes	High	http://www.pdgm.com/products/gocad/ http://www.mirageoscience.com
Geoscience Analyst	Yes	No	Free	http://www.mirageoscience.com
Geoscience Analyst Pro	Yes	Yes	Low	http://www.mirageoscience.com
Earth Vision	Yes	Yes	High	http://www.dgi.com/earthvision/evmain.html

Table 2. List of 3D software tools that have been used by geothermal practitioners.

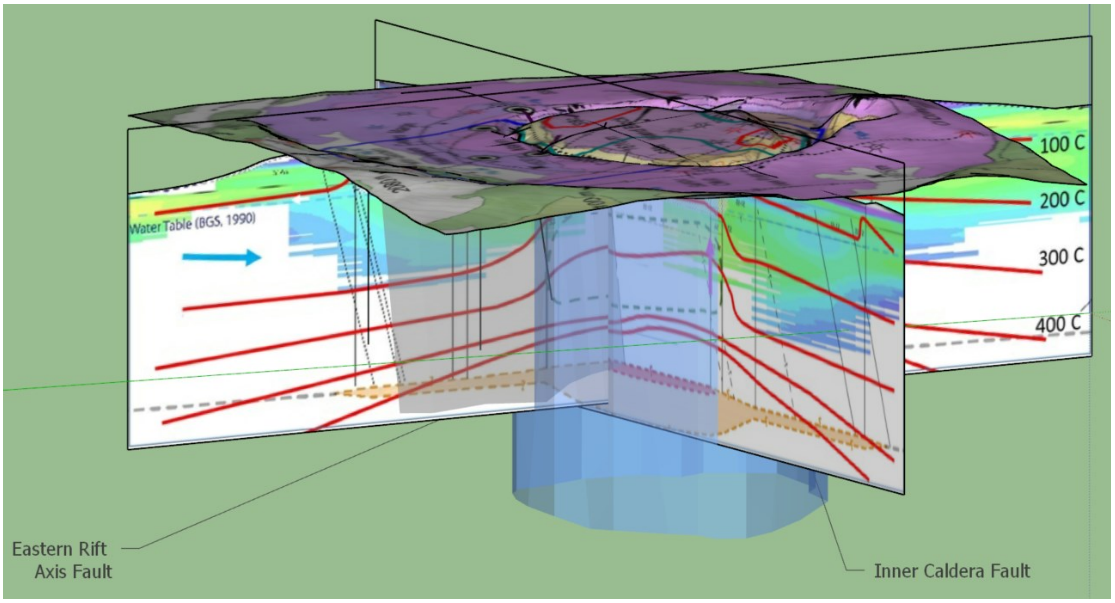

Figure 1. 3D model of the Suswa geothermal system in Kenya (constructed by G. Melosh using geoscience data from Kipngok et al., 2017). Sketch Up Make and Sketch Up Pro were both used to make this 3D model which integrates a geologic map overlain on a DEM, 2D resistivity cross-sections (annotated with red lines to show subsurface temperature), and faults extrapolated into the subsurface.

