3D “Play Fairway” Analysis in Geothermal Reservoir Modelling and Sweetspot Identification

Muhammad Ikhwan
Pertamina

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Muhammad Ikhwan, Sigit Suryanto, & R. Mochamad Tofan. S

Pertamina Geothermal Energy, Grha Pertamina, Jl. Medan Merdeka Timur, Gambir, Jakarta 10110

ikhwan.aziz@pertamina.com

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ABSTRACT

Play fairway analysis (PFA) has long been utilised in the hydrocarbon industry to assess exploration risks from regional to prospect-level scales. The geothermal play fairway concept involves the integration of multiple parameters indicative of geothermal activity to identify promising areas for new development. Here we attempt to characterize the geothermal reservoir through the PFA method by using multiple surface-acquisition data and subsurface data from drilling and well measurements. Geoscience plus geomechanics and geostatistical techniques were employed to define the most likely sites in the geothermal field that have a high drilling success ratio. The weighting of each data refers to their relationship to the heat, fluid, and permeability identification. The 3D probability model is the result of detailed analyses and generates a detailed play fairway 3D model and the estimated most favourable "sweetspot" to drill to support the next well-targeting strategy. The PFA model distribution shows relatively matches with the feedzone interval on the existing production wells and confirms the distribution of the interpreted hydrology in the conceptual model. The PFA model is data-dependent so it will be updated once the new data is available. The scope of the PFA modelling also needs adjustment with the understanding of the conceptual model to avoid the overestimated resource analysis and modelling.

1. INTRODUCTION

Geothermal play fairway analysis (PFA) is a spatial and geostatistical approach that aims to delineate the most favourable area in a geothermal field and reduce the geothermal risk both in exploration and development. Formerly, the play fairway approach was used and proved in the oil and gas industry, published by (Fraser and Gawthorpe, 2003) where they were working on exploration and development risk in a basin assessment. The goal of the approach is to identify the key variables that are required for resource occurrence or 'play' (e.g., permeability, organic source rock, trap, migration pathway, and heat source) and integrate datasets that can constrain these variables either as direct or proxy evidence to identify areas with prospective (i.e., the 'fairway').

PFA is a flexible, scalable, objective, and effective method for integrating multiple, disparate geoscience data types and incorporating input datasets concordant with their importance as related to geothermal system occurrence. The combination of datasets can provide greater insight into the favorability of an area as opposed to map products presenting individual evidence layers such as structure. Application to geothermal prospects began in the early 2000s and has continued to grow in practice globally with studies in places such as Australia, Italy, Japan, Turkey, and the United States (Lindsey et al., 2021). A major push for PFA occurred around 2014, with the U.S. Department of Energy funding a multi-phase PF initiative that ran from 2014-2019. Projects were conducted in multiple locations and geological settings in the USA, including Hawai'i, Nevada, Washington, and Idaho among others (Faulds et al., 2016, 2018).

Here we present the result of the PFA method application on the subsurface data, by using multiple data including the data gathered from the surface acquisition and drilling activity. Instead of delivering the PFA model in 2D or map products only, like the common PFA results in previous studies mentioned above, we focus on yielding the 3D PFA model so it can be used to estimate the best site to drill and support the well-targeting strategy in depth. This method was initially developed by Poux and Brien (2020), yet we developed some parameters that can escalate the confidence level of the PFA model. 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.

2. DATA CLASSIFICATIONS

In a promising hydrothermal system, four main components have to be presented; fluid, heat, permeability and caprock. Fluid is important to transfer heat energy efficiently through convection. Sufficient temperature or heat supply is critical to guarantee the sustainability of power generation. Sufficient permeability is needed to provide the media for hydrothermal fluid circulation including production flow and recharging process of the reservoir through the injection well. The caprock will keep the hydrothermal fluid temperature, preventing the possible heat loss in the reservoir. All the information collected from the surface and subsurface contributes to understanding the four 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 the 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. We called the data a parameter that composes each geothermal component. In this case, considering the geothermal reservoir is assumed saturated and focusing on the hydrothermal system, the fluid component is included in the permeability.

