Enhancing Early-stage Geothermal Resource Assessment through Uncertainty Modeling of the Clay Cap

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ABSTRACT

The development of new geothermal fields faces high subsurface uncertainty and economic risks. This study builds on a new numerical method developed at the University of Auckland for early-stage resource assessment. We introduce an automated tool designed to enhance this method by generating variable geometries of the clay cap. The tool interpolates between two given clay cap geometries, typically an optimistic and a conservative estimate, based on magnetotelluric (MT) data and expert knowledge, extending the range of possible resource potential estimates.

The methodology was validated using a synthetic teaching model and a small-scale model of the undeveloped Maritaing geothermal field in Indonesia. Additionally, the tool was applied to the Kotamobagu geothermal field model, which is larger in scale and currently being explored for development. The tool successfully generated interpolated clay cap geometries for each model. Early results indicate a significant influence of the size of the clay cap on the magnitude of the total upflow and its location at the bottom of the model. This highlights the importance of early-stage resource assessment, as the estimated clay cap geometry depends on limited and uncertain data combined with expert interpretations.

By automating the generation of the clay cap geometry, this tool enhances the new resource assessment method by incorporating additional geological uncertainty. Future research will focus on including this tool in a full resource assessment of an undeveloped geothermal field.

1. INTRODUCTION

A vital component of geothermal systems is the clay cap, which often acts as a seal for the underlying reservoir. This impermeable layer traps the hot and rising fluids below, determining the size and shape of the reservoir. Current modeling procedure defines a predetermined geometry of this cap, after which many other parameters are tweaked to align the model with real-world measurements (Dekkers et al., 2022; O'Sullivan & O'Sullivan, 2016).

To further improve these reservoir models, this paper focuses on developing a tool for automatically generating interpolated clay cap geometries based on optimistic and conservative estimates, which extends the range of possible geological conceptual models.

The extended range of geological models adds to the uncertainty quantification framework that has been developed by the University of Auckland (Dekkers et al., 2022; Power et al., 2023; Gravatt et al., 2023; de Beer et al., 2023). The clay cap interpolation tool is particularly useful for the recently developed early-stage resource assessment method where few data are available (Nagoro & O'Sullivan, J., 2023; Ikeya et al., 2024; O'Sullivan, J. et al., 2024; Pinzon Mendez et al., 2024; Renaud et al., 2024; Dekkers et al., 2025; Rahmansyah et al., 2025; Xicara et al., 2025). Typically, in early-stage resource assessment, the conceptual understanding of the clay cap geometry is based on geoscience data, where magneto telluric (MT) data often plays a key role (Pellerin et al., 1996; Chave & Jones, 2013; Cercato, 2023). MT data requires expert interpretation and becomes less accurate in the deeper subsurface. In contrast, the clay cap geometry is generally better constrained in developed fields where more well data are available.

This paper elaborates upon reservoir modeling theory and early-stage resource assessment, the methodology used for alteration and calibration, the results obtained, and its implications for future geothermal reservoir modeling. The tool is built upon the teaching model, which is a fully synthetic model, and the Maritaing model, an undeveloped field in Indonesia. Both of these models are relatively small-scale and have a low complexity, which makes them ideal as a testing environment for the tool. After this, the tool is implemented in the current model of the Kotamobagu geothermal reservoir in Indonesia. This is both timely and relevant, as the geothermal field is currently under development, which means the results of the new interpretation can be verified in the near future using new borehole data (Nagoro, 2023).

2. METHODOLOGY

A significant amount of uncertainty hinders the accuracy of current geothermal models, mainly in their representation of geological features such as the clay cap. To account for these uncertainties, a recently developed approach employs a wide range of model parameters and conducts thousands of simulations to generate an uncertainty interval for the model predictions. These models can be run fast and simultaneously on Waiwera using widely available high-performance computing (HPC) resources (Dekkers et al., 2022). To further improve this approach, this paper proposes a tool for interpolating different clay cap geometries between two bounding 3D objects, one optimistic and one pessimistic. These bounding objects are based on available MT data and expert insight.

2.1 Model environment & scales

The proposed tool is coded in Python and designed to work with AUTOUGH2 geometry and model files. The PyTOUGH library is used to read and modify the AUTOUGH2 model files (Croucher, 2011). The tool is built using existing small-scale models as a testing environment, and is adapted for real-world circumstances, applying it to the Kotamobagu geothermal model in Indonesia.