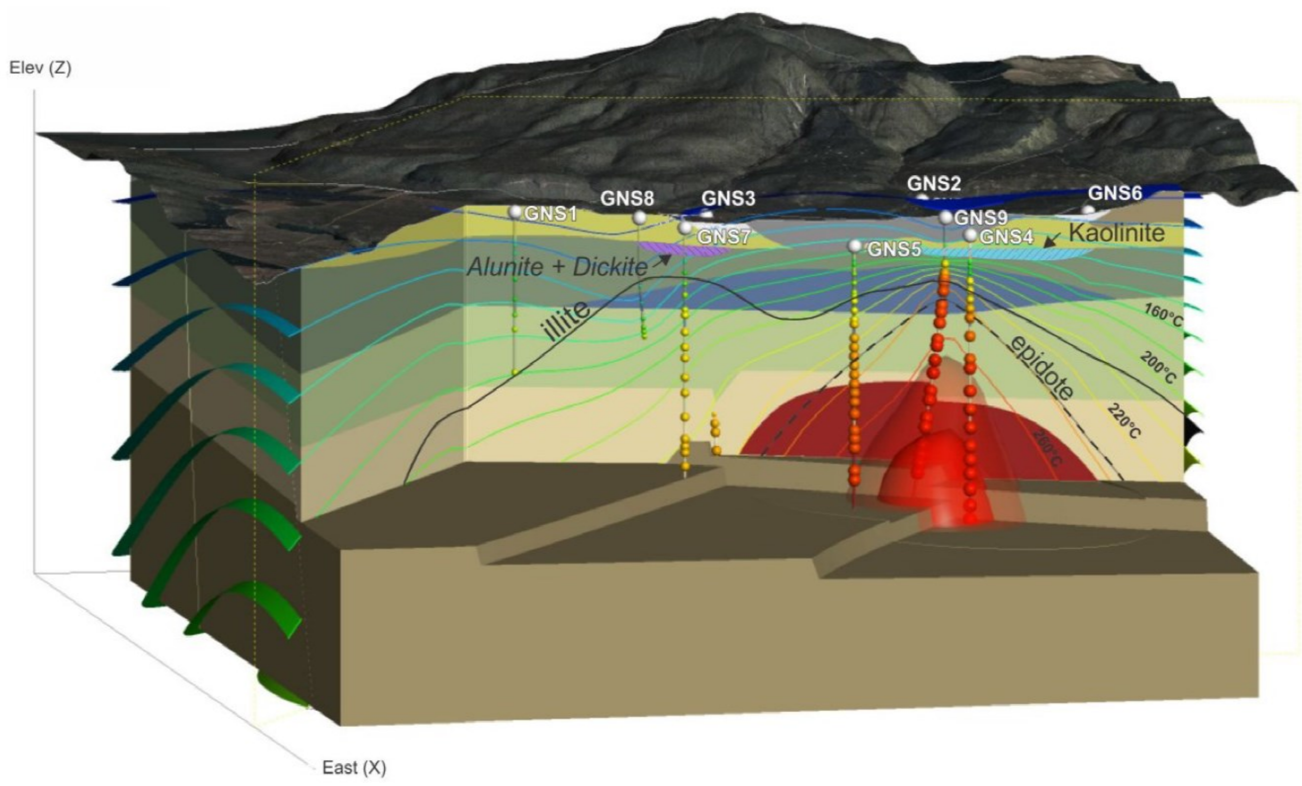

Figure 2. 3D model of a hypothetical geothermal system using synthetic data built with Leapfrog Geothermal software (Alcaraz et al., 2015). The model shows surface topography underlain by a 3D geological block model, well traces with downhole temperatures (strings of small spheres), interpolated temperature isosurfaces (labeled in degrees C), and the first occurrence of epidote and illite in the system.

