A CONCEPTUAL APPROACH TO 3-D "PLAY FAIRWAY" ANALYSIS FOR GEOTHERMAL EXPLORATION AND DEVELOPMENT

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Keywords: *Play Fairway, Resource exploration, 3-D modelling, Leapfrog*

ABSTRACT

"Play fairway" analysis has long been utilised in the hydrocarbon industry to assess exploration risk from regional to prospect-level scales. More recently this methodology has seen increased traction in the geothermal industry and resulted in a series of studies in the US. Some of the projects include the states of Hawai'i (Lautze et al., 2015, 2016, 2019), Nevada (Faulds et al., 2018, 2016, McConnville et al, 2017) and Utah (Wannamaker et al, 2016, 2017).

In a play fairway analysis, several parameters potentially indicating the presence of a geothermal resource at depth are categorized, weighted and combined together. This provides spatial distribution of the geothermal resource favourability to limit exploration risk. These analyses are generally limited to the compilation of surface data or results from past surface-based surveys for extended geographical areas, although some parameters such as the geothermal gradient are calculated using dispersed well data.

In this paper, a 3-D conceptual approach to the play fairway methodology is introduced, based on the existence of sub-surface data obtained at the project scale from advanced geological and geophysical surveys, drilling of exploration and/or development wells, laboratory analyses and well testing. A 3-D subsurface modelling tool was used to integrate the various types of data and then perform calculations and conditional queries using a gridded block model, resulting in a favourability Index model of the geothermal resource

Additionally, this 3-D favourability Index model is always based on the best understanding of the resource as it will dynamically update when new data is integrated. The model can also be refined with additional parameters relevant to specific projects (e.g. local legislative constraints). The methodology and the calculations created can easily be transferred to any other geothermal field dataset to compare results providing a repeatable workflow allowing prospects to be easily benchmarked or compared.

1. OVERVIEW

Applying geographically sparse data to provide an understanding of the subsurface is common across the resource related industries. Over many years of varied subsurface exploration by both governments and private enterprises significant amounts of data has been collected and is available in different forms.

Utilising this data along with data collected recently, geothermal scientists and resource experts conceptualise areas of interest for exploration and development.

The purpose of this paper is to demonstrate the possibility to adapt the Play fairway method, to a 3-D environment for the high grading of areas of interest for geothermal exploration.

In this paper, the dataset used is a synthetic geothermal dataset that was specifically created for the development or improvement of workflows applied to geothermal project data. It combines numerous data types that are frequently available for geothermal prospects around the world, including surface and sub-surface data resulting from surveys at various levels.

To present a wide range of possibilities to integrate various types of data, we have combined data from surface studies (geophysics mostly) with data provided by the drilling of several shallow and deep wells. The method could be used at an earlier stage in the resource evaluation process, even before drilling the first well and be updated with new data being integrated in the model later.

The purpose of this analysis is ultimately to select the best site for the drilling of (a) new production/exploration wells(s). We don't consider here the selection of drilling site(s) for (an) injection well(s). Although the workflow would also work but the data would need to be selected and categorized differently.

2. RESOURCE PARAMETERS

For a geothermal resource to exist and to be sustainably exploited, there are some critical elements that need to be present and fit well together. There has to be enough heat stored to convert it to energy within the surface facility and a heat source to make the system sustainable. Also, permeability is important for the hot fluids to circulate and rise but also for the recharge of the reservoir. The impermeable seal is also critical to the presence of a reservoir as it allows for temperature and pressure to build up underneath it, creating a reservoir that can be tapped into. All the information collected from the surface and subsurface contribute to understanding the three elements described above.

The presence of a reservoir is not the only criteria for the exploitation to be feasible, it also needs to be economically viable. Drilling deep wells is a major cost in exploration and development of a geothermal project. The resource has to be located at depths that can be reached by drilling at a cost that can be recovered quickly once the power plant starts operating. The depth at which it is economically viable to drill is ultimately related to the size and temperature of the resource and how much energy can be generated from it.