2.1.1 Small-scale models

The clay cap interpolation tool uses the teaching and Maritaing models as test cases. The teaching model is fully synthetic with the sole purpose of teaching students and developing new tools. This is an ideal environment for testing extreme boundary cases for the tool. The Maritaing geothermal field is located in Indonesia, but has not been developed. These models are used for their similar size and complexity. Figure 1 presents a vertical slice of the Maritaing model, where the color gradient is a logarithmic representation of the vertical permeability. This shows a clear separation of the different regions in the slice, showing that the clay cap has an approximate permeability of 0.1 mD, the surface 500 mD, and the reservoir has an approximate permeability of 10 mD. These models, each consisting of approximately 12,000 blocks, are significantly smaller than other real-world geothermal models. Their small scale allows for efficient coding and debugging while minimizing computational and processing time.

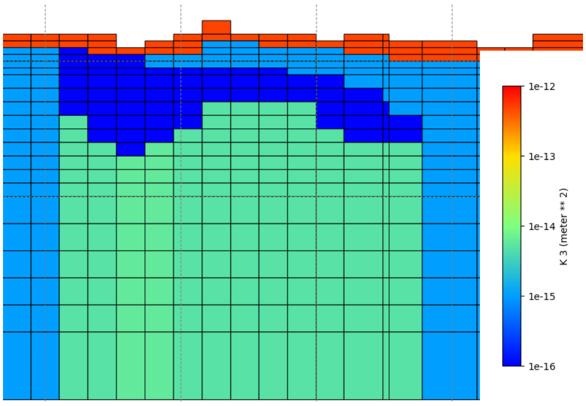


Figure 1: Vertical slice through the Maritaing reservoir, adapted from TIM.

Both small-scale models have a pre-defined clay cap. In order to use the tool, an alternate, either larger or smaller, clay cap is created for each model. These generated clay caps are not real-world accurate and contain intentional geometrical irregularities. This is because their purpose is to test the limits of the interpolation tool and determine to what extent the tool is usable automatically and when user intervention is required.

2.1.2 Kotamobagu model

After the tool is tested on the small-scale models, it is applied to the Kotamobagu geothermal model, introducing new challenges. The Kotamobagu model, which contains 41,299 blocks, has significantly more blocks than the aforementioned models. The model must be geologically accurate and use a representative secondary clay cap for the Waiwera simulation. A schematic representation of the model, along with its geologically realistic bounding clay caps, is shown in Figure 2. The secondary clay cap (C_2) is generated manually, in consultation with the geothermal modelers closely involved in prior Kotamobagu research. This helps ensure that the 'optimistic' and 'conservative' clay caps fall within the bounds set by the geology of the field.

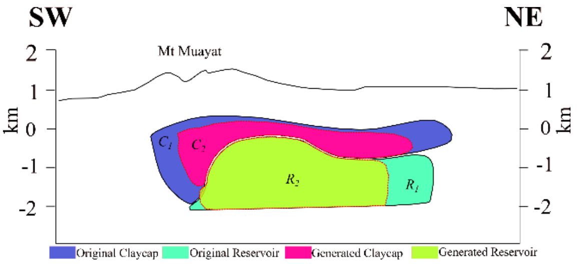


Figure 2: 2D schematic cross-section of the Kotamobagu model with the original (C_1) and alternative (C_2) clay cap and respective underlying reservoirs.

Whereas the small-scale models both originally use conservative estimates for the size of the clay cap, the original interpretation of the clay cap in the Kotamobagu model is more optimistic. Therefore, the tool must also generate smaller, yet realistic, clay cap and reservoir geometries in this real-world case. Secondly, as shown in Figure 3, there is a significant difference in the reservoir geometry relative to the clay cap. This indented reservoir shape is due to the geometry of the clay cap, as rising fluid typically accumulates underneath the dome-shaped part of the clay cap. The methodology to address this difference with the small-scale models is explained in Section 2.3.

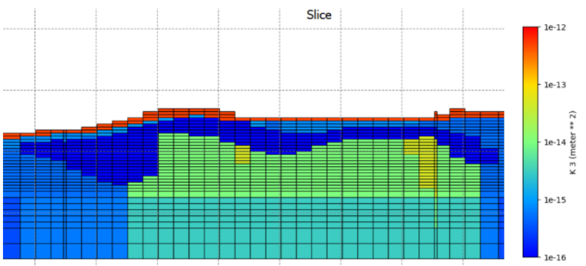


Figure 3: Vertical slice through the Kotamobagu reservoir, adapted from TIM.

2.2 Clay cap generation

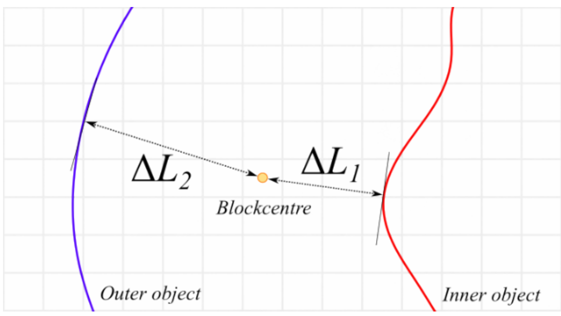


Figure 4: 2D representation of the linear interpolation.