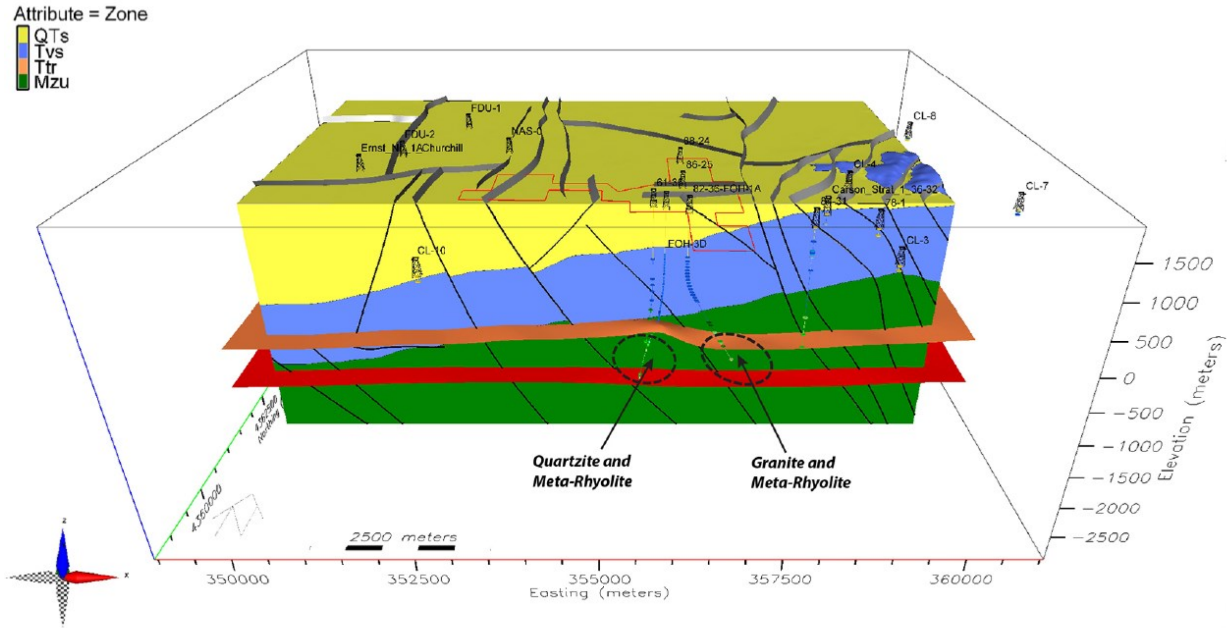

Figure 3. 3D model of the proposed Fallon FORGE site in Nevada built with Earth Vision software (Siler et al., 2016b). Outline of the Fallon FORGE site is the red polygon. The model has been sliced in an east-west direction through the FORGE site. The model was constructed from well log data, 2D seismic profiles, and a depth-to-basement model derived from gravity data. The model shows three primary rock types: Quaternary sediments (yellow), Tertiary volcanic rocks (blue), and Mesozoic basement rocks (green). The 3D fault network is shown as black/grey surfaces. Temperature iso-surfaces are represented by orange (175 °C) and red (225 °C) planes projecting out of the model.

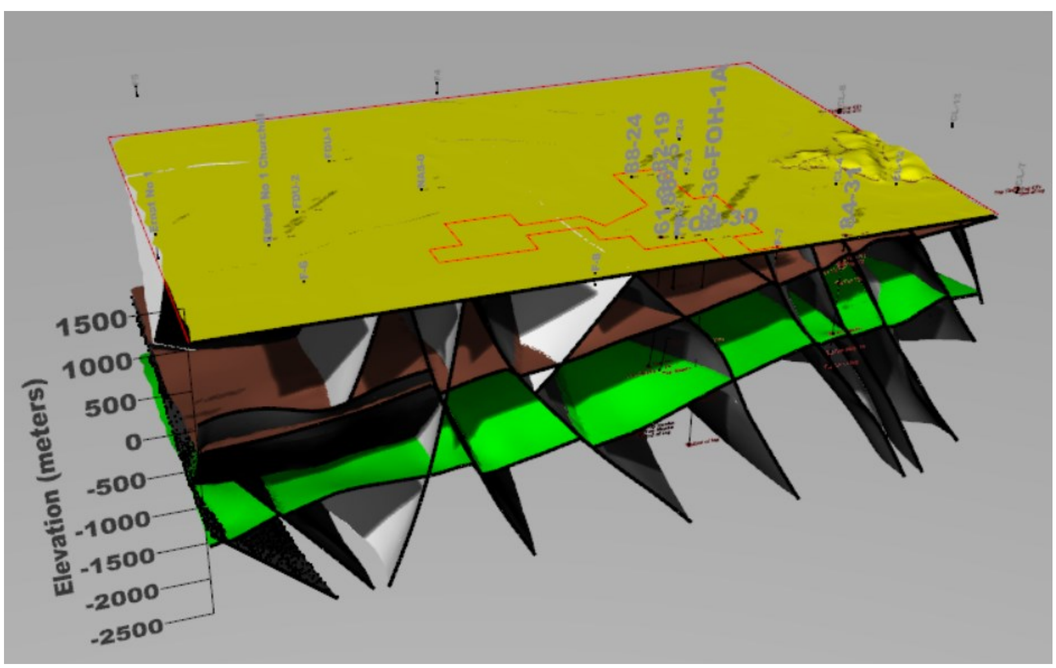

Figure 4. 3D model of the proposed Fallon FORGE site looking to the north-northeast (constructed using Rhino3D software by J. Witter with geoscience data from Siler et al., 2016b). Outline of the Fallon FORGE site is the red polygon. Geologic horizons representing top of Quaternary sediments (yellow), top of Tertiary volcanic rocks (brown), and top of Mesozoic basement rocks (green) are shown. 3D fault network shown as grey surfaces. Well names are labelled.