2.1 Heat

Heat stored in the hydrothermal fluid is the main parameter in a conventional geothermal system that will be extracted from the surface and transformed into energy. In the detailed geothermal system components, several parameters, which can be seen through the data, are could represent the heat including the natural state temperature model and also alteration mineralogy.

2.1.1 Natural State Temperature model

Temperature anomaly is the first parameter in favourable geothermal area identification. The distribution of the temperature extends usually dictates the geometry of the geothermal reservoir. The range of the temperatures also defines the utilization of the thermal energy, either for power generation or direct use such as heating and farming. In this case, the desired temperature is above 250°C (high-temperature anomaly) in a high-temperature hydrothermal system so it can purpose for electricity.

The existing wells' temperature data can be used to delineate the temperature model in a geothermal field as they represent the current and actual reservoir temperature. It also could be combined with the MT data if the data between wells are unavailable so the missing spatial data is unavoidable. In this case, the temperature data or isotherm in the base conductor layer is the key to draw and distributing the expected temperature following the geometry of MT data. In the case of the absence of drilling data, for example, in the greenfield exploration phase, the same method can be used to estimate the natural state temperature contour by using the reservoir temperature information from geochemistry estimation. Interpolation in modelling also contributes to filling the area away from the available data, so the model can be sparsely distributed.

2.1.2 Alteration mineralogy

The alteration minerals in a geothermal system are derived from the primary minerals that are altered due to their interaction with the hydrothermal fluid. Some alteration minerals also could be directly deposited in the rocks which originated from the hydrothermal fluid itself. Most of the alteration minerals among the geothermal systems globally are common, yet need an understanding of the formation origin to define the variability of the mineral.

The alteration mineral is commonly used to estimate the temperature in the formation or reservoir. They can be identified from several methods such as cutting, thin section, and laboratory analysis including XRD. Each alteration mineral is unique and has its temperature range, so it is possible to use them as the geothermometer that represents the heat in the subsurface. Some minerals in geothermal are a good indicator of high-temperature fluid such as epidote, biotite, and actinolite. For the lower temperature minerals or the caprock alteration minerals, smectite clay that is identified from both methylene blue test and XRD analysis is confidently used.

2.2 Permeability

Permeability is needed in developing the geothermal field, either natural or engineered, to transport the fluid which stores the heat energy. Permeability is, in essence, the capacity for fluid to flow through the rock. The permeability in a hydrothermal system is mostly controlled by fault and fractures, although matrix porosity from lithological units sometimes also has a critical contribution either. Permeability has a significant role in circulating the hydrothermal fluid so the sustainability of the system can be guaranteed. However, some external factors could also control the permeability magnitude such as confining pressure, so theoretically the permeability should be greater in the shallower depth.

There are several techniques to identify the areas of higher permeability, some rely on a good understanding of the regional tectonic framework and 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 Fault Core Model

Fractures or faults have a significant role in controlling the permeability of a geothermal field. So modelling the fault framework is necessary. The deterministic prominent fault model is mostly derived from remote sensing analysis and supported by fieldwork. Their interpreted distribution in the subsurface is mostly supported by an enhanced geophysical method such as the second vertical derivative and the Euler deconvolution method from the gravity data (Cooper, 2008). Therefore, To convince the structural interpretation, the gravity model is also used to support the existing prominent fault interpretation. They are assumed as the fault core in a fault geometry, which should be surrounded by a developed fracture zone and expected extensional fractures. Extension fractures and veins are commonly found adjacent to faults and within fault zones at a range of scales and provide a good permeability magnitude. In many cases of extension fractures observed around faults in the field, compelling arguments show that extension fractures formed synchronously with slip on associated faults.