In the following paragraphs we explain which data is used to identify, locate and define each of these elements and their source, as well as how the drilling component was considered

2.1 Heat

Understanding the origin of the heat that created a geothermal system as well as the current distribution of the temperature in the sub-surface are some of the most important criteria to the presence of a viable geothermal resource.

2.1.1 Natural State Temperature model

The sub-surface temperature distribution is used to determine the location and extent of a geothermal resource. Different ranges of temperature might be considered economically viable for power generation, depending on the technology used for the powerplant and the geographical location of the project. It is also important to consider intermediate temperature zones as the fluid can also be used for direct use applications such as heating, although it might not always be the purpose of the geothermal project development.

The natural state temperature model for the dataset presented was generated using the natural state temperature profiles of the existing wells but also considers the geological parameters and results of geothermometry. This model could be further improved by integrating logs from new wells or laboratory results from studies of fluid inclusions for example. The interpolant algorithm used to estimate temperatures away from the data and create iso-surfaces is a linear function which is best to apply to sparsely distributed data.

2.1.2 Alteration mineralogy

In geothermal systems, primary minerals present in formations tend to transform into secondary minerals, also called alteration minerals. Their nature is highly dependent on the chemistry of the primary minerals and the fluids present, as well as the temperature, permeability, pressure, and duration of the hydrothermal alteration processes. These minerals are well-known in most geothermal systems, and do not vary too much between systems. The understanding of their formation conditions and relation to the most prospective areas for a geothermal reservoir, grows along with the advancement of a project exploration and development stages.

The alteration mineralogy data are the results of X-Ray diffraction and microscopic analyses completed on the rock cuttings collected during the drilling of the wells. Important secondary minerals such as Epidote or Actinolite (Amphibole) are good indicators of the highest temperature zones of the reservoir and are of particular interest when analyzing the samples or cuttings and were considered in the synthetic geothermal dataset. Depending on the geology and alteration conditions in a field, other secondary minerals of interest identified might include Zeolites (Wairakite for example) or other high temperature secondary minerals.

2.2 Permeability

For a viable geothermal resource to exist, the ability for fluids to circulate through the rocks in the subsurface is essential; high temperature fluids can circulate to shallower depths and be reached easily by drilling. Colder fluids, either injected into wells or from natural recharge, can reach the reservoir area using permeable pathways to capture heat, making the resource exploitation sustainable. In active volcanic zones particularly, neutral-pH fluids, more appropriate for production, are encountered in the outflow zones, these hot fluids rely on a network of fractures to rise from depth and move laterally from the upflow zone.

There are several techniques to identify the areas of higher permeability, some rely on a good understanding of the local geological structure, based on surface field work, geophysics and well data. Others will require a comprehensive study of the local tectonic behaviour over time.

2.2.1 Structural model

Building a comprehensive structural model of the project area is critical to locate the zones used for fluid circulation. Faults are the first element to consider when looking for permeability, some might be regional and potentially driving the natural recharge of the reservoir and possibly have a wider aperture. Areas with a high density of faults or fault intersections are likely to have a high permeability and must be prioritized.

To understand the fault system, many sources of information can be considered including remote sensing, field mapping, and geophysics (gravity and magnetics), well data if available (fracture filling mineralogy or minerals indicating permeability like Pyrite) or from downhole surveys using FMI (Formation Micro-Imager) or photo logging tools.

The fault system for the synthetic geothermal system is composed by five faults identifiable on surface but also encountered in some of the wells and with geophysical surveys.

2.2.2 Seismicity

Seismic events are directly related to movement along and around geological structures and therefore provide indications on fault locations and activity. Active faults are more likely to have open permeable zones than inactive faults that might be filled with mineral precipitation. The two components to consider when looking at seismicity data are the clusters of seismic events but also their magnitude. Both variables are usually recorded by a number of seismometers deployed on surface in the vicinity of the project area or as a part of a national network. If some wells are being utilised for fluid injection or hydraulic fracturing, it is important to identify and remove these seismic events from the analysis to avoid errors in their interpretation.

