Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

The Role of Three-Dimensional Models in Geothermal Energy, from Exploration to Production

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Keywords: software resource model, reservoir simulation, modelling, 3D, workflow, visualisation, leapfrog, exploration, production

ABSTRACT:

Over the last decade, 3D modelling tools have become more advanced. They are now commonly used in the geothermal industry from exploration to development, due to their accessibility and great technical capabilities. The purposes of 3D models are diverse, as they are an excellent tool to: share knowledge within a team and discuss data interpretation, reduce the risks inherent to any geothermal project during its development, and communicate more easily with a non-technical audience. These models do not have to be particularly complex in the first stages of exploration (when sub-surface information is limited), as they will evolve and become more robust with the integration of new data, resulting from exploration or drilling activities. Beginning to build a 3D model from the early stages of exploration is critical to a project's success, as the model will always represent the best understanding of the resource at a point in time, and provides a baseline for future work planning. This paper intends to provide general guidelines on how to build a well-informed 3D model at various stages during the development of a geothermal project, from initial exploration to power generation. Employing a well-established workflow, when integrating and working on the data in a 3D environment, is important to guarantee the quality of the models created. This paper will demonstrate how to get the most out of all available data when building 3D models.

INTRODUCTION

There are numerous challenges in geothermal resource development, from initial exploration to operation of the power plant. Many of these challenges are related to the resource itself and how geoscientists understand the potential for development, when only a limited amount of data is available from the sub-surface. To delineate a resource, test different hypotheses, select where to drill wells, or to understand the reservoir dynamics, 3D modelling has proven itself to be a powerful tool. Recent developments in the capabilities of these tools make them now essential to manage uncertainty, reduce costs, and make better decisions about geothermal projects.

3D MODELLING TOOLS IN THE GEOTHERMAL PROJECT LIFECYCLE

During a geothermal field lifecycle, 3D models are used to combine, visualise, correlate, and interpret many types of data. This data is mostly geoscientific, but it can also include land permit boundaries and other surface information. The conception of a complete 3D model project involves the generation of a series of models representing different characteristics of the sub-surface, relevant to the geothermal resource. These models can be generated from geophysical surveys or be the result of surface and/or sub-surface observations. However, for most geothermal projects there are a handful of resource characteristics that are commonly represented primarily, including lithologies, structure, alteration mineralogy, and temperature distribution. It is also common practice to develop a resource conceptual model combining the essential elements of the geothermal system and representing the best understanding of the geothermal resource at a point in time.

These models are not static. They will evolve with time, and their accuracy will increase as new data is collected during the lifecycle of the geothermal project. Such developments have been made possible due to recent improvements in modelling software capabilities and the introduction of implicit modelling in geoscience. Implicit modelling uses mathematical tools to derive the model from the data directly, without involving the laborious and rigid manual drawing processes traditionally used in the past.

Numerous publications reporting on 3D modelling results for existing geothermal systems were presented in previous conferences, describing in detail some of the tools and techniques introduced more succinctly here. Stimac and Mandeno (2016) focused on a workflow to build and update temperature models of a geothermal resource, while Newson et al. (2012), Milicich et al. (2015), and O'Sullivan et al. (2017, 2019) introduced a detailed workflow to integrate Leapfrog Geothermal and TOUGH2 for reservoir simulation. Stimac et al. (2017) presented a paper with a methodology to estimate the production capacity estimates in MWe, based on the volumetric estimates of rock volumes in high temperature zones. A paper by Delwiche et al. (2018) also demonstrated how to use 3D modelling tools for well planning and real-time model updating while drilling. Numerous other publications reported on the use of Leapfrog Geothermal for 3D modelling of geothermal systems using well data and other exploration tools (Sepulveda et.al., 2010, McDowell and White, 2011, Massiot et.al., 2011, Pearson et.al., 2012, Milicich et.al., 2014 and 2018, Nusantara et al., 2017, Humphrey et al., 2017, Mibei et al., 2017, Alcaraz et al., 2011, 2012 and 2015, Alcaraz and Barber., 2015, Kandie et al., 2016, Wulaningsih et al., 2017, Poux et al., 2018, Abraham et al., 2018)

The first part of this paper will explore 3D modelling for the main phases of a geothermal project lifecycle:

- Surface Exploration phase
- Feasibility Study phase
- Development and Production phase

It presents how 3D modelling tools are best used to represent and understand the main resource characteristics during each phase, and how it provides necessary information to plan for the following phase.

The second part introduces other applications of 3D modelling tools, that are not phase specific, but can also lower the risks inherent to drilling or geological hazard during the geothermal project development.

1. Surface exploration phase

a. Legacy surface data compilation

The presence of thermal features on surface is generally the first indication of a potential geothermal resource underneath the surface. These could be hot springs, fumaroles, mud pots, or others, and these features are generally well-known by the local population. Combined with other geoscientific surface data, a first understanding of the possible extent of a geothermal resource can be established.

Nowadays, most areas have undergone some type of historical surface geological mapping, possibly for mineral or hydrocarbon resource exploration, or as part of larger scale surveys. These maps can provide a good understanding of the regional and local geology and can potentially identify some of the main structures likely to control permeability in a geothermal system. Studying the relationship between the geology and the surface thermal features is a great starting point to start planning for future field exploration work.

Other available data may include satellite images and digital elevation models, different kinds of GIS data (populated area, vegetation, roads, river streams, etc.) and should also be considered for the evaluation. The topography is a critical element to be integrated when building a 3D model, as it represents the upper boundary for all the data to be collected during future work.

At this stage in a geothermal project lifecycle, it is good practice to start establishing a new 3D model project to set up the framework and boundaries for the upcoming exploration surveys (like shown in Figure 1). Additionally, by studying the topography of the area and its relationship with the river streams or roads, it will facilitate the planning of the field work and ensure maximum efficiency and lower deployment costs.

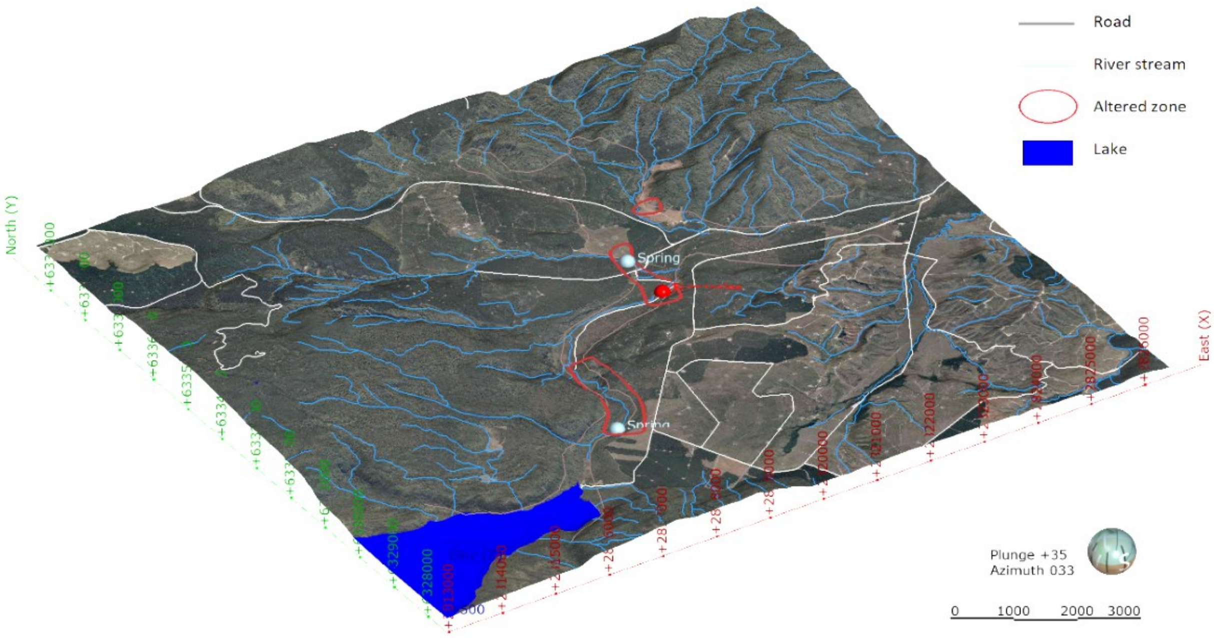


Figure 1: Example of satellite image draped on topography with surface thermal features (red sphere for fumaroles and white spheres for thermal springs) and other elements (roads, rivers, etc.)

b. Preliminary Geological model

During field investigations, a substantial quantity of new data will be gathered on the geology of the area of interest, but also important information regarding the presence of a potential geothermal system. giving greater context to the thermal manifestations and the surrounding geological features. A preliminary geologic map will be established showing lithologies, contacts, and structural elements (like faults) with the measurements taken (dip and azimuth) as these will be important to begin building the geological model. Zones of thermal features and hydrothermal alteration will be clearly identified and delineated, and samples of hydrothermally altered lithologies may be collected for further petrographic analysis (thin sections, X-Ray diffraction, etc.).

Using this new information, a simple version of the geological model can eventually be created, if the surface observations and legacy data provide enough information to understand the chronology of geological events and the relative age of the lithologies. However, it can also just report the lithologies on surface with the sub-surface structure from the measurement taken during the field investigations (Figure 2).

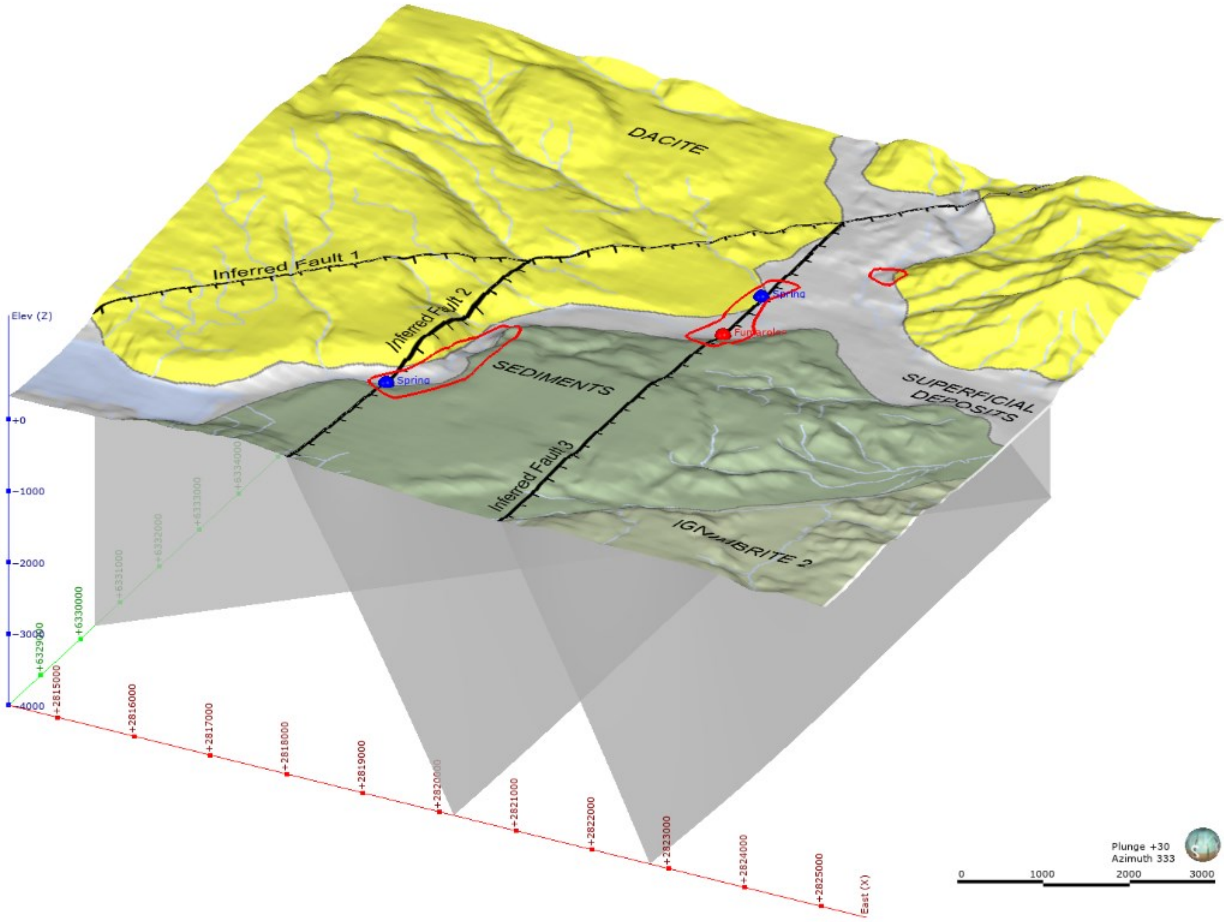


Figure 2: Preliminary geological model of the area of interest

c. Geophysical data

As part of the exploration program, a geophysical campaign is usually completed. This campaign can include gravimetry and aeromagnetic survey, resulting in a series of 2D surface grids and a better understanding of the geologic structure. Most importantly, a magnetotelluric survey is usually carried out to obtain a distribution of the resistivity in the formations. After careful 1D and 3D inversion by geophysicists using the appropriate software, the output can be gridded block models or a point dataset, representing the interpolation of the resistivity distribution to great depth (usually several kilometres) as shown in Figure 3.