The idea of using the fault core model as the permeability parameter is that fracture will be more developed and localized around the fault core, so the deterministic fault core model here can be used in a distance function. So the closer an area to a fault, the more fractures they get, which means there will be more fracture intersections that will enhance the potential natural secondary permeability. The fault core in this stage is assumed as a relatively planar fault plane without significant geometry and orientation changes. This method also will generate more fractures in a fault intersection area, as it is believed as a favourable zone for well targeting in a tectonic-controlled geothermal setting due to more fractures will be interconnected in the vicinity of the intersection fault plane.

2.2.2 Discrete Fracture Network (DFN) / Permeability

The discrete fracture network or DFN modelling is already considered one of the prominent methods to characterize the naturally fractured reservoir and is widely used in oil and gas and also mining industries. A "discrete fracture network" (DFN) refers to a computational model that explicitly represents the geometrical properties of each individual fracture (e.g. orientation, size, position, shape and aperture), and the topological relationships between individual fractures and fracture sets (Lei et al., 2017). The DFN model is derived from several methods and data input. 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 image log or photo logging tools. The DFN model was upscaled into a permeability model by inputting the fracture attribute such as fracture length and fracture aperture

2.2.3 Microearthquake

The microearthquake (MEQ) or microseismic data also can be interpreted as the permeable zone in the reservoir. The MEQ is the energy coming from low-magnitude earthquakes and small-scale movements. They occur due to the volume change within the rock mass or change in the shear-stress components (Zhang et al., 2015). However, they can also be caused by man-made sources (i.e. drilling, mining and hydrocarbon production). In this study, the MEQ event is interpreted as triggered by the movement of fluid flow through the fractures that cause the fracture. However, sometimes the MEQ events are not clustered or well correlated with the fault model. The density of the MEQ also could be influenced by the water injection from the injection well. In many cases, a MEQ event is not only triggered by fluid movement but also a pure tectonic event without involving fluid. Besides looking for the data density, the MEQ data is also possible to show the spatial pattern, which can be interpreted as a lineament related to a fault or fluid conduit. Nevertheless, events clustering is easier to determine from the available data instead of the spatial events pattern. Therefore, using MEQ data needs further quality control and data analysis.

2.2.4 Loss Circulation Zone

In geothermal drilling activity, permeability is often related to the occurrence of loss circulation zone, ether it is partial loss or total loss. Although loss circulation is one of the drilling problem causes, it also gives a good sign of a successful geothermal well targeting that hits a permeable formation. In this model, the lost circulation zone is classified based on the volume of drilling fluid loss during drilling. However, it is necessary to note that the loss circulation interval recorded in drilling parameters does not always represent the true depth of productive interval due to several factors. If available, the spinner logging data is more recommended to determine the feedzone interval.

2.2.5 Formation / Rock Unit

In some cases, the rock unit in the reservoir formation also contributes to the permeability through the matrix porosity or microfractures. For example, the pyroclastic unit that contains ignimbrite or volcanic breccia often identified has a significant role in the well-scale hydrothermal fluid flow although the fractures or fault is not considerably well-developed in the feedzone interval. Therefore, the rock unit can also be used as one of the permeability parameters.

2.3 Caprock

In a geothermal reservoir, the caprock or the impermeable formation is rock units on the higher level of the reservoir that seal the heat, maintaining the pressure and temperature to keep economically viable. The caprock was influenced by the lower temperature hot fluid (< 150°C) that altered the host rocks and formed clay minerals mostly smectite, and reduced the permeability magnitude of the host rock. Thus, the caprock in the geothermal reservoir is also often called the clay cap. Some data can be used to determine the spatial extension of the caprock in the reservoir, including MT and alteration mineralogy.

2.3.1 Magnetotelluric data

The MT method is a passive electromagnetic (EM) method where orthogonal components of electric and magnetic fields are measured at the surface of the Earth. The source fields are a wide spectrum of EM waves that naturally occur due to lightning discharges and interactions of solar winds and the Earth's magnetosphere. Information about the subsurface resistivity structure, from a few meters to hundreds of kilometres depth, can be interpreted from the collected data. Resistivity is a relevant parameter in the case of geothermal exploration as it highlights the changes in the physical properties of the formations (Ussher et.al, 2000).