The data available for the synthetic project includes twenty years of seismicity and micro-seismicity recordings with magnitude values ranging between 0.5 (lower bound detection limit) and 3.76 for a total of 10 191 events

2.2.3 Fluid entries

There is no better indication of the presence of hot geothermal fluids in a permeable faults or formation than when they have been intersected in a well and fluid flows naturally out of them. Ultimately, if available, the flow rate of each of the fluid entries and their location in the well will allow to prioritize zones with the highest energy production potential on the fault plane or formation.

If the information on each of the fluid entry is not available, their location and the total flow rate of the well will provide a great insight into the reservoir as well.

2.3 Seal

The impermeable seal above the reservoir is the third element essential to the presence of a reservoir beneath it. Hot fluids circulate upward through permeable pathways until they are stopped by the impermeable seal and create the high pressure, high temperature reservoir

The seal is generally formation or alteration driven and also called the “clay cap”, as it is generally constituted by various clays minerals resulting from the hydrothermal alteration of the primary minerals. Consequently, various data sources can be used to determine the location and extent of the seal.

2.3.1 Magnetotelluric data

The Magnetotelluric method (MT) is a passive geophysical method that involves measuring time variations in natural electric and magnetic fields and is used to identify resistivity patterns in the subsurface. Resistivity is a relevant parameter in the case of geothermal exploration as it highlights the changes in physical properties of the formations (Ussher et.al, 2000).

Clays are hydrous aluminium phyllosilicate minerals and the Smectite clay in particular is a good conductor of electric current. MT is the best method to resolve low resistivity/ highly conductive areas corresponding to the clay cap, usually with resistivity lower than 10ohm-m and at depths shallower than 2000m. The base of the conductive clay cap is commonly considered as the expected depth of the reservoir temperature.

2.3.2 Alteration mineralogy

The same way as the observation of high temperature secondary minerals may indicate the reservoir zones, alteration minerals such as Smectite, Illite, Chlorite or a Mixed-layer clays are direct indicators of the depth and thickness of the clay cap. These minerals are hardly recognized while looking at drill cuttings, except for some Chlorite minerals or using the methylene blue titration for the Smectite, but they can be clearly identified with the X-ray diffraction analyses.

2.4 Drilling economics

Some of the data presented previously are the direct result from drilling deep wells. The data obtained and the resulting interpretations will permit to select the best drilling site(s) for (a) new well(s) based on the characteristics of the resource. However, to make sure the new wells are drilled at the lowest cost possible and with the highest chance of success, the target must be carefully selected. The drilling depth and the distance from existing wells needs to be considered in the analysis.

2.4.1 Drilling depth

Drilling costs increase exponentially with depth. Most wells in geothermal fields are drilled to depths between 1500 and 3000 meters. Below this depth, wells might only be considered economical if the resource is composed by steam only like in the Geysers in California. In this synthetic geothermal project, we are considering a liquid-dominated resource similar to most of the developed geothermal resources worldwide.

2.4.2 Distance to existing wells

Depending on the geothermal field, connectivity between the wells varies a lot. Drilling a well too close to an existing producer or injector might results in lowering the output of one or both wells. When selecting the drilling target at depth, it is important to consider the distance from existing wells, the greater the distance, the lower the risk.

3 PROCESS AND RESULTS

Once all the data have been gathered in the 3-D environment and the different models described previously have been created and represent the best understanding of the resource elements, they can be prepared and utilized for the 3-D play fairway analysis. This process can be divided in three phases; first the datasets and models will be projected on a 3-D grid called Block model to convert them all in a similar format. Then, each of the projected models or dataset will be categorized to attribute Index values based on their interest to indicate the presence of a geothermal resource. Finally, all the Index Models created will be factored and combined to obtain the final Favourability Index Model. Each of these three steps is detailed in the following paragraphs

3.1 Block model

Block models are essentially a set of blocks of a size specified by the user aligned along a given azimuth on which is it possible to project any model previously created. All the blocks have the same size, but their characteristics will vary based on the model being evaluated on the block model. It is widely used in the mining industry for mineral resource estimation as it also facilitates the use of advanced geostatistics.