Seismic surveys can also result in vertical 2D seismic images and 3D seismic block models. Though they are rarely carried out in conventional geothermal environments due to the geological context and their cost, they are often included in exploration programs for low temperature geothermal projects in sedimentary domains or in area of metamorphic rocks (e.g. Larderello in Italy). In some cases, seismic tomography has also been used to study seismic-wave velocity perturbations in the sub-surface and determine fluid presence. Other surveys could also include the utilisation of temperature probes at shallow depth (less than 2 m) to study temperature gradient distribution. These results can be easily vizualised in a 3D environment, draped over the topography.

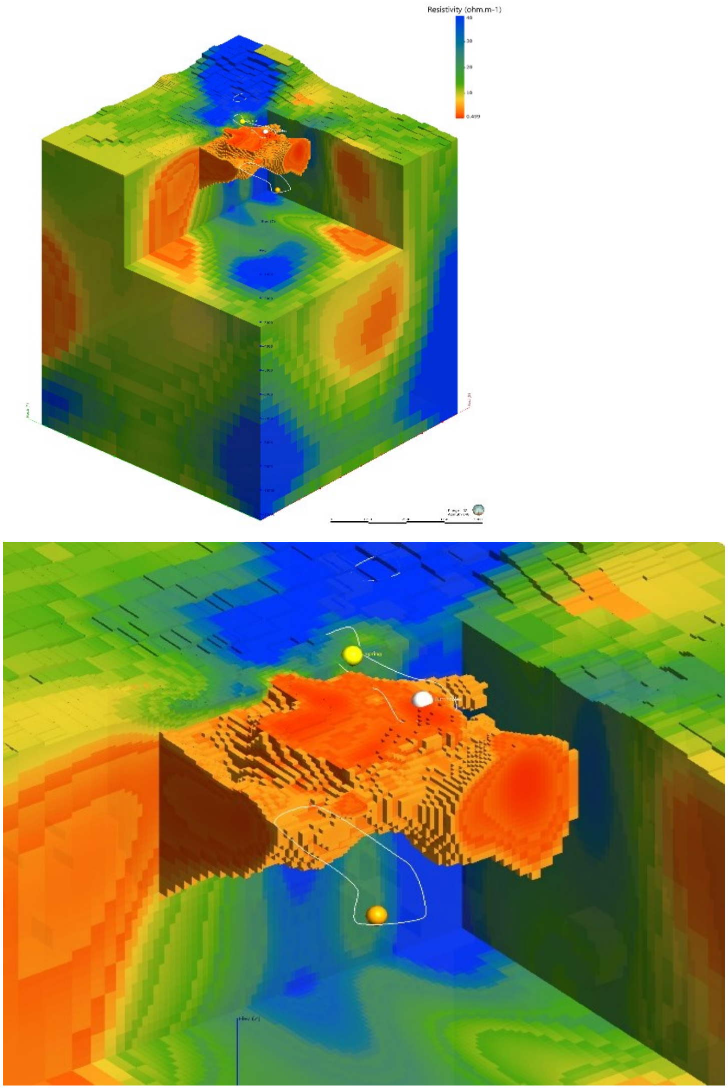


Figure 3: Example of a resistivity model obtained from a Magnetotelluric survey. The filtered volume corresponds to the zones with resistivity lower than 10 ohm.m^{-1}.

d. Geochemical data

Fluid sampling and geochemical analyses of surface thermal features is an important part of any geothermal exploration program. Although this type of information is not particularly adapted to be visualised in a 3D environment, the results of the analysis can be represented on surface using color coded symbols (for example representing the pH, temperature, or concentration of a particular chemical species). This information can be used when interpreting the geothermal fluid circulation patterns. With more data, geochemical data can be normalised to the well pivot point or major feedzone, and allow the creation of z-based geochemical contour maps which are more aligned with 3D visualisation.

e. Preliminary Resource Conceptual model

Conceptual models are important in resource development plans, as they are used to select well locations and targets to increase the probability of success. They represent the best and most recent understanding of the geothermal resource and its components at any time in the project lifecycle. They are the base for any resource size estimation and are the result of the collaboration between all the disciplines and individuals involved in the project.

At the exploration stage, a conceptual model is mostly based on surface data and the results of geophysical surveys. However, once wells are drilled, the subsurface characteristics of the resource will be integrated. Several hypotheses may be developed and integrated into a conceptual model, which will be tested and possibly confirmed or modified during future stages.

With all the surface data gathered from legacy information or the exploration campaign, it is now possible to represent the first few sub-surface elements controlling the potential geothermal resource obtained during the geophysical campaign. These could include some geological units and faults identified and characterised during surface investigations or using geophysical methods as the distribution of the resistivity resulting from the magnetotelluric survey. First estimates of the reservoir temperatures have also been obtained from the fluid's geochemical analyses and resulting calculated equilibrium temperature, when put in correlation with structure locations it permits to identify which structures are carrying the geothermal fluids to the surface.

In the example used here (Figure 4), the resistivity distribution suggests the location of a low resistivity anomaly (below 10 ohm.m^{-1}) in the centre of the area of interest, that could correspond to the clay cap above the reservoir. Intermediate resistivity values (between 20 and 50 ohm.m^{-1}) along some of the fault plans suggest increased permeability and fluid presence, possibly hot fluids rising though the permeability. It can also be noted that the permeable zones match the surface location of thermal features. The recharge system is still unknown, but the topographic highs and other larger extent structures, suggest the possibility for meteoric water infiltration and circulation into the resource area.

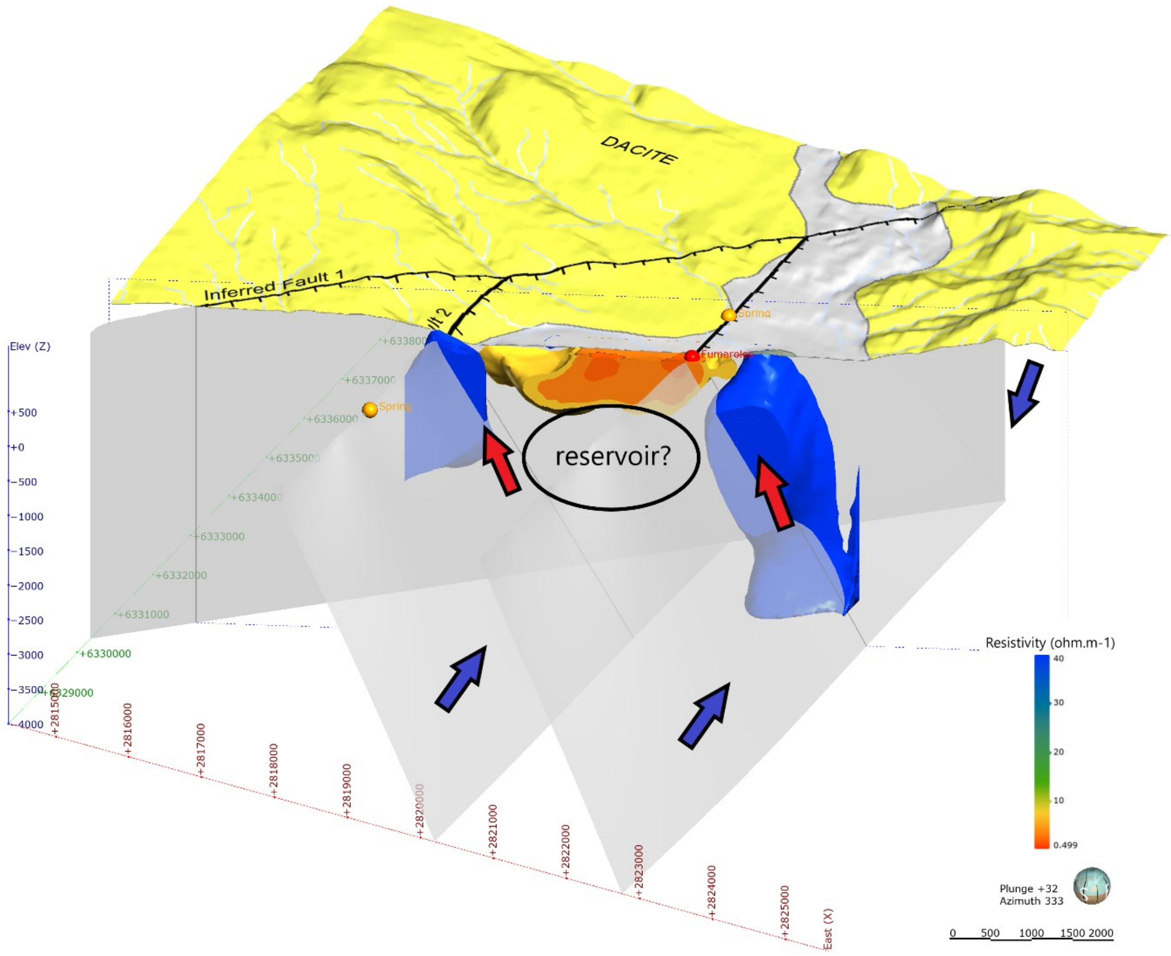


Figure 4: Preliminary conceptual model established after the surface exploration program. The blue areas represent intermediate resistivity zones (50-100ohm.m^{-1}) and the orange/yellow zones represent the low resistivity anomalies (<10ohm.m^{-1}).

2. Feasibility Study phase

a. Exploration drilling:

The first stage of a feasibility study is to confirm the presence of a resource by drilling a few exploration wells. Even though in many cases these wells are not designed to flow, they will provide valuable information on the lithologies, structure, and alteration mineralogy, as well as the sub-surface temperature distribution. Fluids can also be collected for further geochemical analyses.

Sometimes, temperature gradient holes (TGHs) are drilled first to shallow depths (200 m to 1000 m). This is done to locate areas with the highest temperature gradient, and to learn more about the sub-surface geology (by meticulous examination of the cores or drill cuttings).