The tool's first step is to extract all relevant information from the input data file and objects. This includes all block names, block center coordinates, and their rocktypes. It then scans through the center coordinates for all blocks and checks whether they are within one of the input clay cap boundaries. Subsequently, the distance from every block center to the boundary clay caps is calculated, as shown in Figure 4. With these relative distances, it assigns a weight ('*w*') to the block.

The weight calculation is done by means of linear interpolation using the formula below:

$$w = \frac{1}{2}\left(\frac{\Delta L_1}{\Delta L_1+\Delta L_2} - \frac{\Delta L_2}{\Delta L_1+\Delta L_2} + 1\right) \quad (1)$$

As this step requires the most computation, its results are stored in an output file such that the weight calculation can be skipped if a later part of the tool has to be altered.

The user then chooses a desired weight between 0 and 1, where 0 represents the original clay cap geometry and 1 represents the alternative clay cap geometry. The tool automatically generates a new clay cap based on the chosen threshold weight.

2.3 Reservoir generation

Generally, in volcanic geothermal settings, geoscientists assume the potential geothermal reservoir lies below the clay cap, captured within the dome shape. In geothermal modelling, this potential reservoir typically has different properties (e.g., higher permeability) than outside the reservoir. Therefore, the underlying reservoir geometry must also be updated after a new clay cap geometry is generated. In both small-scale models, the reservoir is defined in a straightforward manner: All blocks under the clay cap are defined as inside the reservoir. As mentioned before, this typically means the blocks inside the reservoir have a higher permeability than the surrounding blocks. However, as mentioned in Section 2.1.2, in certain real-world cases, this is different. Therefore, the tool has three distinct 'reservoir modes' from which the user chooses one to determine how the reservoir is generated.

The first is 'regular', in which the reservoir has the same top-down geometry as the clay cap, which is the case in both small-scale models.

The second mode is 'polygon', in which the user has to provide a polygon within the horizontal boundaries of the clay cap. This is especially useful when geological features like volcanoes alter the reservoir non-uniformly.

The third mode is 'pieslice' mode, or the 'getDome' tool, the most automated mode. In this mode, the clay cap is subdivided into a user-defined number of slices around its z-axis. Within each slice, the tool locates the lowest block of the clay cap, the distance from the center of mass to that point, and the outside perimeter. This horizontal distance ratio between the lowest point and the perimeter with respect to the center of mass of the clay cap ($\Delta L_1/\Delta L_2$) is then projected on all other columns within the cut to approximate the dome shape, even in asymmetrical clay cap geometries. A schematic representation of such a slice is shown in Figure 5. As the block resolution is not very fine, multiple blocks may be on the same lowest elevation. In this case, the tool will select the inner block and inform the user via the terminal. To compensate for this, the user can alter the 'inset factor' to modify the dome perimeter by a small margin. The getDome tool also proved helpful in filtering the natural state samples, another part of the resource assessment process. This filtering process relies on the dome shape of the clay cap and is currently done manually.

The tool checks every block of the original model and assigns it one of the four following 'old' locations: "CC" (clay cap), "UCC" (Under clay cap), "NUCC" (Not Under clay cap), or "ATM" (atmosphere). It repeats this process for the newly generated clay cap and reservoir and assigns one of the four 'new' states to each block. After this, the states of all blocks are compared, and the model updates the block only if the new state is different from the old state (to improve code efficiency). When a block has to be updated, its new rocktype name is generated in the TOUGH2 format requirements. If this rocktype already exists, the model assigns the block to that rocktype; if the generated rocktype is new, it gets the permeabilities assigned to it in the input parameters for either CC, UCC, or NUCC. The tool informs the user anytime a new rocktype is generated, so that the user can manually alter these rocktypes in the rocktype library if deemed necessary.

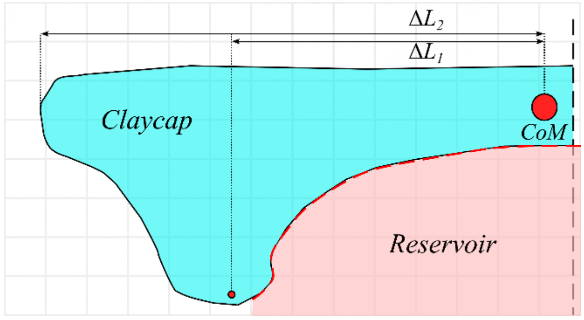


Figure 5: 2D representation of the 'pieslice' method to locate the reservoir under the clay cap.