Figure 1 shows an example of the lithological model being evaluated on a block model. The block model used in this analysis is 10 x 10 km and 5 km thick, it is aligned along the X and Y axis (azimuth 0°). Each block is a cube of 100 m edges. There is a total of 500,000 blocks in the model used for this study, but the block model dimensions and the block size could always be modified later if necessary.

In the cases of the lithological, alteration mineralogy, natural state temperature and drilling depth models, no preparation was necessary before evaluating them on the block model. For other models, such as the structural model, where faults and fault intersections were considered and for the location of wells, a distance function analysis was applied to create a 3-D models from the 2D surfaces and lines.

In the case of the resistivity model, the seismicity and the fluid entries, some interpretation, pre-categorization analyses and/or calculations were completed before assigning the Index values.

The resistivity values can not be directly correlated to the presence of a geothermal system, instead geophysicists analyze the spatial variations of the resistivity values to interpret where the geothermal reservoir is most likely to be found and identify possible fluid circulation patterns. The resistivity model was cut to a minimum elevation of -3500 meters to match with the other datasets and divided into five zones, varying from very low to very high favourability to the presence of a geothermal resource.

A density analysis to estimate the number of seismic events in a block was first completed to highlight the zones with earthquake clusters and the number of events in each block was then multiplied by the average magnitude of the events in that same block. This analysis permits to highlight both the areas with a high density of seismic events but also where the events with the highest magnitude are located.

For the fluid entries in the wells, a distance analysis from the production zones was first completed. The value used for categorization is equal to the square of the flow rate (in liters per second) of a productive zone divided by the distance from that zone. The goal is to increase the influence of the most productive zone on the attribution of the Index value instead of only considering the distance from it.

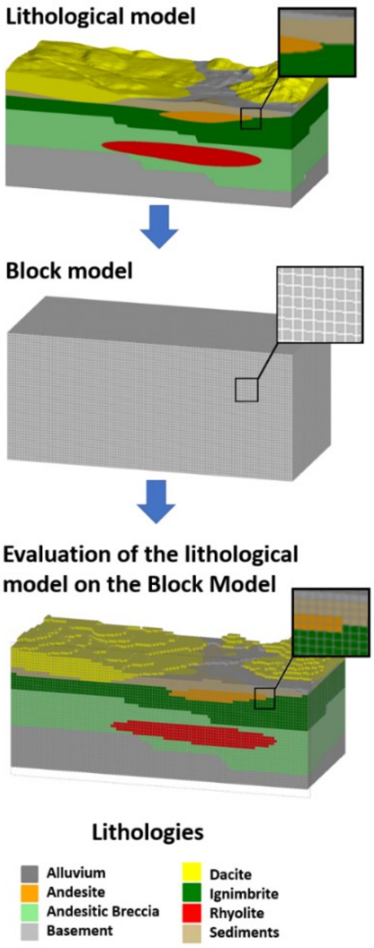


Figure 1: Principle of Block Model evaluation using the case of the lithological model

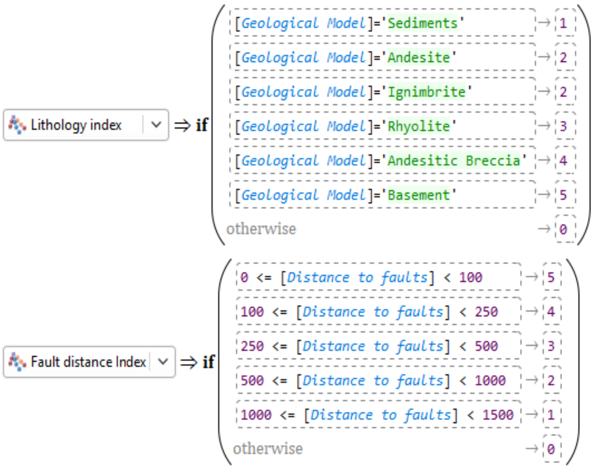
3.2 Categorization

Creating block models within Leapfrog Geothermal, gives the possibility to run calculations, apply filters or do conditional queries on the data for each of the blocks. These tools will be used to complete the play fairway analysis.