Based on the TGHs, the 3D model can be updated. Several sites can then be selected for exploratory drilling, which involves the drilling of deeper wells. This is to confirm the presence of a reservoir with temperatures high enough for geothermal energy production or direct use. It is common to drill a few exploration wells, to gain an understanding of the resource, its extent, and to increase the chances of success when drilling full size production wells. The exploration wells are usually smaller diameter than production wells and are drilled vertically to limit costs.

The 3D model can be used when selecting drilling targets for the exploration wells. Parameters to consider include:

- The topography for access
- Land access and permitting

- The low resistivity layer acting as the clay cap
- The faults to find the most permeable zones
- The geochemistry to target structures associated with high temperature fluids
- The temperature gradient distribution (if TGHs were drilled)
- Slim hole vs. standard bore hole, depending on the nature of the exploration program and the objectives of the well

b. Geological model

During exploration well(s) drilling, lithological boundaries have been clearly located on the well path. Highly fractured zones may also have been identified and possibly correlated with faults identified on surface during the exploration stage. This information allows calibration of the geological model, previously started with information on the thicknesses of the units and depth to the lithological contacts. Other lithologies, that were not observed on surface, may also be encountered in the deeper sections of the well(s) and added to complete the geological models. Intersection of faults in the well(s) will be used to estimate the dipping of some of the faults recognised on surface.

This 3D model will represent the best understanding of the subsurface. It constitutes the first conceptual model of the geothermal resource integrating observed sub-surface data. In the model shown in Figure 5, it can observed that the presence of an andesitic unit was discovered in two of the wells, and a thick ignimbrite unit was found in the three wells, but the bottom was not reached. Two of the wells also encountered a loss circulation zone in their deepest portion, which provides new information regarding the location of the two normal faults at depth. This information increases the level of confidence on the fault locations or permeable zones at depth for future well targeting.

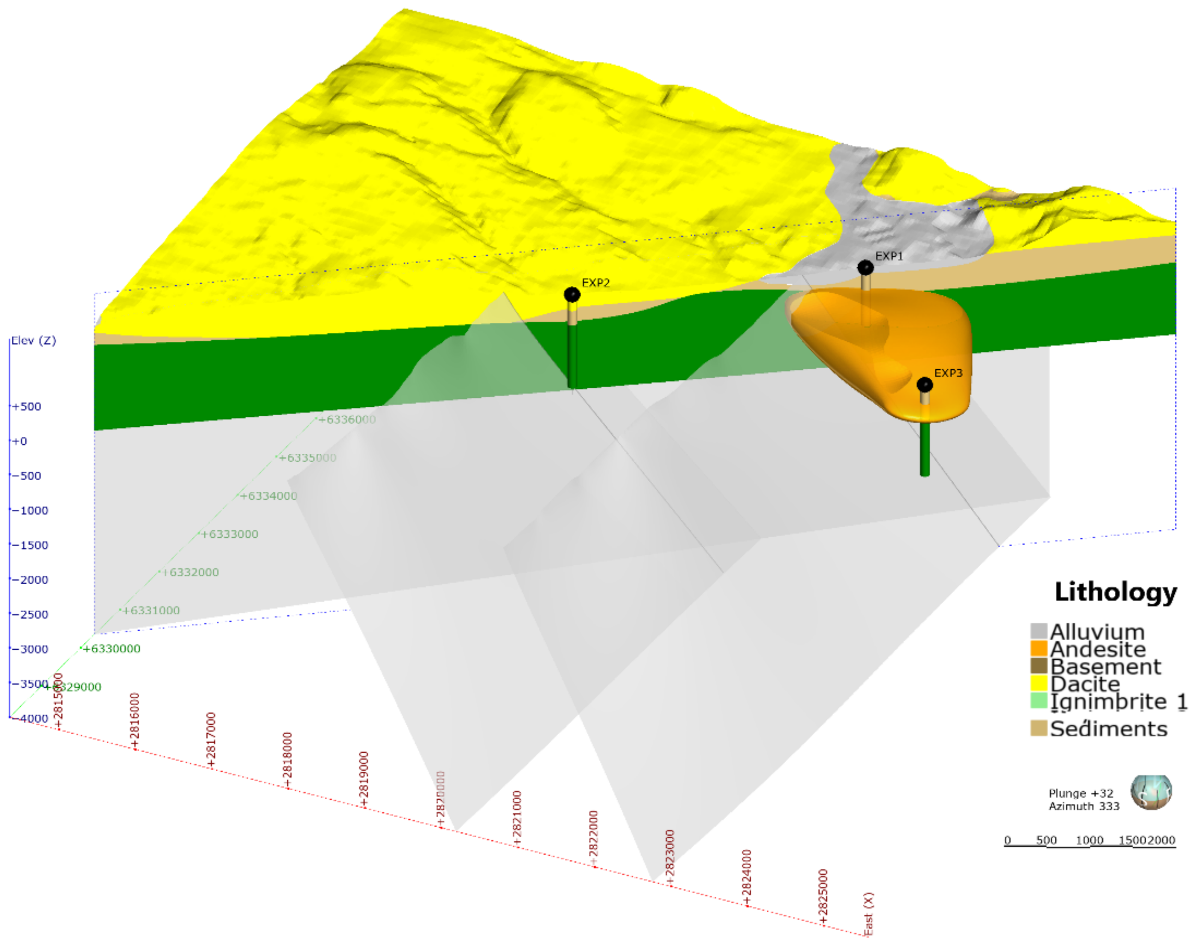


Figure 5: Geological model based on the data from surface exploration and the exploration wells

c. Alteration Mineralogy model

Typically in geothermal systems, the primary minerals present in the lithologies will alter to secondary minerals, due to temperature or pressure increases and fluid circulation. Secondary minerals present in geothermal systems have been studied extensively, and the temperature ranges and chemical environment favourable to the formation of these minerals are well-informed. Smectite clay is commonly found within the clay cap and has equilibrium temperature between 100 and 180°C, and up to 200°C. When interlayered with illite, epidote is usually formed at temperatures above 200°C, and usually marks the top of the geothermal reservoir. These minerals can be identified by the wellsite geologist during the drilling, but most commonly x-ray diffraction and microscopic analyses of the collected cuttings are needed. Based on the analyses, an alteration mineralogy model can be established to represent the zones where these minerals are likely to be found. An example is shown in Figure 6.

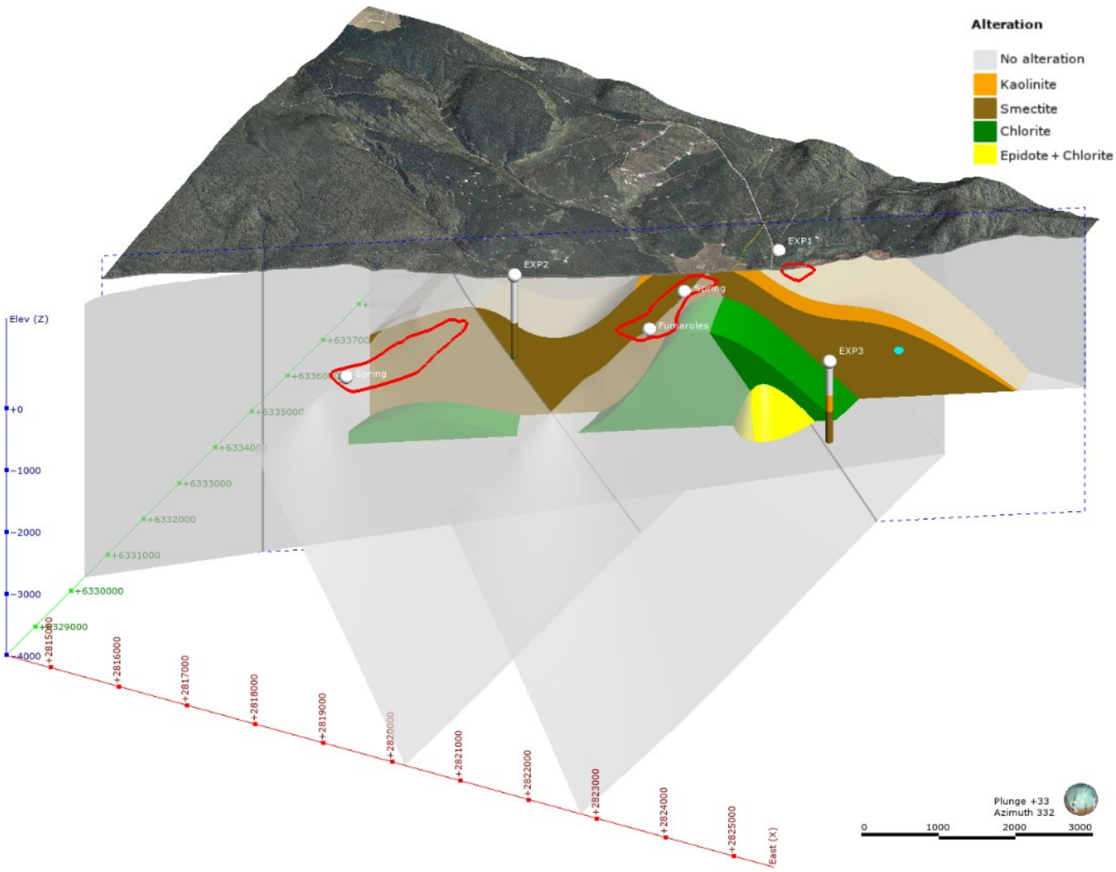


Figure 6: Alteration mineralogy model based on the data from surface exploration and the exploration wells

d. Natural State Temperature model

Heat distribution is one of the most important parameters to understand in a geothermal resource. It is usually directly measured by running temperature logs into the wells with adapted tools. Temperature distribution can indicate zones of fluid convection and circulation patterns through the geological formations. The hottest areas are likely regions of upflow, whereas anomalously low temperatures may indicate downflow of cooler fluids and overturns of temperature typically indicate tabular outflows (Stimac and Mandeno, 2016).

At this stage in the project lifecycle, temperature data are only available for a few wells and the natural state temperature model is at the preliminary stage. Along with the drilling of new wells and the completion of new temperature logs, the accuracy of the model will increase. This will provide a more accurate representation of the equilibrated temperature distribution characteristics. Additionally, alteration mineralogy and equilibrium temperature for secondary minerals can provide valuable information on the temperature distribution. This information must be used with care, as the alteration mineralogy corresponds to the temperature distribution at the peak of geothermal activity in the area, which doesn't necessarily reflect the current conditions.

In the current example, three slim wells were drilled to a maximum of 1500 metres, and temperature logs were run for each. The model shown in Figure 7 represents the natural state temperature model, based on the information collected in the wells only. However, it already shows an area with higher temperatures, to about 275°C at depth, measured in the well EXP1 (the northernmost one) in the vicinity of one of the normal faults (fault 3).