2.4 Waiwera integration

The intended purpose of this tool is to expand the range of model possibilities, especially in greenfield models. This reflects the uncertainty of the clay cap interpretation based on the limited data. Therefore, the modified AUTOUGH2 models are converted to Waiwera models, and subsequently, sample models are generated and simulated. The parameter sampling process and production algorithm for resource potential estimation are explained by (Dekkers, K. et al., 2022).

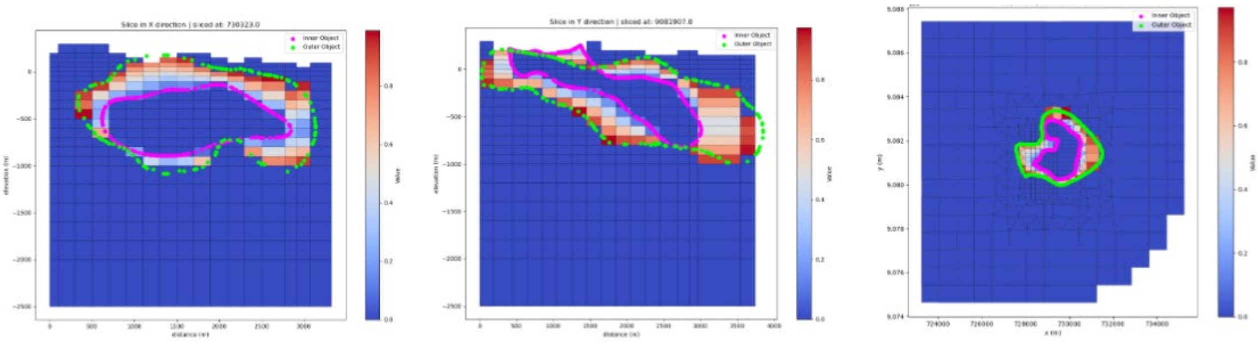
One important aspect of the uncertainty quantification process is filtering the natural state (or steady state) sample models. In the case of greenfield models, where typically no well data is available, the natural state sample models are filtered on the temperature under the clay cap. In volcanic geothermal settings, geological formations are hydrologically altered to form a clay cap under temperature conditions of around 180-200°C (e.g., O'Sullivan, J. et al., 2024). The 'upper dome' of the clay cap has a higher likelihood of meeting the temperature condition due to the location of the upflow and the way the hot fluid gets captured under this part of the clay cap. After this filtering process, the selected samples are run through an iterative production algorithm to get an uncertainty interval for the resource potential estimate (e.g., O'Sullivan, J. et al., 2024).

2.5 Visualization

In order to get a better understanding of how the interpolation tool works, two visual representations have been developed using Python and the PyTOUGH library.

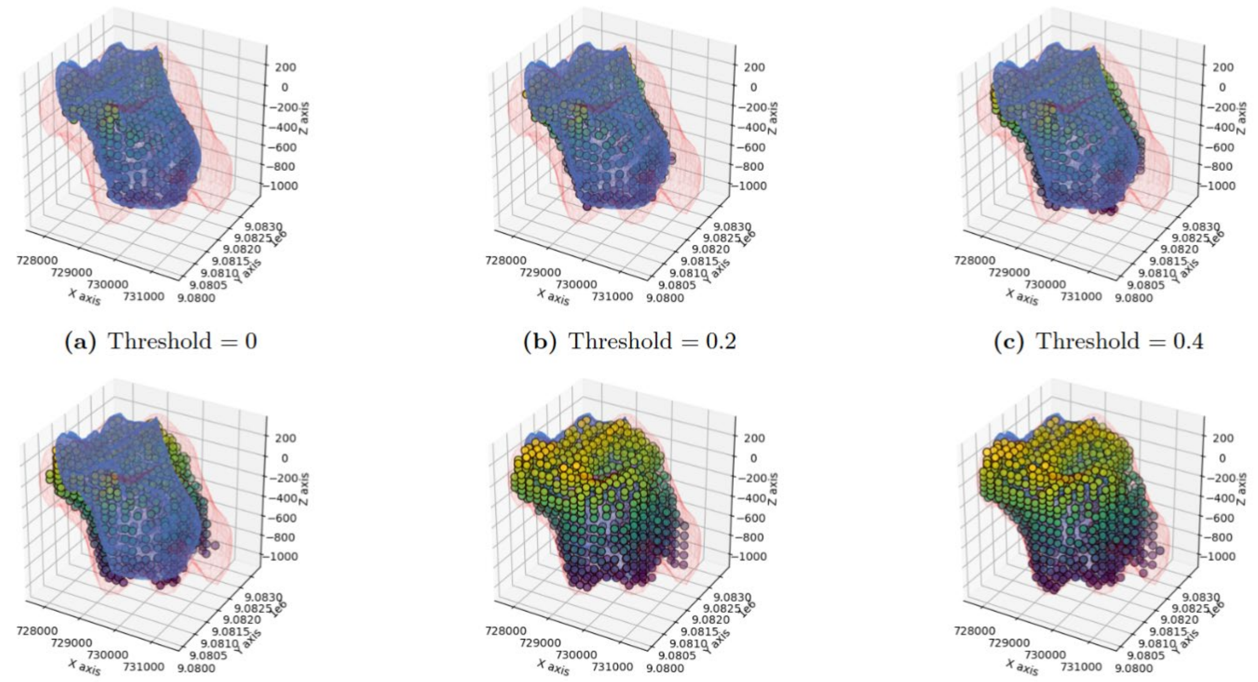
The first visualization generates multiple slices for the x, y, and z-directions. Each slice plot shows the outline of the inner and outer clay cap object and assigns a color gradient to each block based on its respective interpolation weight.