The MT measurement in a geothermal reservoir is very sensitive to the smectite minerals in the caprock layer. Smectite is known as a very conductive clay mineral due to its high content of cation exchange capacity (CEC) (Levy et al., 2018). The occurrence of the smectite layer will give a contrast in the MT measurement of the reservoir conductivity. This method results in the determination of the base of the conductor layer so the top of the reservoir, which is more resistive, can be estimated.

2.3.2 Alteration mineralogy

As the caprock consists of alteration clay minerals, it is useful to perform the XRD analysis from the borehole cutting or core samples to delineate its distribution. An in situ measurement such as the methylene blue test (MBT) could also support the initial clay mineral analysis or support the MT data interpretation.

3. MODELLING PROCESS AND RESULTS

To determine the relative importance and ultimately the weightings for each dataset used to build a 3D play fairway model, we first reviewed each parameter dataset to determine which components of a geothermal system it was related to. It was determined that some datasets were positive indicators for more than one attribute; for example, the presence of alteration mineralogy could indicate the current or past presence of subsurface heat, and/or caprock, although in differing degrees. Where this was the case, the data layer was used in each of the attribute models (i.e., heat, permeability, and caprock) with appropriate weightings for that model.

For our PFA, two stages of data weighting were conducted at different stages of our workflow. First, each of the parameters above was weighted on a scale of 1 to 5 (5 being the most favourable) according to inferred importance or relevance to each model. Once all the data have been gathered in the 3D environment and the different parameter models described previously have been created and represent the best understanding of the resource elements, they can be prepared and utilized for the 3D play fairway analysis. The datasets and models will be projected on a 3-D grid or properties model to convert them all into a similar format and weighting scale. Second, the attribute models themselves were weighted on a scale of 0 to 1 (1 being the most favourable) to build the final composite 3D play fairway model. This workflow of the modelling is referred to Poux and Brien (2020). All weights for each stage of our workflow were determined using an expert-driven approach (knowledge-driven). We incorporated the expertise and local knowledge from our team to achieve consensus on appropriate weights and relative importance of the various evidence parameters and properties models. All of the models in this study were built using Petrel software.

3.1 Parameter's Properties Model

Each parameter described above is constructed into a 3D properties model, both for those collected from surface survey and drilling activity. Property modelling is the process of filling grid cells of the grid with discrete or continuous properties. This stage relies heavily on the input data and geostatistical methods, such as the Kriging or Gaussian method. Kriging is a deterministic interpolation griding one "best" local and smooth estimate. Uses variogram to search, collect and distribute data. Gaussian simulation is a stochastic method based on kriging, but capable of capturing extreme values in a heterogeneous reservoir. In reservoir modelling, several modelling approaches can be performed. Some of deterministic, providing one result, while others are stochastic, providing several equally probable results based on the same input data (only varied by a seed number used in a Monte Carlo simulation). The kriging is used to calculate the best estimate (by minimizing the error variance) of rock properties, interpolating well data. The limitation of such a method is that in a large model, low values tend to be overestimated and high values underestimated. Stochastic simulation methods are better at capturing the heterogeneities (extreme value variation) of the subsurface by assessing its (expected) spatial variability. So in this study, the Gaussian method was used to distribute the input data in building the properties model (Figure 1). The target is to use all geological information available to build a realistic property model.