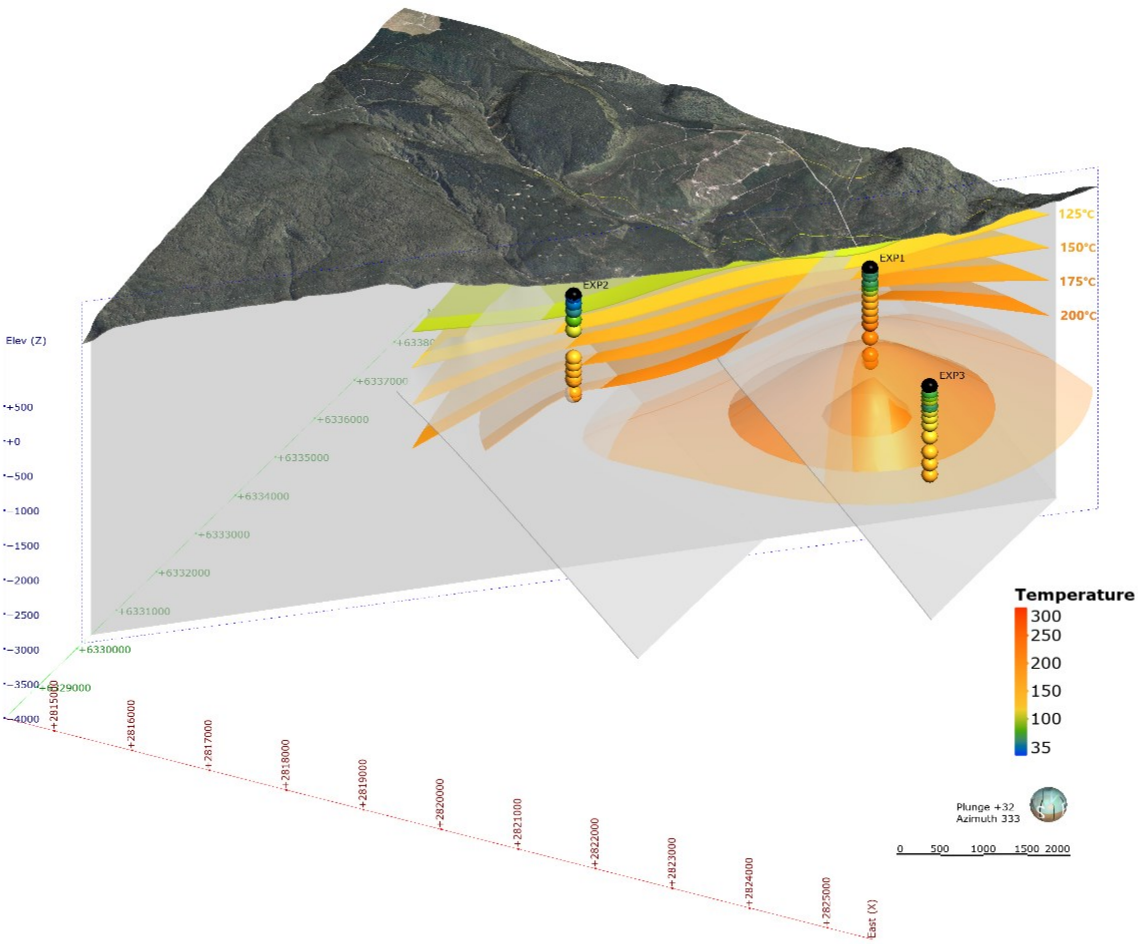


Figure 7: Natural state temperature distribution model based on the data from the exploration wells

e. Resource Conceptual model

At this stage of a geothermal project lifecycle, a good understanding of the elements controlling the geothermal system have been established, based on the exploration drilling. The main structures controlling the permeability have been identified, the main geological units (to a certain depth) have been located and analysed, and the first sub-surface temperature information was recorded. The conceptual model built with the results of the surface exploration can be updated with the new information provided by the drilling of the exploratory wells (Figure 8). In the area where the wells were drilled, information on the clay cap can be compared to the resistivity model and will be particularly useful to design the deep wells and pick the appropriate casing depths.

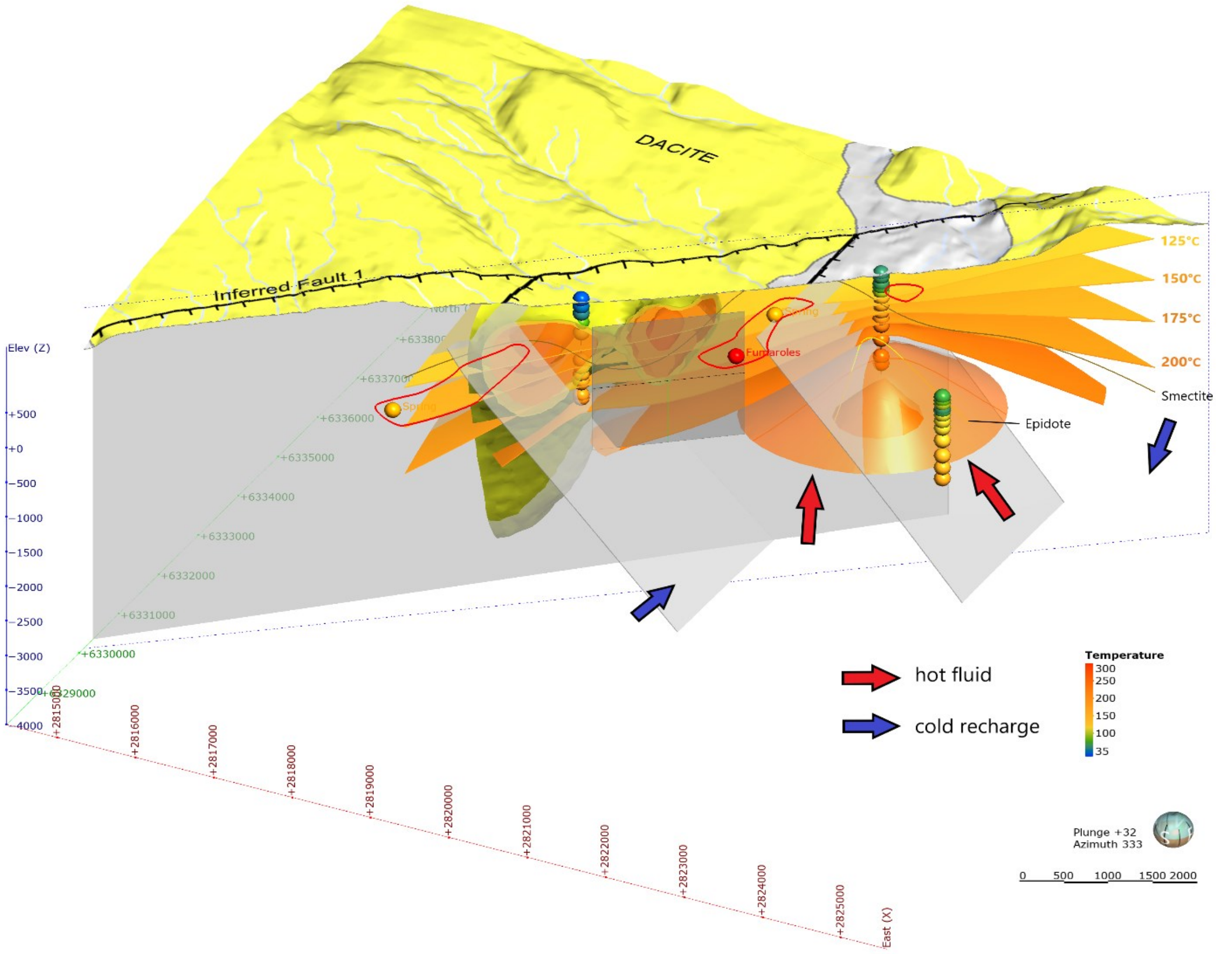


Figure 8: Updated resource conceptual model after integrating the data from the exploration wells

f. Resource Capacity evaluation

Seequent's Leapfrog Geothermal software provides the volumes for each temperature value interpreted, based on temperature data from the well and integration of the exploration results. By obtaining the rock volume at selected temperature ranges (high enough for power generation with the currently existing technology) and combining this with porosity values, the amount of electrical energy that can be generated is estimated. This is done by applying the adapted recovery and power plant efficiency factors based on well-known geothermal fields around the world. This methodology was applied by Stimac et al. (2017) to estimate the generation capacity of three supercritical geothermal resources in the USA.

3. Development and Production phase

a. Establish a development drilling strategy

Based on the selected location and design of the exploratory well, certain prognosis can be evaluated using the model created:

The clay cap area where swelling clays could be encountered and result in drilling problems. Plan and prepare clay inhibitors. Also, if the well to be drilled is directional, the geologist needs to be able to give guidance to the drilling engineers of what formations are best to build angle in to avoid getting stuck or a well collapse.

Planning zones where it is likely to encounter fractures. These zones will influence the drilling speed, but may also cause fluid losses. This may mean compensating with new drilling fluids, or possibly cementing these areas.

This information is valuable to the drilling engineers. The model can help predict them more accurately and limit the risks associated with the drilling activities.

After the drilling of each well, all the collected data should be integrated to update the model. This includes the lithologies, the structure, the results from all types of logs run into the well, as well as any results from laboratory analysis on the rock samples. This ensures the resource model is up-to-date and can provide insight as to where the next well should be drilled.

b. Geological model

With new development well drilling, comes a lot of new geological information and lithological contact depths. These are used to update the geological model accordingly (Figure 9). Some new or deeper units have been informed, which were not previously reached by the shallower exploration wells and can be added into the model. Due to dynamic model updating when integrating new data in Leapfrog Geothermal, the lithologies will automatically connect to the ones in the of the existing model. If wells were drilled in different sides of faults, the offset can be estimated and represented.

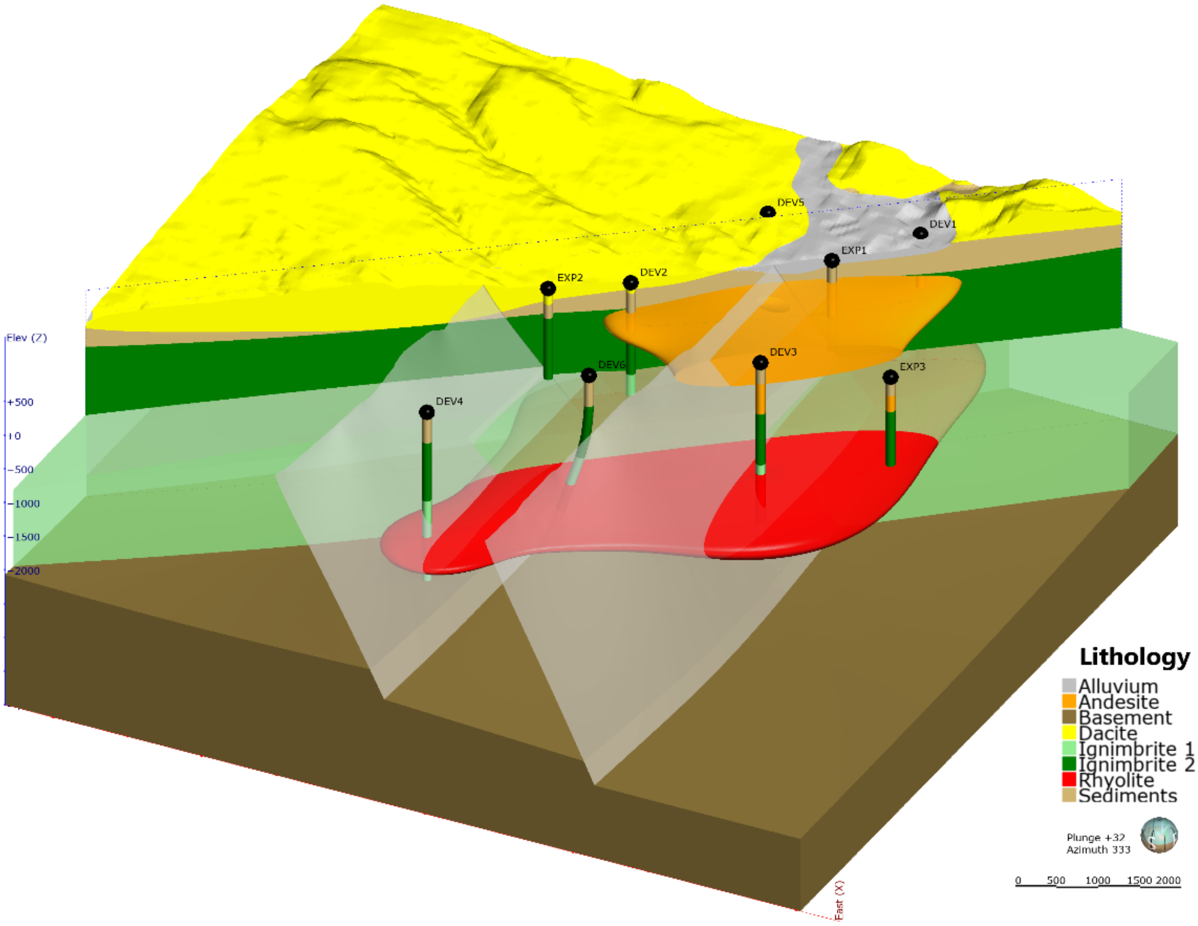


Figure 9: Updated geological model after integrating the data from the development wells

c. Natural State Temperature model

Similarly, the newly available temperature data from the new well will be integrated in the software, and the natural state temperature model will update and evolve to take into account all the new temperature information (Figure 10). Temperatures above 300°C have been measured in some of the deeper wells (DEV3 and DEV5), providing more information about the reservoir characteristics. This also provides insights regarding the hot geothermal fluids' circulation patterns; how they reach shallow depth and eventually the surface, to create the thermal features observed. The natural state temperature model suggests the highest temperature zones match with the eastern normal fault (fault 3) plane, particularly at its intersection with the sub-vertical strike slip fault (fault 1). This is in accordance with the conceptual model that was established during the previous stages, considering the location of the resistivity anomalies and the temperature data from the exploratory wells.