For this step, it is necessary to convert all the models into categorized models using Index values to be able to combine them later using mathematical operations. The results of the categorisation from the models created a series of Index models. For each of the Index models, values assigned for the Index are between 0 to 5, 5 being the most favorable areas or value intervals for the presence of a geothermal resource or indicating a better location for drilling a new well and 0 being assigned for low favourability.

To create categories for each of the models available, conditional queries (type IF-THEN-ELSE) where used on the values or categories assigned to the blocks in the block model. For categorical models, such as the lithological, alteration mineralogy or resistivity interpretation models, the assignment of an Index value to each category is based on their degree of favourability to the presence of a geothermal reservoir. For models based on numeric values representing a physical parameter (e.g. temperature), the distance to one of more objects (e.g. faults and wells) or the results of more advanced calculations (fluid entries, seismicity analysis), the Indexes were attributed using mathematical operators (lower ≤ n < upper).

Figure 2 shows how the lithologies and the distance to faults was categorized and the Index attributed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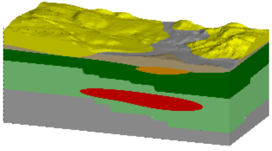
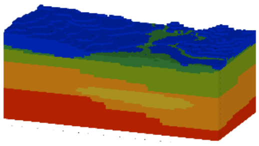
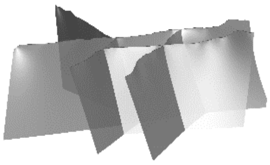
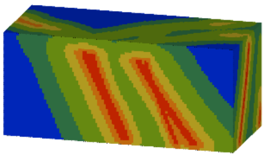
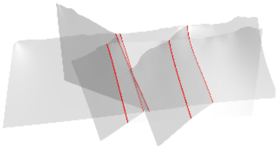
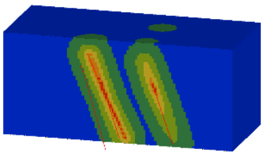
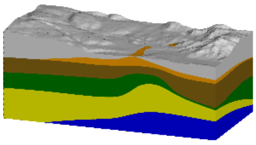
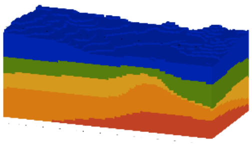
Lithology index  ⇒ if ( [Geological Model]='Sediments'          → 1
                        [Geological Model]='Andesite'           → 2
                        [Geological Model]='Ignimbrite'         → 2
                        [Geological Model]='Rhyolite'           → 3
                        [Geological Model]='Andesitic Breccia'  → 4
                        [Geological Model]='Basement'           → 5
                        otherwise                               → 0 )