The second visualization is a 3D representation of the clay cap at different weight thresholds. The visualization shows



(a) X-Direction (b) Y-Direction (c) Z-Direction

Figure 6: 2D slices of the generated clay cap weight distribution in x-, y- and z-direction. The color gradient represents the generated weight per block center.



(a) Threshold = 0 (b) Threshold = 0.2 (c) Threshold = 0.4

(d) Threshold = 0.6 (e) Threshold = 0.8 (f) Threshold = 1

Figure 7: Side-by-side comparison of clay cap geometries generated with different threshold values, illustrating the exponential scaling process. The color gradient represents depth. The inner and outer input objects are represented in blue and red respectively.

plots for a set number of weight thresholds. The inner and outer clay cap object is outlined in each plot, and the dots represent the interpolated clay cap at the specified weight threshold. Both visualization types will be used to validate the work done in Section 3.

3. RESULTS

3.1 Clay cap generation

The tool generates interpolated clay caps between any two given bounding objects. It is a robust script capable of producing realistic clay cap geometries. An example of the generated weight distribution, slices in all three axes using the teaching model, is provided in Figure 6. The tool automatically generates these slices in all directions to allow the user to visualize the weight distribution and show potential bugs. The green and purple dots represent the slices of the input clay cap objects, whereas the color-coded blocks show the assigned weights of each block.

Figure 7 shows a 3D plot of interpolated clay caps at different weight thresholds, where the blue object represents the inner clay cap, the red object represents the outer clay cap, and the dots represent the interpolated clay cap at specified weight thresholds. Figure 7 provides six plots of 6 specified thresholds between 0 and 1, showing the progression of the clay cap from the inner to outer objects. Based on the results, the effectiveness of the linearly interpolated weight allocation is validated, and the generation works accordingly. This concludes the strict geometric part of the process and provides the basis for the reservoir generation.

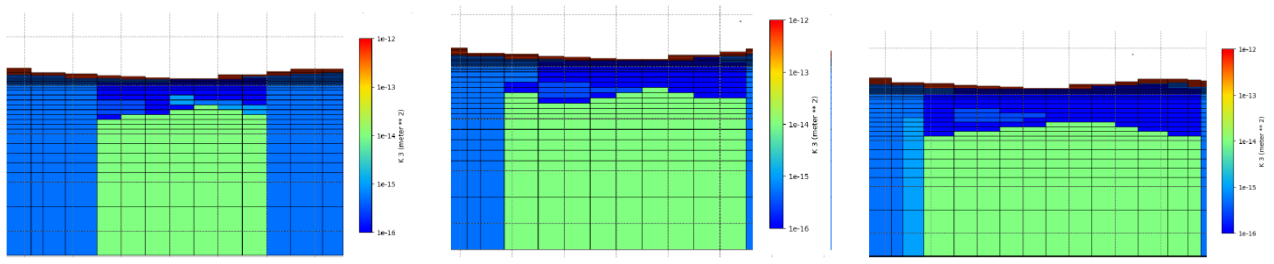
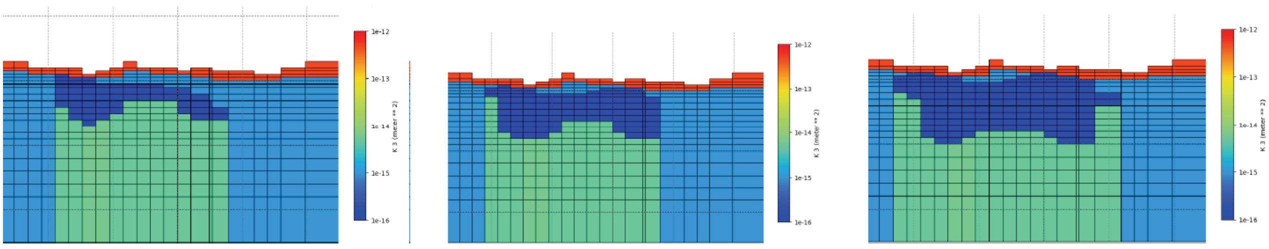


Figure 8: 2D slices of the generated clay cap and underlying reservoir of the teaching model for 3 different clay cap geometries, visualizations adapted from TIM.