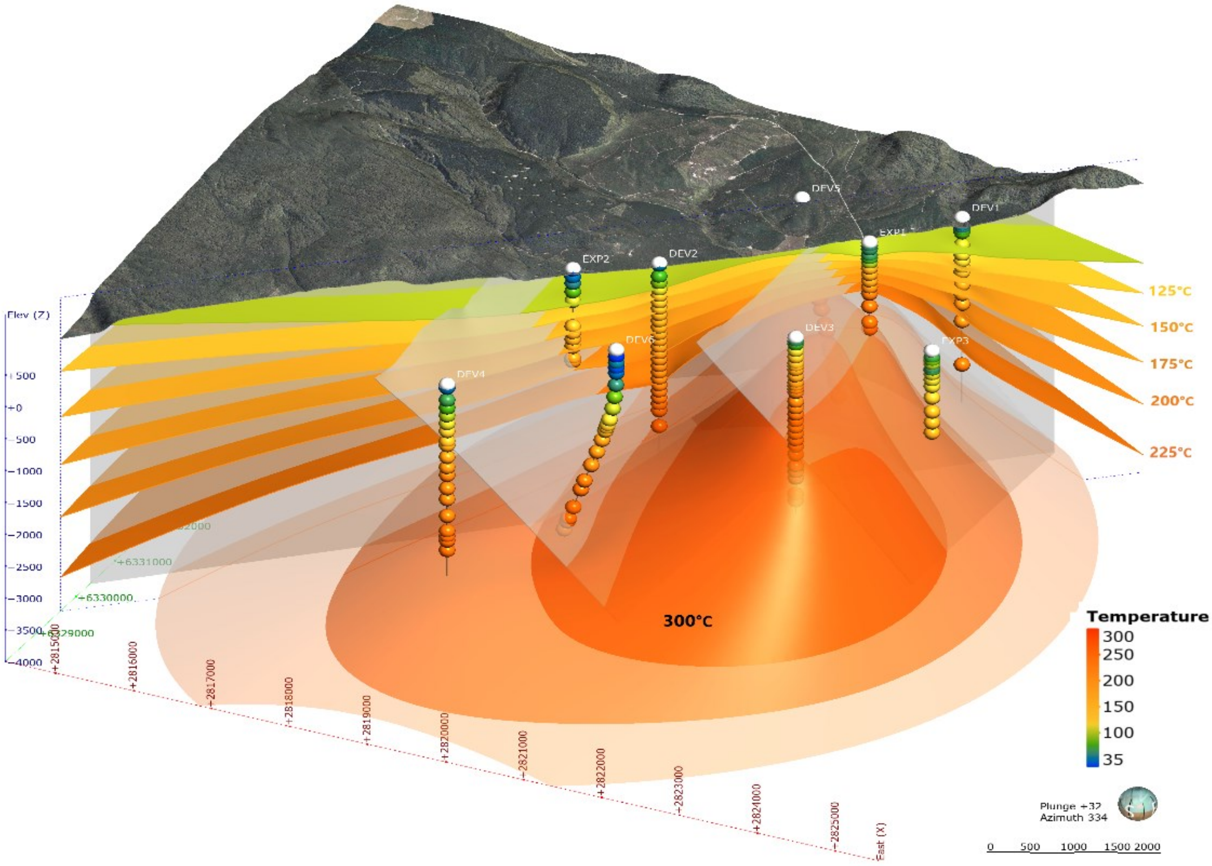


Figure 10: Updated Natural state temperature model after integrating the data from the development wells

d. Alteration Mineralogy model

From the wellsite geologist's drilling observations, and the results of laboratory analyses on the samples collected during drilling, the alteration mineralogy model (Figure 11) can also be updated.

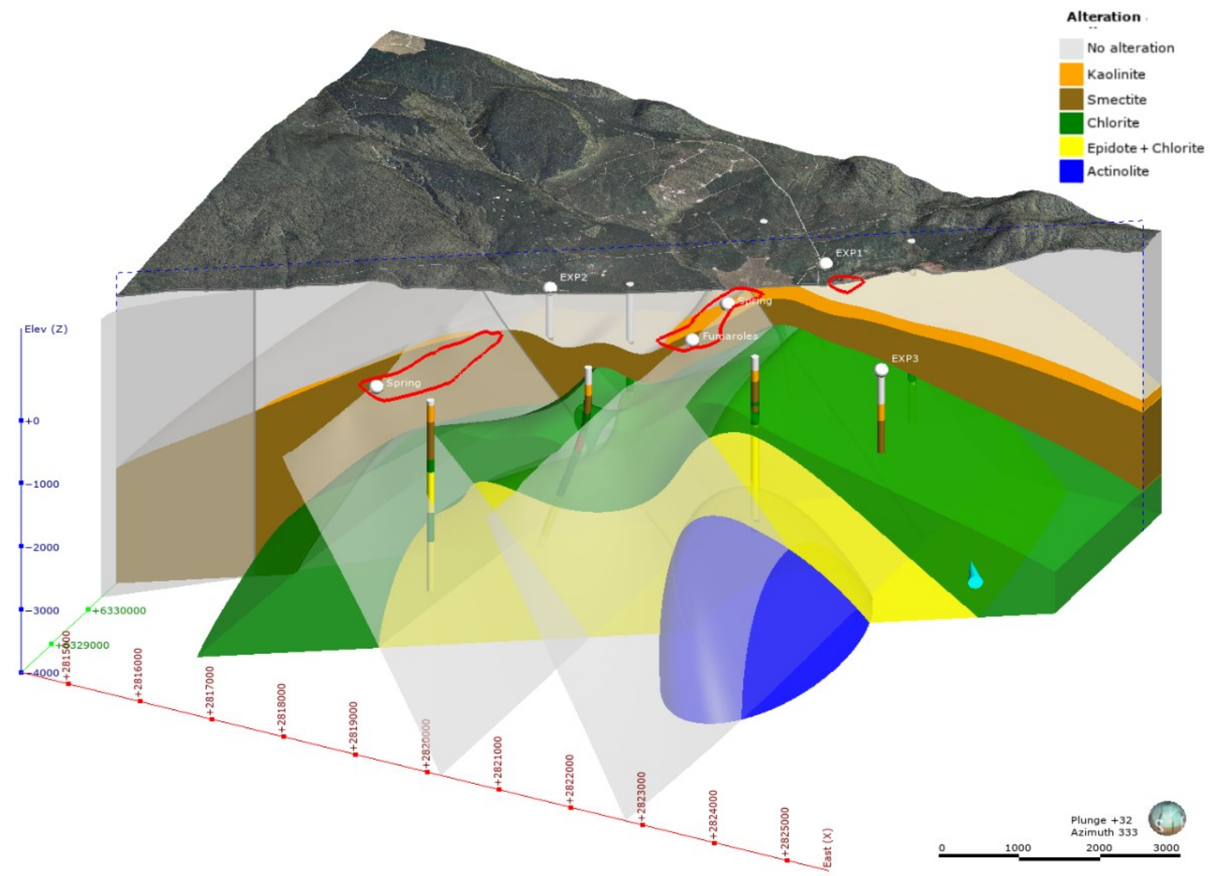


Figure 11: Updated Alteration mineralogy model after integrating the data from the development wells

e. Resource Conceptual model

Combining the updated geological mode, natural state temperature model, and alteration mineralogy model, the resource conceptual model can be updated and show the most relevant information of the geothermal resource (Figure 12). This model can be used to understand the resource, and plan for the next wells. It’s also a great tool to communicate with non-technical stakehoders, as it summarises all the knowledge on the resource at this time in the project lifecycle.

This model provides valuable information on the geothermal resource. The clay cap, mostly composed of smectite and located above the reservoir, is located within the ignimbrite lithologies. This formation is more easily altered by hydrothermal fluids due to it porous nature, whereas the crystalline units (such as the rhyolite) tend to resist better to hydrothermal alteration in the absence of secondary permeability. However, the role of rhyolite in the resource could be related to its crystalline nature and higher potential for fracturation under tectonic stress, opening ways for the hot fluids to circulate.

The equilibrated temperature values observed within the wells matches the secondary mineralogy equilibrium temperatures. The first appearance of epidote is generally located in the 220-250°C measured temperature range, which indicates that the temperature in the reservoir is currently at its highest in recent geological times, and the heat source still present.

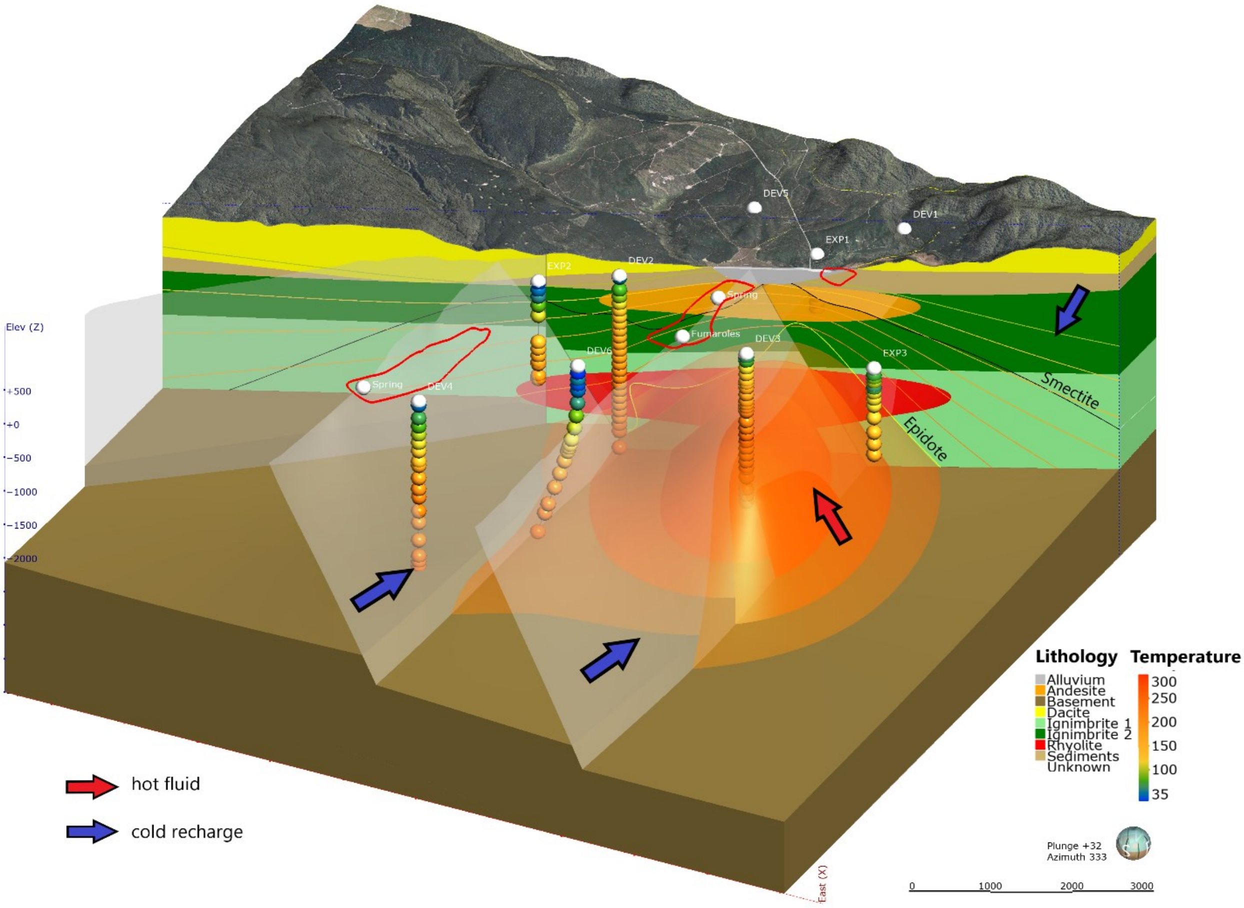


Figure 12: Updated Resource Conceptual model after integrating the data from the development wells