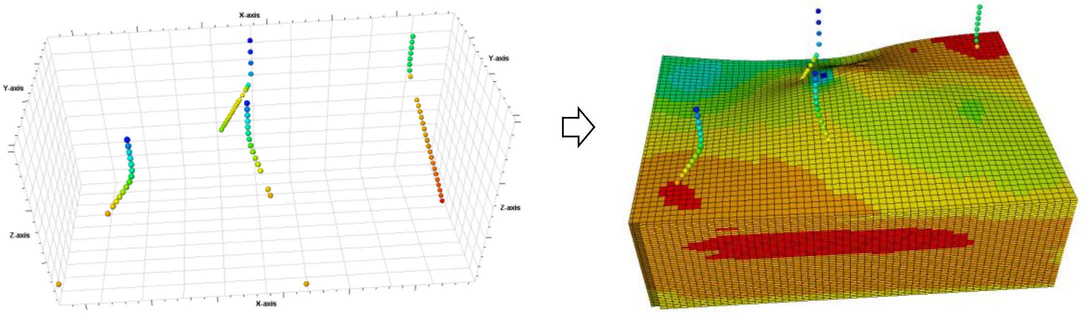

Figure 1: Result's example of the well data interpolate and distribute into a 3D properties model using the geostatistical method. Only a few wells show in this figure.

All the models will be converted into categorized models using Scale values to be able to combine them later using mathematical operations. The results of the categorisation from the models created a series of Scale properties models (Figure 2). For each of the Scale models, values assigned for the Scale are between 0 to 5, 5 being the most favourable 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 probability (Table 1). For categorical models, such as the formation, alteration mineralogy or resistivity interpretation models, the assignment of a Scale 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 objects (e.g. fault core and MEQ) or the results of more advanced calculations (DFN), the Scales were attributed using mathematical operators. The vertical boundary of the model in this study was cut from -400 mRSL to -2000 mRSL, considering the production or reservoir interval only.

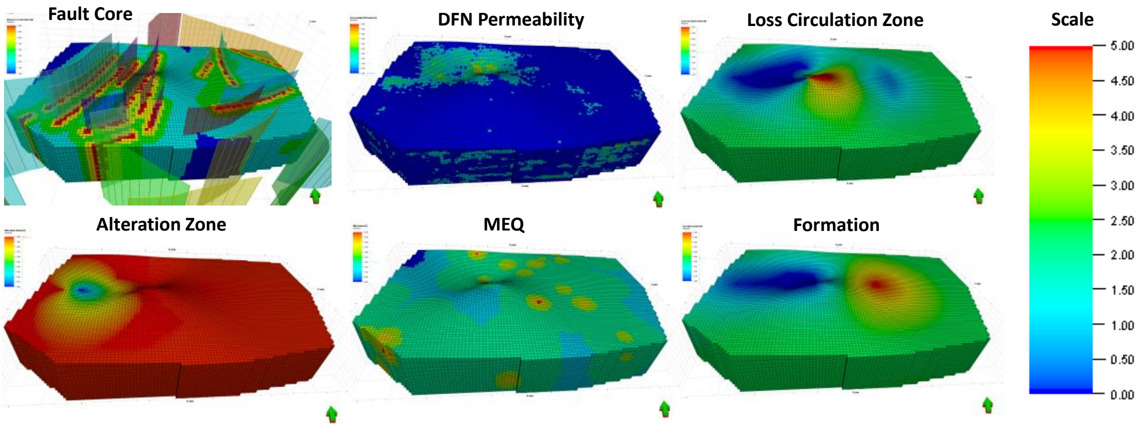

Figure 2: The properties model of each parameter that is used in building the 3D play fairway model. Some of the properties are not shown in the figure due to data confidentially.

Table 1: Examples of assigned categories or scales used for the individual parameter in this play fairway model

Natural State Temperature Model (°C)	Distance to Prominent Fault (m)	Permeability (mD)	Scale
< 25	> 2500	0 – 2.5	0
25 - 75	1500 - 2500	2.5 - 5	1
75 - 150	500 - 1500	5 – 7.5	2
150 - 200	250 - 500	7.5 - 10	3
200 - 250	100 - 250	10 -12.5	4
250 - 300	0 - 100	> 12.5	5

3.1 Play Fairway Model

All of the 3D parameter properties models were combined to yield one final probability model, that contains the most favourable or sweetspot area to drill in the reservoir. Before combining the properties 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. In this case, an extra multiplying factor was credited for some properties model such as temperature, DFN's permeability, MT, prominent fault and formation. For example, a factor of 2 was assigned to the temperature properties 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 DFN's permeability model values, as it is important to consider the distribution of permeable fractures in the reservoir as the main fluid path. On the contrary, the loss circulation model has a 0.5-multiplying factor as this model is highly uncertain regarding its true depth and could potentially constitute a bias in the analysis. In the final probability model process, the scale total is divided by 42.7 to keep the Scale value between 0 and 1 for an easier interpretation of the final probability model results. These factors could easily be modified if the user would like to increase the influence of one of the properties model.