(a) Unaltered model (b) Threshold = 0.5 (c) Threshold = 1

Figure 9: 2D slices of the generated clay cap and underlying reservoir of Maritaing model for 3 different clay cap geometries, visualizations adapted from TIM.

3.2 Reservoir generation

Based on the weight distribution and preset threshold, the script allocates the old and new states per Section 2.3. The results are first validated on both small-scale models using the standard reservoir 'mode'. Figures 8 and 9 show that the horizontal extent of the reservoir is modified according to the horizontal extent of the clay cap. Only the blocks underneath the clay cap have been updated to have reservoir rock properties, while those above remain unchanged. With these results, the standard reservoir mode for changing the reservoir block properties functions as designed.

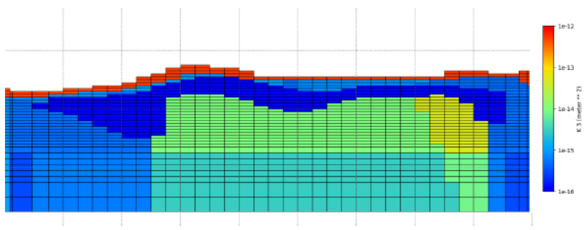
3.3 Kotamobagu integration

The Kotamobagu model differs from the small-scale models in two key ways: it is significantly larger and its alternative clay cap is smaller than the original. The tool handles these differences well. The resulting generated clay caps and reservoirs for different thresholds are shown in Figure 10. As shown in these plots, the tool successfully isolates the dome beneath the clay cap, ensuring that the columns outside the dome are excluded from the underlying reservoir.

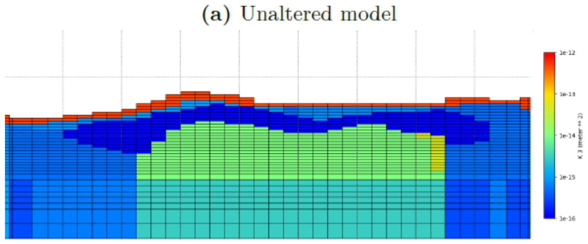
3.4 Waiwera integration

With the clay cap geometry validated, the next step is to assess its effects on the numerical model. In order to assess the impact of the clay cap alteration on its resource potential, the resulting models have been simulated using the Waiwera simulator. The getDome tool is used to determine the blocks in the upper dome of the clay cap, which are used for filtering. The inset filter factor of 0.8 is used as an initial estimate to represent the upper dome with a high likelihood of reaching temperatures between 180 and 200 °C. The difference in dome shape with the old manual method is visualized in Figure 11. This figure depicts a top-down view of the columns in the clay cap, where the red dots represent the blocks selected for natural state filtering and the crosses represent the remaining clay cap columns.

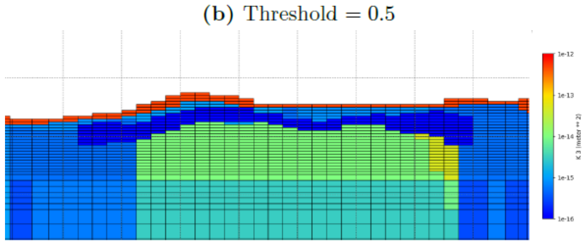
The automatically determined dome shape extends significantly further into the southern part of the clay cap compared to the prior dome shape selection. Due to the slight difference in clay cap geometry for the 'large' and 'small' boundaries, the Waiwera simulations are only run for three distinct variations at weight thresholds 0, 0.5, and 1. To ensure a fair comparison of the different clay cap geometries, each set of sample results was filtered by the clay cap temperature from the clay cap blocks selected using the getDome tool with the same inset value.