f. Reservoir simulations

After enough wells have been drilled and tested (and are proven sufficient to sustain the intended production capacity for the power plant to be drilled), it is necessary to run industry standard reservoir simulations to forecast the potential behavior of the resource for decades to come. This stage is crucial to establish a reservoir management strategy and avoid any decline in geothermal fluid flow entering the turbine. The most commonly used simulation tool within the geothermal industry is TOUGH2/TOUGH3.

A detailed workflow using Leapfrog Geothermal and TOUGH2 was developed and presented by O’Sullivan et al. (2017). This workflow explains how Leapfrog Geothermal links the multidisciplinary data together to form a conceptual model, and combines with PyTOUGH scripts to provide the two-way integration with the TOUGH2 models (Natural State, Production History and Future Scenarios). Additionally, dynamic updating of the geological model makes it easier to integrate new data and update the conceptual resource model. These changes can be transferred directly to the reservoir model. This allows a fourth dimension (time) to now be considered in the same space as the 3D model.

Figure 13 shows the resulting model from the conversion of the geological model into a TOUGH2 simulation model. Cells were also generated in the model for the fault zones and intersections, separate from the lithologies, to assign different values for the simulation (such as a higher permeability for example). The grid defining the model can also be refined in a region where the wells are located, or along the main faults controlling the flow circulation. Leapfrog Geothermal allows a quick and seamless conversion from the geological model into a TOUGH2 simulation model (either structured or voronoid). Following any changes in the geological model, the TOUGH2 model will dynamically update to reflect these changes, making the history matching process easier before running the simulation forecasts. Rock and fault zones physical properties (such as density, porosity, permeability, conductivity, specific heat, initial pressure, and temperature) necessary to run a TOUGH2 simulation can then be defined, as well as the simulation parameters (as seen in Figure 13), before generating the simulation input files.

The results of the flow simulation can be visualised in Leapfrog Geothermal, with the possibility to observe the changes of pressure, temperature, gas saturation, and other simulation output parameters with time (usually in years). As an example, Figure 14 shows the pressure changes in the field from a TOUGH2 flow simulation from initial conditions (t=0) and after 30 years of production (t=30). A slight drop in the pressure distribution, accentuated by the colour choice, can be observed in the central part of the field, corresponding to the location of the production wells. The pressure drop simulated here for a 30 year period is limited,and might only have limited consequences on the production capacity of the reservoir. A better reservoir management strategy, or the drilling or new injection/make up wells, could possibly negate this.

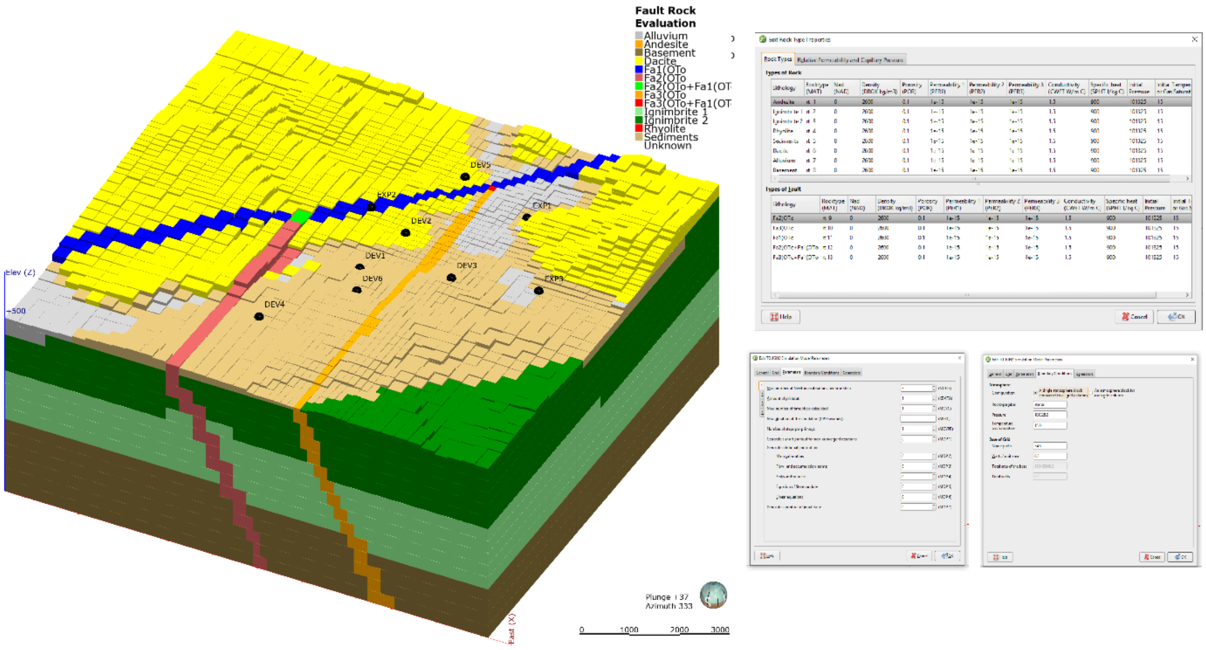


Figure 13: TOUGH2 Input 3D grid and assignment of rock properties and simulation parameters in Leapfrog Geothermal

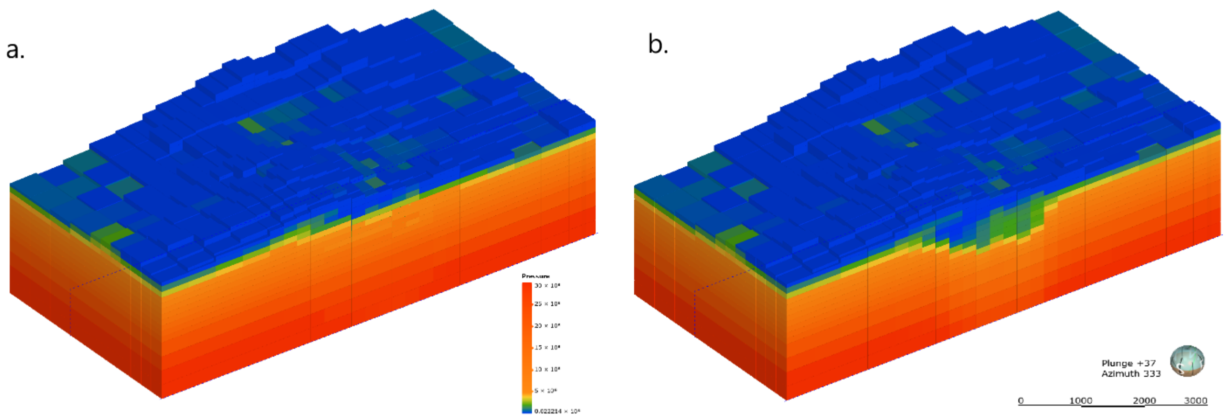
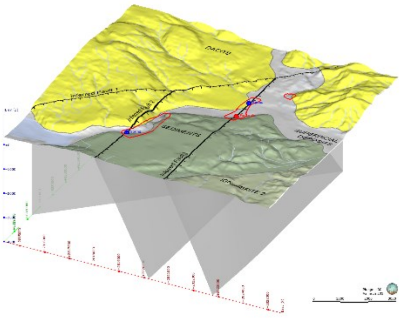
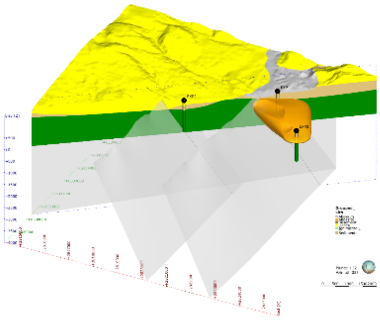
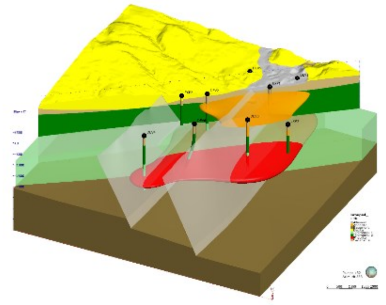
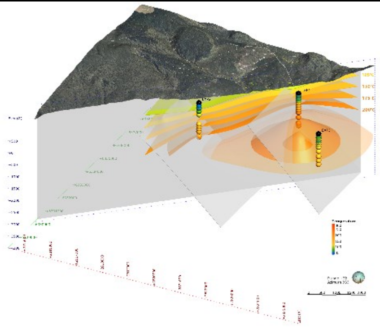
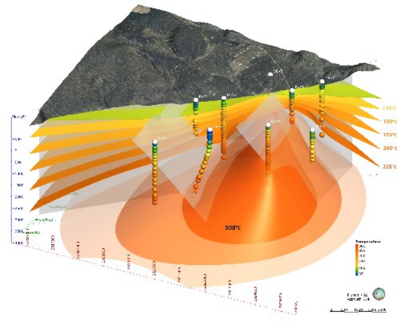
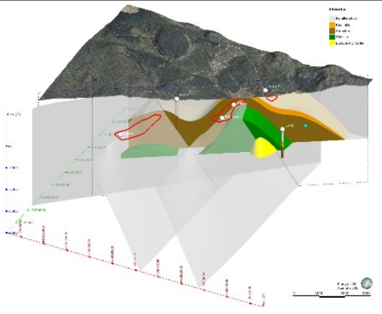
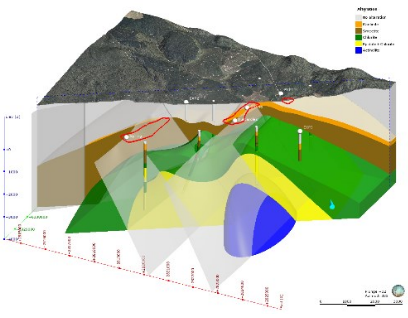
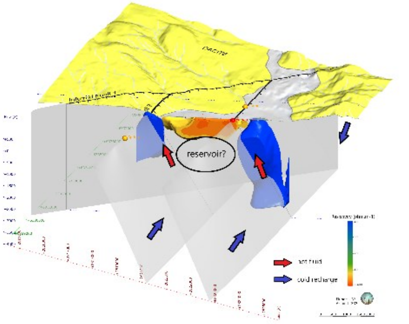
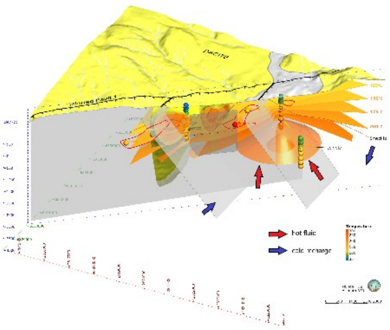
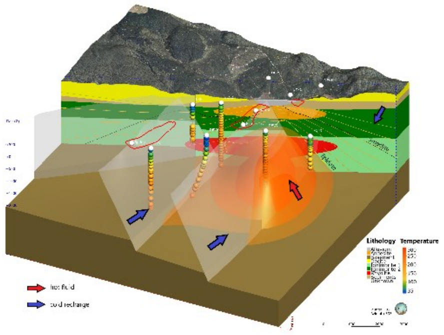
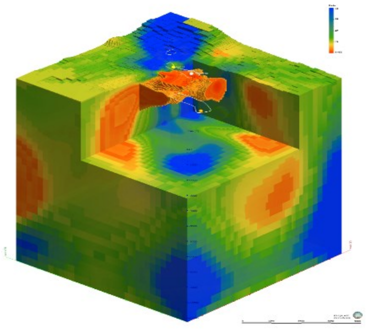
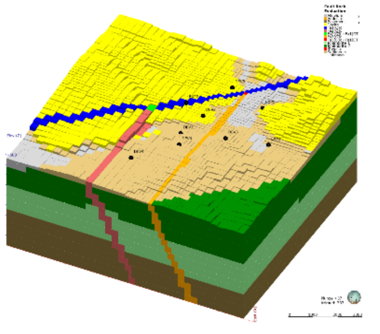