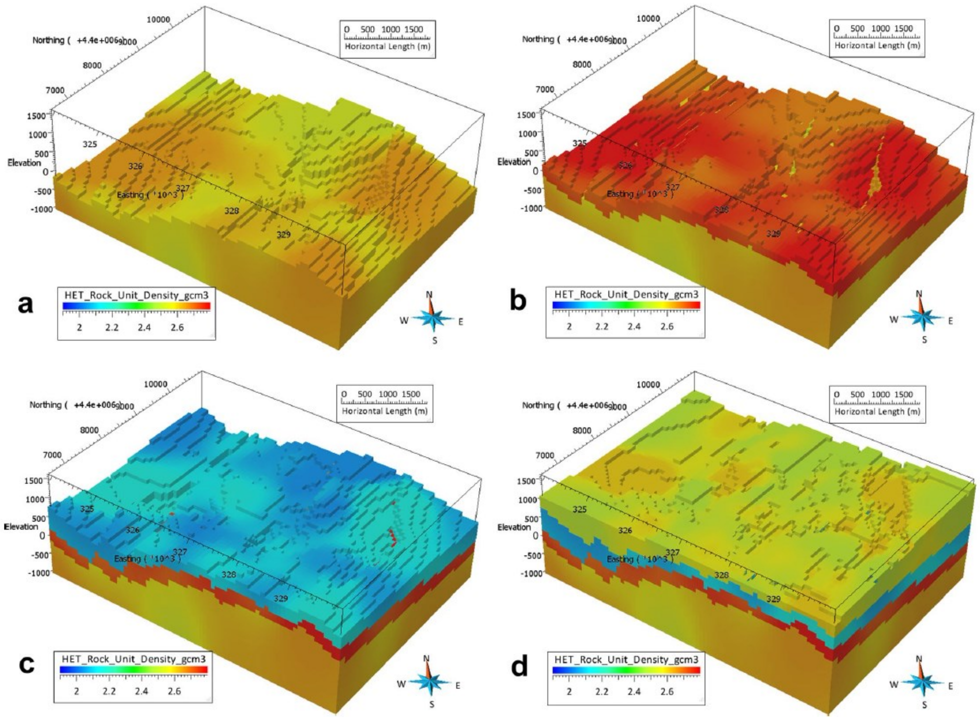

Figure 5. 3D model of the Bradys geothermal area built with GOCAD (Witter et al., 2016a). Perspective view towards the north of a 3D density model, derived from gravity survey data and constrained by the Bradys 3D geological model of Siler et al. (2016c). The model has a blocky appearance because it is constructed of 100 m size cubic cells. Each cell is colored according to density with cool and warm colors representing low and high density, respectively (as shown in the color bar). Each panel shows the different rock unit layers: Mesozoic basement rocks (bottom layer), Tertiary rhyolite (red layer), Tertiary dacite (blue layer), and Tertiary basalt (green-yellow layer on top).