(a) Unaltered model

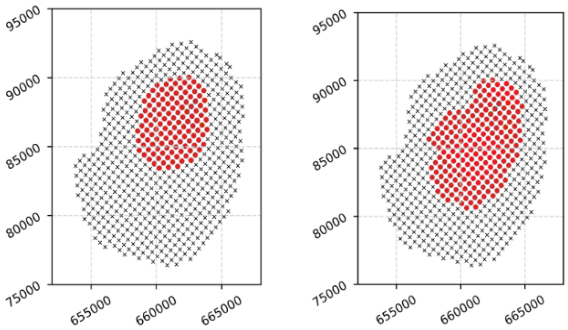


(b) Threshold = 0.5



(c) Threshold = 1

Figure 10: 2D slices of the generated clay cap and underlying reservoir of the Kotamobagu model for three different clay cap geometries, visualizations adapted from TIM.



(a) Old filtered Kotamobagu model (b) New filtered Kotamobagu model

Figure 11: Top-down visualization of the Kotamobagu reservoir showing its clay cap (crosses) and filtered underlying dome (red circles), using a polygon-drawn dome (a) and numerically calculated 'piesliced' dome (b).

Figure 12 shows the three generated clay caps and resulting filtered domes, confirming that the clay cap generation tool and the getDome tool work as intended. In total, 1000 natural state sample models per clay cap threshold model are simulated. These sample models are filtered to the 10% best fitting samples using the temperature condition in the 'upper dome' under the clay cap, which is automatically identified with the getDome tool using an inset of 0.8.

Due to time limitations, the production algorithm was not run for the filtered sample models, and more research needs to be done to see the correlation between clay cap size and resource potential. Although the resource assessment has not been fully completed, some observations can be made. Figures 13 and 14 show the prior and filtered results of the upflow at the bottom of the model. Figure 13 shows prior (in blue) and filtered (in red) distributions of the thermal energy of the upflow at the bottom of the model. The differences in filtered thermal input seem small, but they are consistent and indicate a larger thermal input for larger clay cap geometries.

An interesting result is shown in Figure 14, where the filtered results show a different location for stronger upflows for the different clay cap sizes.

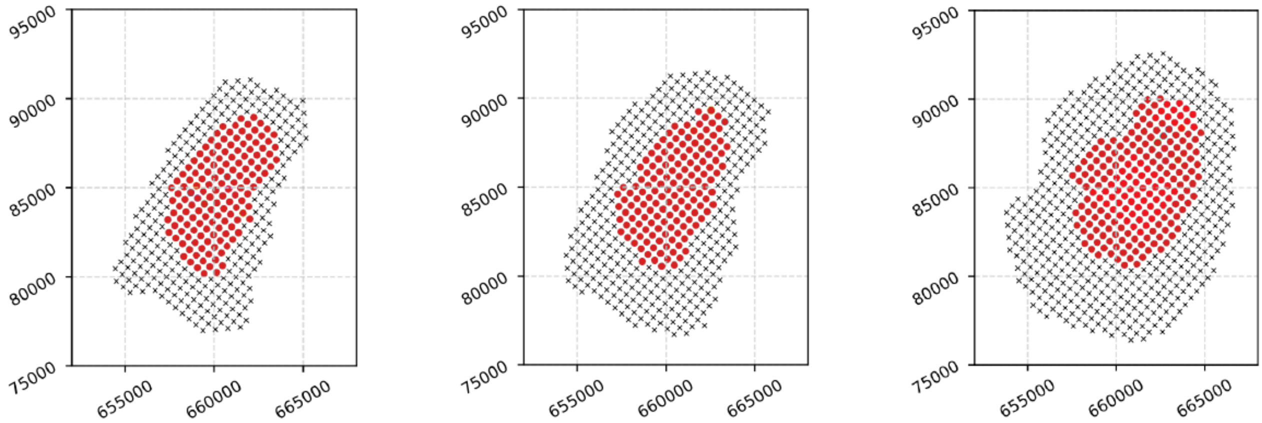
CONCLUSIONS AND RECOMMENDATIONS

In summary, this paper presents a tool for generating interpolated clay caps for any two given clay cap geometries, modifying the corresponding blocks regarded as the reservoir, and visualizing the process. The tool uses AUTOUGH2 model files as input, but can easily be converted to Waiwera-compatible files.

The tool is particularly useful in early-stage resource assessment, where data availability is often limited. Automating the generation of multiple variations of the clay cap and reservoir model, based on a conservative and optimistic estimate of the clay cap, can provide a broader range of estimates of resource potential without the need for extensive manual input. Additionally, when more clay cap data are acquired, the resource potential estimates can be efficiently updated.