Figure 14: Visualisation example of pressure distribution in the reservoir before production (a) and after 30 years of production (b) resulting from a TOUGH2 simulation visualised in Leapfrog Geothermal.

4. Summary of the models from surface exploration to production

	Surface exploration	Feasibility study	Development and operations
Geological model			
N.S. Temperature model	N/A		
Alteration mineralogy mo	N/A		
Conceptual model			
Other model			

5. Other applications of 3D modelling during the project lifecycle

a. Interactive well planning

Using all the datasets available on the resource to determine a new well target increases the chances of success. A 3D multidisciplinary conceptual model (such as the one created previously), combining geology, temperature, alteration, surface data, and well data permits to select the most promising target and to design the well appropriately as well as to predict the temperature likely to be encountered (Figure 15). Wells can be targeted to reach a geological structure in an area of high temperature. They can also be designed to cross a structure at different depths to increase productivity. Multiple proposed wells can be compared and ranked during the planning exercise, and the 3D visualisation constitutes a great communication tool with stakeholders. When the best planned well is selected, the casing depths can be picked based on the well path and the lithologies encountered.

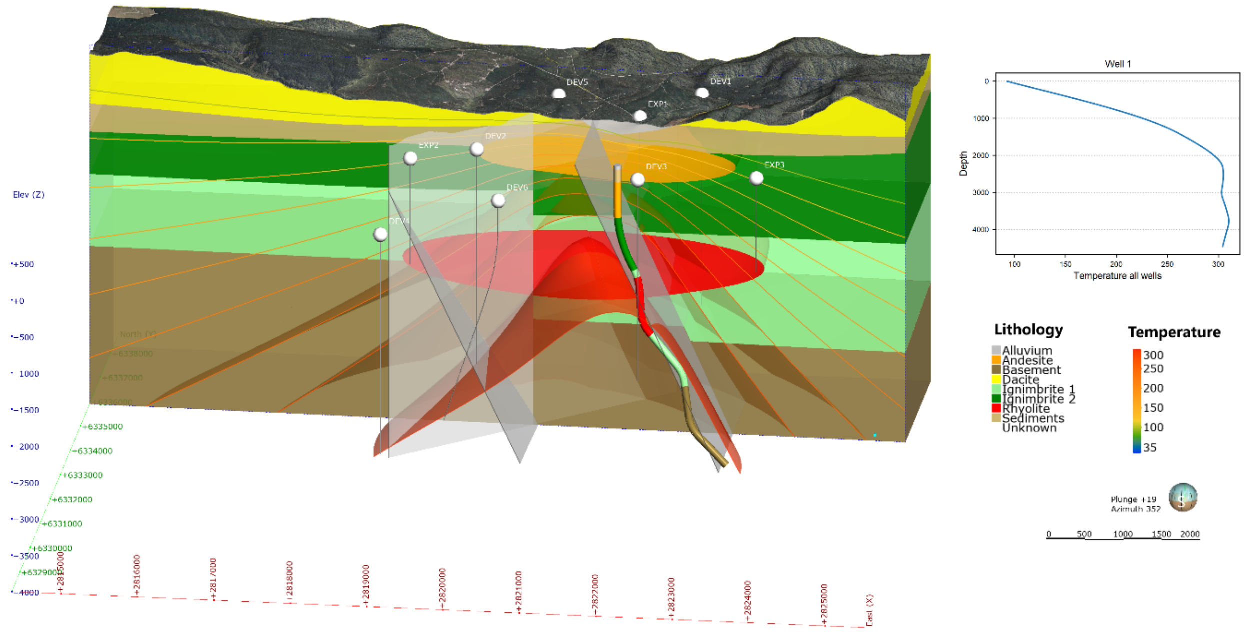


Figure 15: Example of a well planning exercise with multiple fault crossing and temperature profile prognoses

b. Seismicity monitoring

During the production phase of a geothermal project, seismicity is closely watched by a network of micro seismic monitoring stations spread around the site. These stations record earthquakes and micro-earthquakes related to the natural local tectonic activity, as well as those due to changes in the reservoir. These changes can be caused by pressure changes due to production, by the re-injection of colder fluid in the peripherical areas of the resource, or even by drilling activities.

Figure 16 shows the seismicity recorded in the area of interest over approximately 10 years, while the field was in production. The maximum magnitude earthquake recorded was M=4.54. A 3D visualisation of the earthquake data allows clusters of micro-earthquake's directly beneath the wells in the South-West part of the field to be highlighted. This location corresponds to the re-injection wells which can cause this type of events.

Seismicity data can be filtered out by location, date/time, or magnitude, which is particularly useful when trying to correlate seismic activity with other events (such as drilling or well stimulation). If a large enough seismicity dataset is available for a field, further geostatistical analyses can be completed to study the stress/strain field or to correlate them with structural features. This data may also help with providing an estimate of the base of commercial permeability as an input for reservoir simulation.

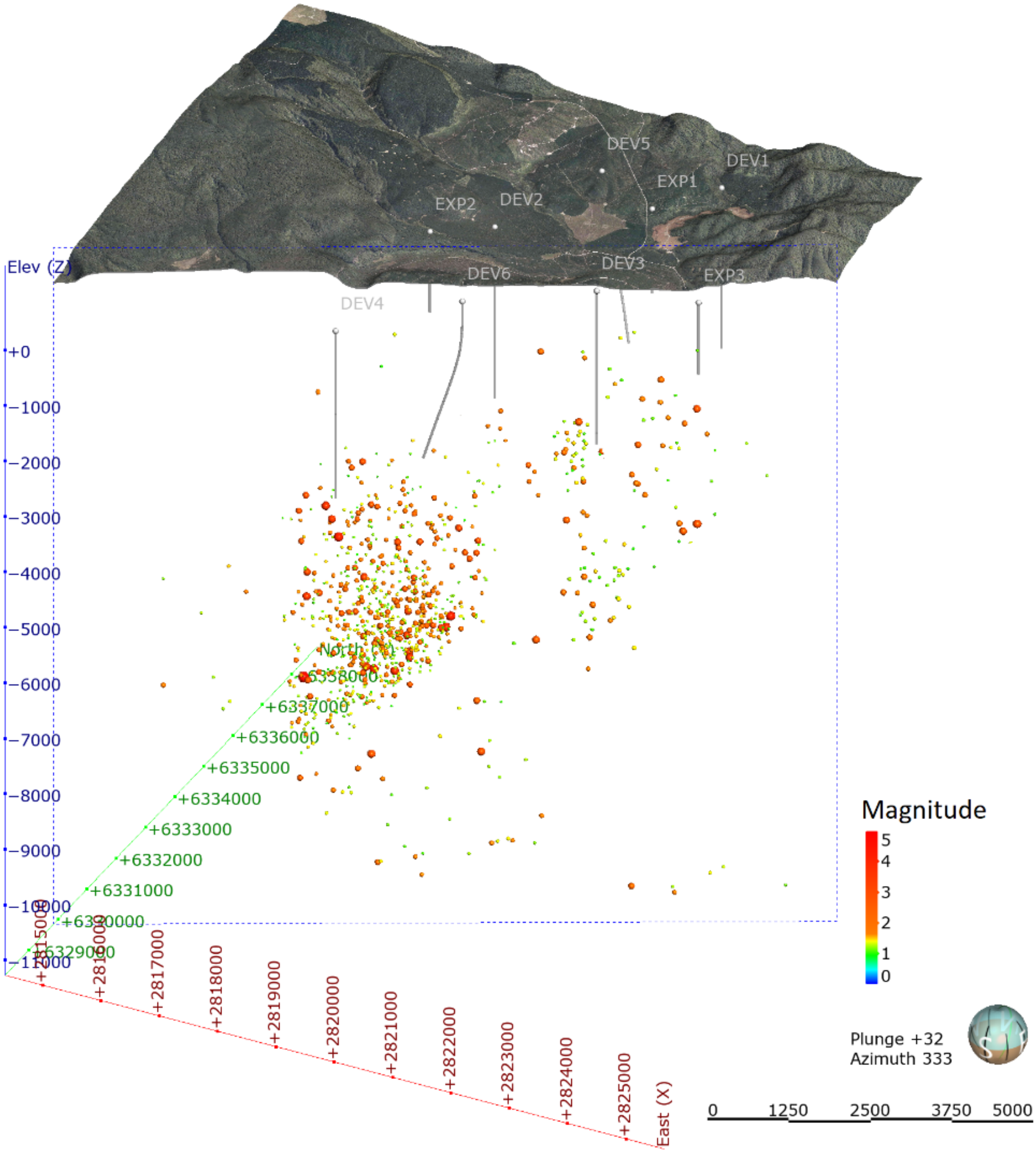


Figure 16: Visualisation of the seismicity recorded below the area of interest over a 10-year period

c. Combined model

By creating a series of 3D models representing multiple geoscientific datasets, whether it is temperature, geology, alteration, or otherwise, there is a possibility to provide even more information on the geothermal system by combining them together to study their spatial distribution relations. This approach was presented by O'Brien et al. (2018) and is illustrated by several case studies.

One of the most powerful abilities of 3D modelling packages is when combining multiple models constrained by different datasets (Figure 17). This technique compliments the other current methods applied in geothermal resource assessment and is a valuable tool which can speed up the process and remove the ambiguity around spatial correlation of different subsurface parameters. It improves the spatial context in resource assessments which are normally limited to the 2-D space (O'Brien et al.,2018) and can also be particularly useful in a well planning exercise.