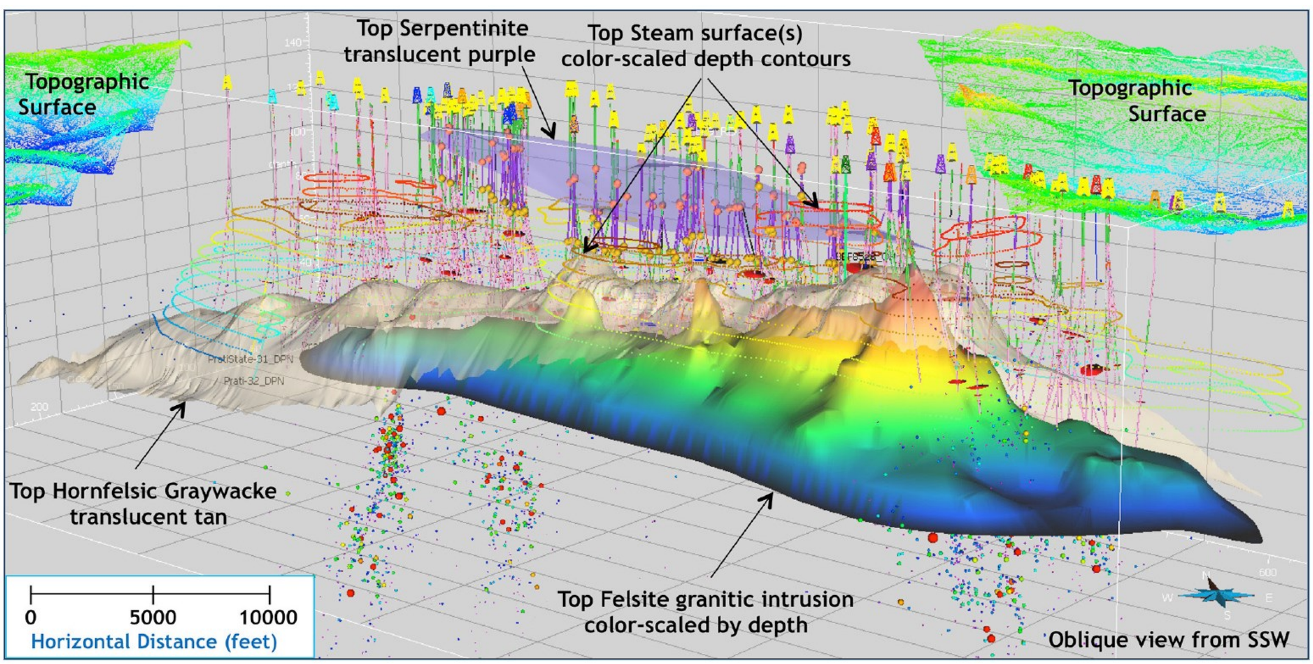

Figure 6. 3D model of the Geysers geothermal area built with GOCAD (Hartline et al., 2015).

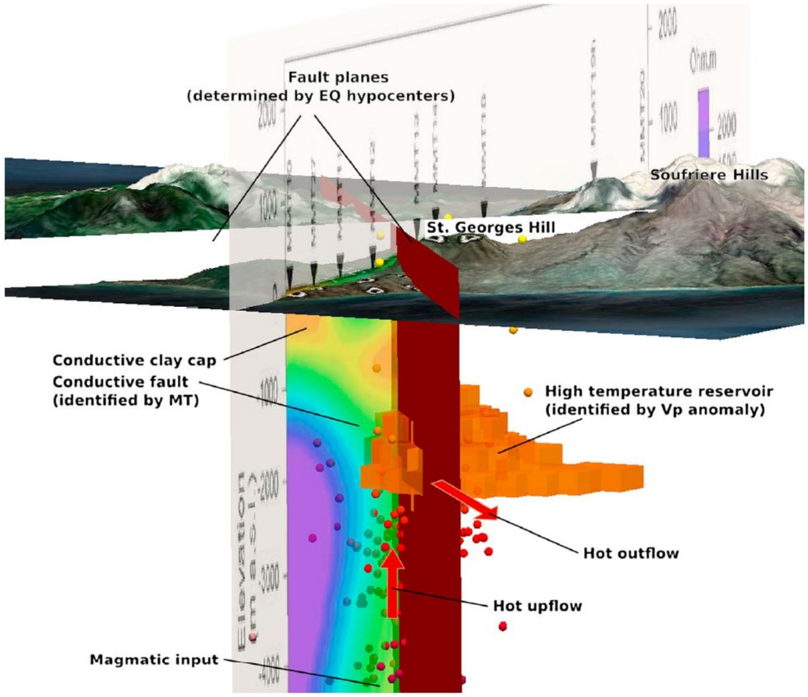

Figure 7. 3D model of the Montserrat geothermal system (Caribbean) visualized in Paraview software (Ryan et al., 2013). The model depicts a DEM, fault surfaces (red and white), a resistivity profile derived from MT data (in rainbow colors), and the inferred location of the high temperature reservoir (orange blocks) derived from seismic velocity data. Spheres indicate the locations of earthquake hypocenters.