Fault distance Index ⇒ if ( 0 <= [Distance to faults] < 100       → 5
                            100 <= [Distance to faults] < 250     → 4
                            250 <= [Distance to faults] < 500     → 3
                            500 <= [Distance to faults] < 1000    → 2
                            1000 <= [Distance to faults] < 1500   → 1
                            otherwise                             → 0 )
```

Figure 2: Example of categorization and Index value attribution for the Lithology and Fault Distance Indexes

The color codes used in the Index models shown in Figure were assigned as: blue:0, dark green:1, light green:2, yellow:3, orange: 4 and red:5. The only exception is for the temperature model that was divided in 10 Index values every 0.5 from 0 to 5. Temperature being an important element of the evaluation, it was more adapted to create additional intervals.

Lithologies 	Lithology Index 
Structural model (Faults) 	Fault distance Index 
Structural model (Fault intersections) 	Fault intersection distance Index 
Alteration Mineralogy model 	Alteration mineralogy Index 

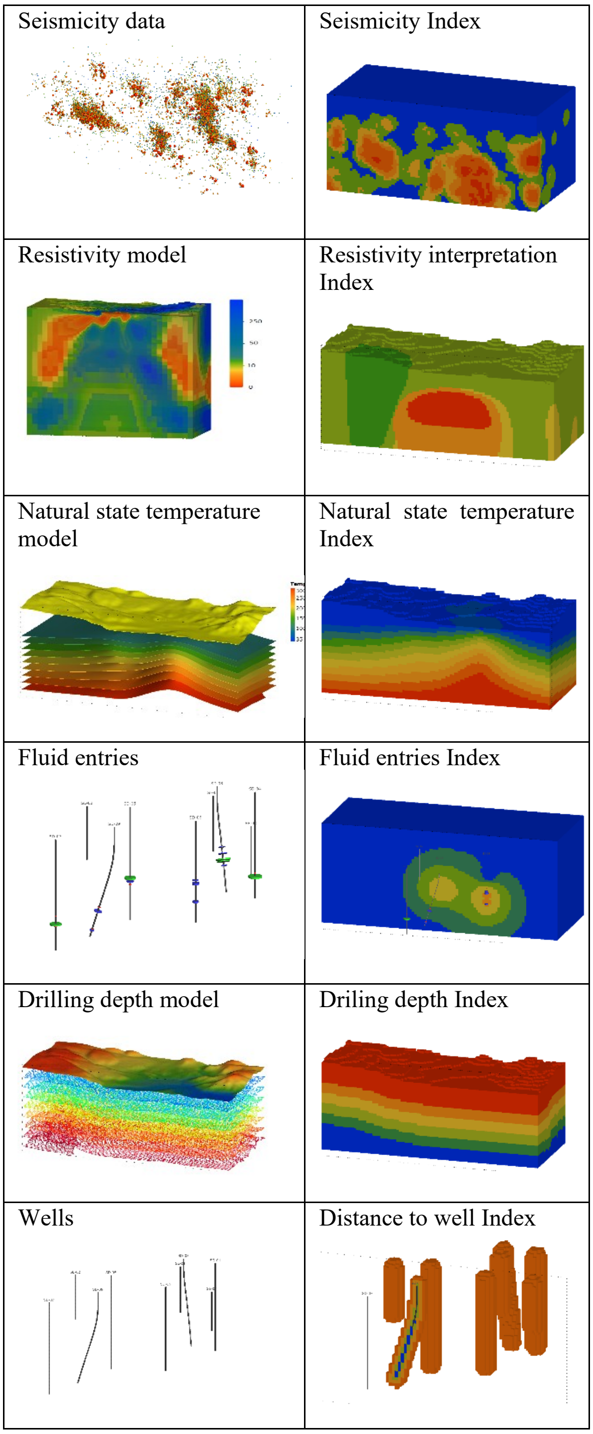

Seismicity data
Seismicity Index
Resistivity model
Resistivity interpretation Index
Natural state temperature model
Natural state temperature Index
Fluid entries
Fluid entries Index
Drilling depth model
Driling depth Index
Wells
Distance to well Index

Figure 3. Input models or dataset with their respective Indexes Models used for the processing

3.3 Favourability Index model

Once all the Index models have been created, the last step consist in combining them all into one main Favourability Index models, which will show where are the most promising areas for drilling based on the data that were used.

Before combining the Index models, multiplying factors were attributed for some of them considered of higher or lower importance with regards to their favourability to indicate the presence of a geothermal resource or for drilling economics

For example, a factor of 2 was assigned to the temperature Index model values as the temperature is one of the most important parameters when identifying a geothermal resource. A factor 2 was also assigned to the distance from existing well Index model values, as it is important to consider interference with existing wells. To the contrary the fluid entries Index has a 0.5-multiplying factor as this Index is highly influenced by the location of existing wells and could potentially constitute a bias to the analysis. The full calculation to determine the final Favourability Index values is shown below. The total is divided by 55 in order to keep the Index value between 0 and 1 for an easier interpretation of the results. These factors could easily be modified is the user would like to increase the influence of one of the Index Model.

Favourability Index = (Lithology Index +1.5* Fault distance Index + Fault intersection distance Index + Alteration Mineralogy Index + Seismicity Index + 1.5 * Resistivity Index + 2 * Temperature Index + 0.5* Fluid entries Index + 0.5* Depth Index + 2* Distance from well Index) /55

The resulting 3-D Favourability Index Model is shown in Figure 4. The model was sliced through to better visualise the central area with higher favourability and the red zones that are unsliced represent the highest favourability areas (Index above 0.9).

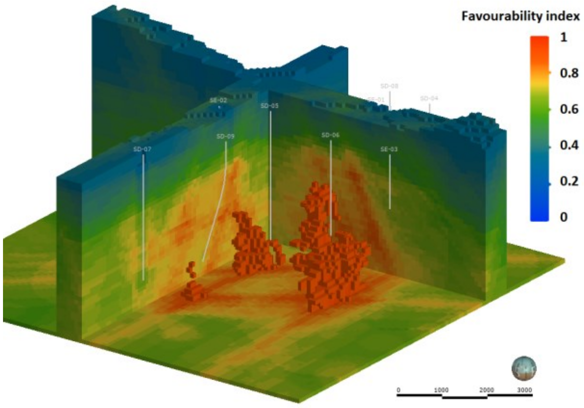


Figure 4: 3-D Favorability Index Model, red blocks show the Index of 0.9 and above