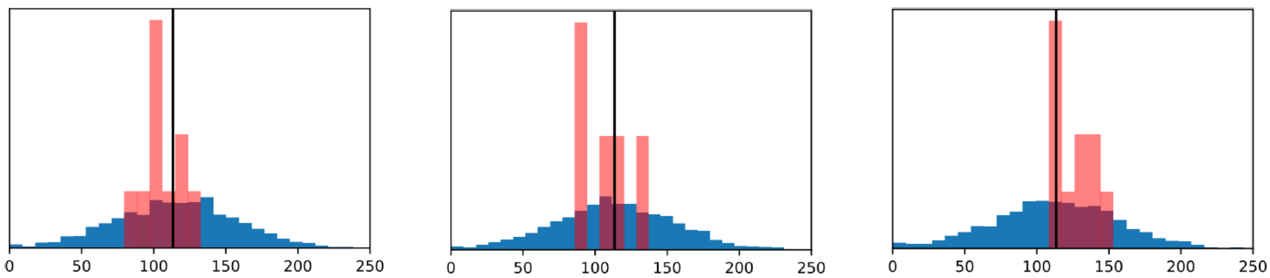
The methodology is validated on two small-scale models before being applied to the Kotamobagu geothermal field, which is currently under development, demonstrating its adaptability to real-world, full-scale cases. The results confirm that the clay cap generation tool generates intermediate clay caps and can isolate the underlying reservoir beneath the dome. The linear interpolation method proves to be both computationally efficient and sufficiently accurate given the geological uncertainty in input data. By automating the clay cap and reservoir generation process, this tool enhances the efficiency of numerical geothermal modeling and provides a systematic approach to testing different clay cap scenarios.

Although the clay cap generation tool is functional, its full potential has yet to be utilized. A main contribution to this is the cases presented, where a secondary bounding clay cap had to be created to interpolate with the existing one. Due to the existing clay cap being an average estimate, the difference between it and the alternative clay cap is small, making the effects of interpolation subsequently small. In future early resource assessment, when implementing different clay cap sizes in the process, two distinct boundary clay caps must be created further away from the average clay cap estimation,



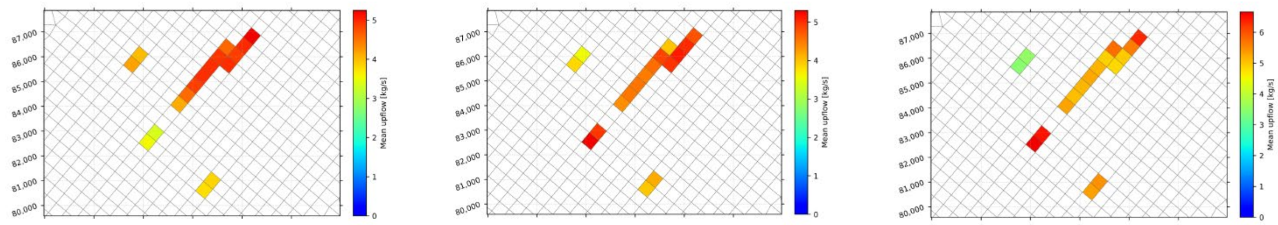
(a) Threshold = 0 (b) Threshold = 0.5 (c) Threshold = 1

Figure 12: Top-down view of the clay cap blocks of the three different clay cap geometries. The red dots are showing the blocks selected by the getDome tool for filtering and the crosses show the remaining clay cap blocks.



(a) Threshold = 0 (b) Threshold = 0.5 (c) Threshold = 1

Figure 13: Total thermal energy histogram of the upflow at the bottom of the Kotamobagu model in MWth. The prior samples are in blue and the filtered samples in red. The thresholds 0, 0.5 and 1.0 are the conservative, interpolated and optimistic clay cap.



(a) Threshold = 0 (b) Threshold = 0.5 (c) Threshold = 1

Figure 14: Top-down visualization of the upflow sources in the Kotamobagu models for three different clay caps at threshold 0, 0.5 and 1.0. Color gradient represents the magnitude of the mass upflow.

and thus provide a broader range of possible clay caps in between. This expands the range of possible clay caps, allowing for a broader assessment of reservoir potential.

Furthermore, the getDome tool has also shown its ability to filter the geometry of the clay cap to locate the dome shape underneath. The getDome tool automates locating the dome shape underneath naturally formed and irregularly shaped clay caps. This improves the merits of the filtering process and decreases the amount of human guesswork and workload. The getDome tool allows the user to scale the dome by applying a scaling factor, although the effects of this scaling are yet to be concluded definitively.

Lastly, running sample models based on the different clay cap geometries has shown that the clay cap size influences the total magnitude and location of the upflow at the bottom of the model. These observations were made by comparing three clay cap sizes for one geothermal field, which is insufficient to draw significant conclusions. Additional information from geoscientific exploration, notably geophysics, such as gravity or seismicity, could be integrated to improve the generation of models for resource potential assessment. The results obtained so far give a good starting point for future research into the effects of clay cap size on the resource potential of a geothermal field.

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