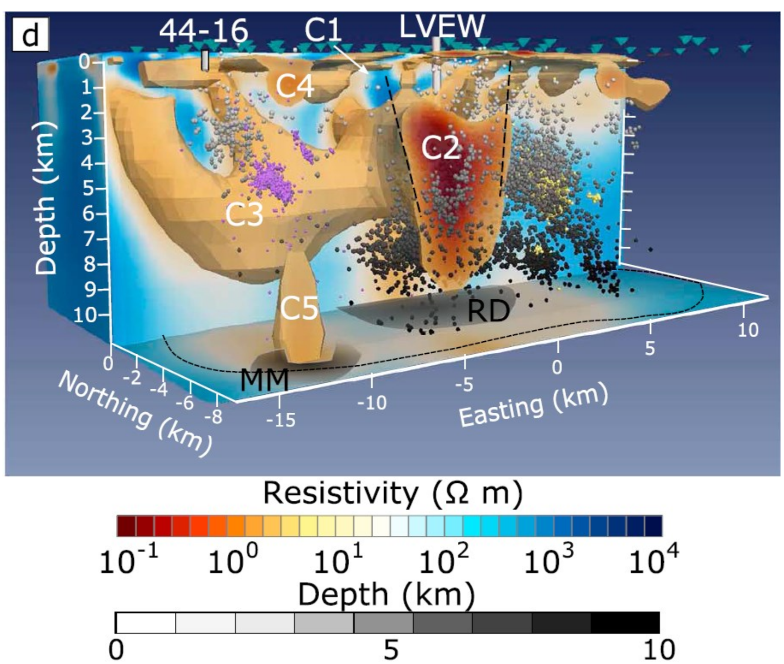

Figure 8. 3D model of the Long Valley geothermal system visualized in 3D with Paraview software (Peacock et al. 2016). Labels C1 – C5 represent low resistivity anomalies identified in a 3D resistivity model derived from magnetotelluric survey data. Purple and yellow spheres are earthquake locations. White-grey-black spheres are also earthquake locations, colored according to the depth scale. The subvertical, black dashed lines are inferred medial graben faults. RD, resurgent dome; MM, Mammoth Mountain; LVEW, Long Valley exploration well. The tan body represents a 20 Ωm resistivity iso-surface (picked for its representation of anomalous conductive zones). In the 3D model, warm and cool colors, representing low and high resistivity, respectively, are shown in the color bar.

5. DISCUSSION

3D models can play an important role in improved interpretation of the subsurface as part of geothermal exploration and development programs. The simple ability to visualize all of a project's geoscience data in the same 3D environment is crucial for understanding the spatial relationships of complex data. As such, a well-constructed 3D model can be a valuable communication tool for both technical and non-technical participants in a geothermal project.

However, construction of 3D models is not a silver bullet for successful geothermal exploration; there are limitations. For example, uncertainty in a 3D model is important to characterize in order to understand what level of confidence we should have in the 3D model overall, as well as the level of confidence in different portions of the model. Uncertainty can be difficult to quantify and communicate in 3D models, and in practice, it is usually not done. This is partly due to the challenge of quantifying uncertainty and partly because there is no accepted, industry-standard approach for doing so. This is an important gap in 3D modelling which needs to be resolved. Current practice includes a commitment to building at least three 3D models showing different versions of what might occur at depth. Aspects of these models can be traded between models to create hybrid models. A longer-term solution may be for academic researchers and industry to pursue new R&D focused on quantifying and visualizing uncertainty in 3D geothermal models. Alternatively, one could investigate what our colleagues in the mining and oil & gas industries are doing to quantify exploration uncertainty in 3D (e.g. Suslick and Schiozer, 2004) and adopt some of the learnings to geothermal.