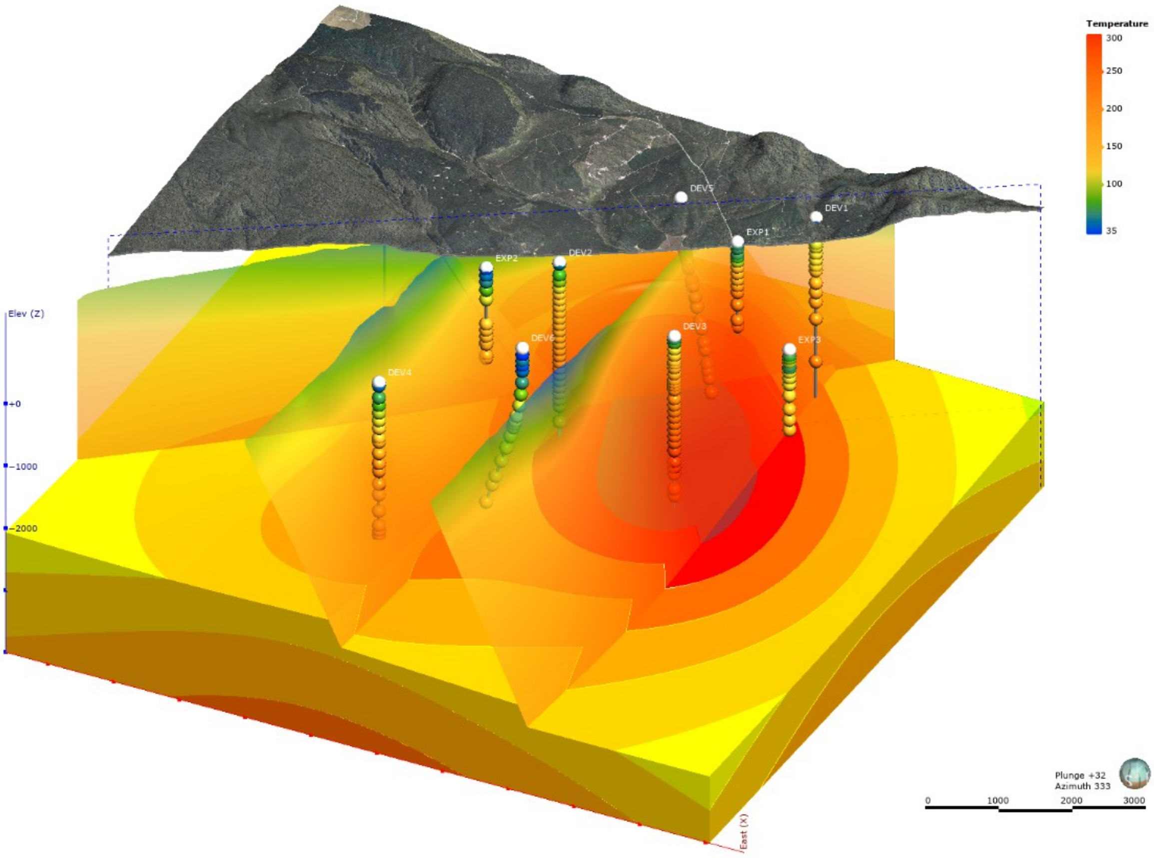


Figure 17: Model showing the temperature distribution on the basement formation and on the main faults

d. Drilling parameters and other well data

Many of the parameters recorded by the rig system, during the drilling of any type of well, can be easily integrated into a 3D model as far as they depend on depth. In the case of drilling without returns, which happens frequently in geothermal (especially while drilling through highly fractured formations), drilling parameter records are the only data available during and right after the well drilling, before any log has been run into the hole. A variation in the Rate of Penetration (ROP), for example, can bring valuable information on a change of lithology or the presence of a less competent fractures zone. The differential (Δt) between the temperature of the mud injected into the well and the temperature when it gets out of the well with the cuttings, can indicate zones of higher thermal signature, possibly related to hot geothermal fluid entries into the wellbore.

To simplify the identification of zones with remarkable values or variations of these parameters, it is recommended to filter them to the most significant intervals. In some cases, these intervals can be correlated between wells, establishing a trend likely to be related to a geological element such as a fault of a zone of alteration. These zones can later be investigated closely when running geophysical logs.

Drilling parameters, similarly to any data being recorded or created during the drilling operation, can be updated on a daily basis into the geological model for 3D visualisation and eventually to update the model while drilling.

e. Geophysical log visualisation

During or after the drilling of an exploration or development well, a series of specialised geophysical logs may be completed for the whole length of the well or only for (a) selected interval(s). A wide range of different measurement types can be completed with logging tools (Figure 18):

- Natural gamma ray
- Gamma ray
- Neutron-Neutron
- Resistivity
- Sonic log
- Televiewer (FMI)

Figure 18: Example of geophysical logs: Interpretation of fractures from FMI log and Upscaled Gamma Ray log.

CONCLUSIONS:

By employing specifically developed 3D modelling tools in the early stages of a geothermal project, it's possible to represent the evolution of the understanding of a resource over the project's life. While more data is gathered during surface exploration, drilling, or with the analyses carried out in the laboratory, their integration into the 3D modelling software will create new insights into resource characteristics or the accuracy of previous assumptions.

At any time during a geothermal project's lifecycle, the model will represent the best understanding of the geothermal resource and will be fundamental to future work planning. Whether an organisation is planning to drill new wells, select an area for geophysical surveying, or wants to ensure the reservoir simulation model best represents the conceptual model, the 3D model will guarantee the best-informed decision will be made.

REFERENCES:

Abraham, S., Kimani, F., Njau, K., Baxter, C., O'Brien, J., 2018. Early Stage 3D Model Construction for Well Planning:A Case Study from Barrier Volcanic Complex, Kenya. Geothermal Resources Council Transactions, Vol. 42, 11p.

Alcaraz, S., Lane, R., Spragg, K., Milicich, S., Sepulveda, F., Bignall, G., 2011. Proceedings, 36th Workshop on Geothermal Rservoir Engineering, Stanford University, Stanford, California, January 31-February 2, 2011, 6p.

Alcaraz, S.A.; Rattenbury, M.S.; Soengkono, S.; Bignall, G.; Lane, R. 2012 A 3D multi-disciplinary interpretation of the basement of the Taupo Volcanic Zone, New Zealand. *Stanford Geothermal Program Workshop report SGP-TR-194. 8p.*

Alcaraz, S., Chambefort, I., Pearson, R., Cantwell, A., 2015. An Integrated Approach to 3D Modelling to Better Understand Geothermal Reservoirs. Proceedings, World Geothermal Congress 2015, Melbourne, Australia, 19-25 April 2015, 7p.

Alcaraz S.A., Barber J. 2015. A 3-D geological model of the Rotorua Geothermal Field. *New Zealand Geospatial Conference*, Christchurch, 7- 9 December 2015.Delwiche, B., Peters, B., Sophy, M., Smith, C., O'Brien, J., 2018. Successful Deployment of a Multi-Crossing Directional Drilling Method at Ormat's New Tungsten Mountain Geothermal Field in Churchill Country, Nevada. Proceedings, 43rd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 12-14, 2018, 15p.

Kandie, R., Mbuthia, P., Stimac, J., 2016. Use of Leapfrog Geothermal Software in Data Integration and 3D Visualization, Case Study of Olkaria Domes Geothermal System. Proceedings, 6th African Rift Geothermal Conference, Addis Ababa, Ethiopia, 2nd-4th November 2016, 12p.

Massiot, C.; Bignall, G.; Alcaraz, S.A.; van Moerkerk, H.; Sepulveda, F.; Rae, A.J. 2011 The history of the Ohaaki Geothermal Field in 3D. *NZ Geothermal Workshop 33,* paper 41 (4 p.)

McDowell, J., and White, P., 2011. Updated Resource Assessment and 3D Geological Model of the Mita Geothermal System, Guatemala. Geothermal Resources Council Transactions, Vol. 35, 99-108.

Mibei, G., Mutua, J., Kahiga, E., Lopeyok, T., 2017. The Use of Leapfrog Software in Geothermal Conceptual Modelling: Case Study of Menengai Geothermal Field. Geothermal Resources Council Transactions, Vol. 41, 12p.

Milicich, S.D.; Bardsley, C.; Bignall, G.; Wilson, C.J.N. 2014 3-D interpretative modelling applied to the geology of the Kawerau geothermal system, Taupo Volcanic Zone, New Zealand. *Geothermics, 51:* 344-350; doi: 10.1016/j.geothermics.2014.03.002

Milicich S.D., Alcaraz S.A., Pearson-Grant S.C.P. 2015. An integrated approach to geological and fluid flow modelling: from 3D geological model to Tough2. paper no. 17. *NZ Geothermal Workshop 37, Taupo.*

Milicich S.D., Pearson-Grant S.C., Alcaraz S.A., White P.A., Tschritter C. 2018. 3D Geological modelling of the Taupo Volcanic Zone as a foundation for a geothermal reservoir model, New Zealand Journal of Geology and Geophysics, 61:1, 79-95.

Newson, J., Mannington, W., Sepulveda, F., Lane, R., Pascoe, R., Clearwater, E., O'Sullivan, M.J., 2012.Application of 3D modeling and visualization software to reservoir simulation: Leapfrog Geothermal and TOUGH2. Proceedings, 37th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 30-February 1, 2012, 6p.

Nusantara, V.D.M., Prasetyi, L.M., Thamrin, M.H., Siahaan, E.E., 2017. #D Geological Modelling: An Advanced Method to Build Geological Baseline Model in Hululais Geothermal Prospect, Bengkulu, Indonesia. Proceedings, New Zealand Geothermal Workshop 2017, 4p.

O'Brien, J., Sepulveda, F., Williams, B., Mitchell, T., McLennan, T., 2018. Combined Models: Integrated geothermal resource assessment using multi-parameter 3D models. Geothermal Resources Council Transactions, Vol 42, 2018.

O'Sullivan, J., Croucher, A., Popineau, J., Yeh, A., O'Sullivan, M., 2019. Working with Multi-million Block Geothermal Reservoir Models. Proceedings, 44th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 11-13, 2019, 11p.

O'Sullivan, J., Archer, R., O'Sullivan, M., Krom, T., Williams, B: A New Geothermal Modelling Workflow Using Leapfrog and TOUGH2. *Proceedings*, 6th ITB International Geothermal Workshop 2017. Institut Teknologi Bandung, Bandung, Indonesia, March 22-23, (2017).

Pearson, S.C.; Alcaraz, S.A.; White, P.A.; Tschritter, C. 2012 Improved Visualisation of Reservoir Simulations: Geological and Fluid Flow Modelling of the Tauranga Low-Enthalpy Geothermal System, New Zealand. *Geothermal Resources Council 36.* p. 1293-1297.

Poux, B., Gunnarsdottir, S.H., O'Brien, J., 2018. 3D Modeling of the Hellisheidi Geothermal Field, Iceland, Using Leapfrog. Geotehrmal Resources Council Transactions, Vol.42, 19p.

Sepulveda, F.; Alcaraz, S.A.; Lane, R.; Rosenberg, M.D.; Rae, A.J.; Bignall, G.; Mannington, W. 2010 3D geological model of the Wairakei Geothermal Field. *GeoNZ 2010, Auckland. 129A.*

Stimac, J., Mandeno, P.J., 2016: A workflow for 3D Geothermal Conceptual Models – Moving Beyond the Flat Cartoon. Geothermal Resources Council Transactions, Vol. 40, 14p.

Stimac, J., Wilmarth, M., Mandeno, P.E., Dobson, P., Winick, J., 2017. Review of Exploitable Supercritical Geothermal Resources to 5km at Geysers-Clear Lake, Salton Sea and Coso, Geothermal Resources Council, Vol.41, 30p.

Wulaningsih, T., Fujii, Y., Tsutsumi, S., Inagaki, H., Umee, Y., O'Brien, J., 2017. A 3D Model of the Yamagawa Geothermal System: Insights into Reservoir Structure and Future Field Management. Proceedings, New Zealand Geothermal Workshop 2017, 7p.