The results show the important role played by the faults in the analysis and this was done on purpose by considering both the faults and the fault intersections and by increasing the multiplying factor. Permeability is an important parameter when selecting a drilling target and this result reflects it. However, it is also clear that temperature, lithologies and alteration mineralogy are playing a major role in the evaluation as the permeability as shallow areas are not included in the most favorable areas.

The MT interpretation definitely plays a role as the areas interpreted as the most favorable were located in the central part of the model similarly to the final model.

The role of models such as the seismicity one is harder to appreciate as the data were spread all around the study area, but it has an influence on selecting the most seismically active areas of the faults.

It can also be noticed that the areas around the existing wells, even where should have been a higher favorability area have been integrated in the evaluation.

Figure 5 shows the histogram for the Favorability Index values. The blocks with an Index value greater than 0.9 represent about 0.3% of the total, and the blocks with values greater than 0.8 represent about 5%. This result confirms that this method identified only limited areas to prioritize when planning the drilling of future production wells to limit the risks.

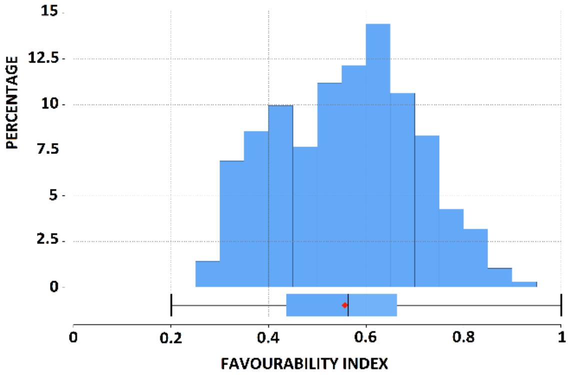


Figure 5: Histogram of the Favourability Index distribution

4. DISCUSSION

We have demonstrated the feasibility of Play fairway analysis in the 3-D space for geothermal resources, how it would enable a better understanding of the sub-surface characteristics and lead to reduced drilling risks.

The number of models that were integrated in the analysis could be extended, the more datasets are integrated in the process, the better and more reliable the results will be. Some of these datasets could include fluid or rock geochemistry, advanced fracture analysis, stress/strain analysis or more cost-related elements.

The intervals created to assign the index values as well as the weights used when combining the various index models can be changed to reflect the characteristics of a resource or the priorities of such evaluation. For low to medium temperature geothermal projects for example, the Index models could be adapted as the drilling depth would become an important limiting factor in the feasibility of a project; the connectivity between the wells and the temperatures intervals considered would also differ.

To be validated and improved, this method should be deployed on a number of existing projects at various stages of exploration and development and in different geological contexts. This would allow, with enough datasets available to establish the best ways the categorize the Index Models and to use the best fit for the multiplying factors when calculating the Favourability Index values. The process could easily become repeatable and allow for benchmarking and comparing geothermal fields. To further enhance establishing the categories and multiplying factors, machine learning and advanced geostatistics could prove particularly useful.

ACKNOWLEDGEMENTS

The authors would like to thank the organisations who have contributed to the creation and enhancement of the synthetic geothermal model including GNS Science, the University of Auckland and other Seequent employees.

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