It can be argued that another challenge to 3D modelling is the tools themselves. Some software tools for building 3D models are elaborate, not designed for geothermal, difficult to use, and quite expensive. Thus, securing the monetary and personnel resources to construct high-quality 3D geoscience models can be a burden to geothermal developers. In short, to facilitate the construction of multiple 3D models, the mechanics of 3D model construction must be relatively quick, straightforward, easy to learn, and require tools that are low in cost. Easy modification or re-creation of an existing model set can then help describe new thinking as new data become available. This allows the models to renew their value and help lead the resource assessment effort, instead of holding it back.

Good quality and accurate 3D modelling is also a strongly interdisciplinary exercise which requires knowledge in geology, geophysics, and drilling as well as software skills. This requires a team-based approach. In addition, 3D modelling requires logic and critical thinking skills to assess which model features are permissible by the existing data and which are not. 3D software tools assist geothermal practitioners in <u>visualizing</u> complex data in 3D space. But it is the <u>critical thinking</u> process which is vital to the development of a viable 3D understanding of the subsurface. A key element of the interpretation process is for geothermal practitioners to advance multiple possible interpretations for the geothermal system, all of which are valid and consistent with the data at hand. This approach of proposing multiple hypotheses is particularly crucial in the early stages of exploration when data are sparse and the majority of the exploration volume is empty. We recommend that a different 3D model be constructed for each of the competing hypotheses under consideration. Once constructed, each 3D model can be assessed for its level of uncertainty and then debated amongst the exploration team. As new data are obtained, each model can be tested and the models which are not consistent with the new data can be revised or thrown out.

We recommend that geothermal explorers take the following step-by-step approach to 3D modelling, starting with simple tasks and then, slowly, add complexity.

1) Build a 3D DEM of the project area; overlay a geologic map on the 3D topography
2) Build multiple geologic cross-sections and post them in 3D space. Include multiple versions of each cross-section where appropriate.
    a. ensure that the topography on the cross-section matches the DEM
    b. ensure that the geology on the cross-section matches the geologic map and other intersecting cross-sections.
3) Extrapolate surface traces of faults into the subsurface at multiple, geologically-reasonable angles. Do this first on the cross-sections, then afterwards connect them together as fault surfaces
4) Add well information to the 3D model (if available)
5) Place 2D cross-sections of geophysical models in 3D space, if available (such as a resistivity section derived from an MT survey or a density cross-section from a gravity survey). One approach is to overlay the geology and geophysics on a set of cross-section images and place the overlays in 3D space.
6) Place 3D geophysical model volumes in 3D space, if available and considered valid (e.g. resistivity, density, magnetic susceptibility models). Consider masking areas with artifacts or highly uncertain geophysical results. In some cases, this can be accomplished by limiting the geophysical model depth.
7) Interpret the 3D data compilations with at least three different models
8) Construct multiple versions of the 3D model that depict different hypothetical subsurface scenarios that can be tested with additional data collection and/or drilling
9) Record and document which portions of the model have high, medium, low, or no confidence
10) Debate the multiple models amongst the exploration team

CONCLUSIONS

Do not be fooled into thinking that hiring a computer-savvy geoscientist and buying the right software will enable your company to make the "right" 3D model of a geothermal system. 3D models have many components and must be built with care, rigor, and a healthy level of skepticism. To reduce exploration risk, multiple 3D models should be built that represent different possible subsurface scenarios. Each scenario should be debated by a multi-disciplinary exploration team and then tested with new data. A key challenge in

3D model construction is the characterization of uncertainty. Although an industry-accepted methodology to characterize uncertainty does not exist, efforts should be made to document, at least qualitatively, the level of confidence in a 3D model. Overall, a series of well-constructed 3D models, built from multiple streams of geoscience data, assessed and debated by a team of experts is an effective way to reduce risk in geothermal exploration.

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