The resulting 3D play fairway or probability model is shown in Figure 3A. The model was filtered so only the highest probability areas that shown in the model (Scale above 0.95) (Figure 3B). In general, the results show the important role played by the faults in the analysis, as the most favourable area mostly follows the prominent fault framework, and this was done on purpose by considering the faults as the main control of permeability and by increasing the multiplying factor, like some of the other parameters as explained above. However, the temperature, lithologies and alteration mineralogy are also playing a major role in the evaluation of permeability. To test the model before drilling, we can use the actual sweetspot zone recorded in the well by using the spinner test data. In this case, most of the feedzone from wells fit the most favourable zone (Figure 3C).

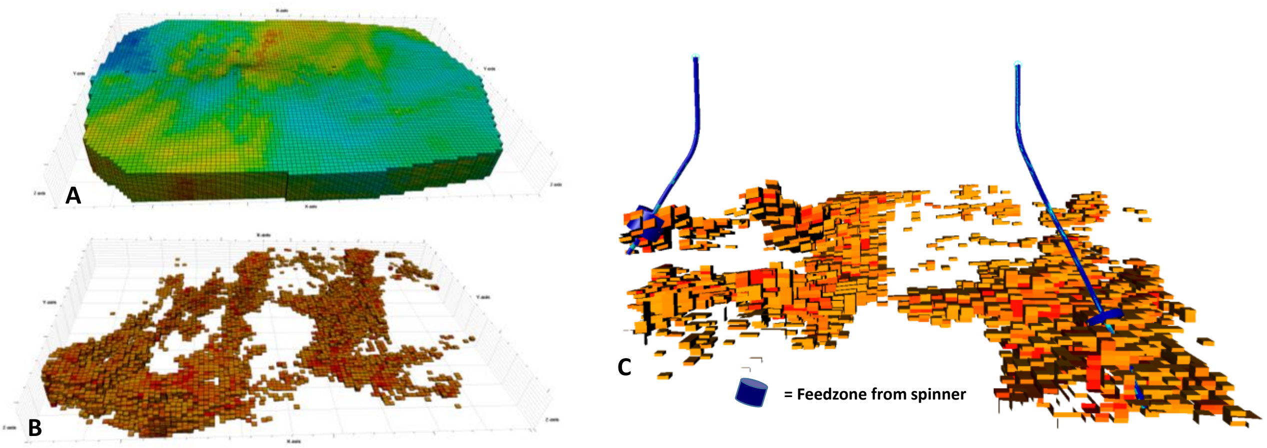

Figure 3: The final 3D probability model from the play fairway analysis. A) The unfiltered probability model. B) The filtered model to probability scale > 0.95 to only show the most confident sweetspot in the geothermal area. C) Sliced model, looking to the north, shows the high probability model fits the actual feedzone from spinner measurement.

4. CONCLUSION

We present the 3D probability model as the result of the play fairway analysis method in the geothermal field, which give us a comprehensive image of the most favourable area to drill. The play fairway analysis is data-dependent, therefore the parameters that are used in the modelling process could be updated, both for quality and quantity. The advance additional data and methods are also important in the next study such as geochemistry data and advanced computational methods such as machine learning. The weighting process also becomes critical in building the model from the play fairway analysis method. The experience of the expert and the unique characteristics of each geothermal field extremely dictate the scale that will be used in weighting the parameters. To be validated and improved, this method should be deployed on several 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 Scale values. The process could easily become repeatable and allow for benchmarking and comparing geothermal fields.

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