AN APPLICATION OF 3D TEMPERATURE MODELING DURING AND AFTER DEVELOPMENT DRILLING AT MUARA LABOH, SUMATERA, INDONESIA

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ABSTRACT

3D temperature models were constructed utilizing static well temperature data to better understand the thermal anomaly and likely reservoir extent of the Muara Laboh field. Model iterations were built and updated during and after development drilling in 2017-2018. The 3D temperature models were developed using Leapfrog Geothermal© software. Multi-disciplinary datasets were selected and incorporated to provide constraints on the likely temperature distribution away from wells.

Considering the complexity of the horizontal and vertical temperature distribution in the field and limited well data, instead of using conventional 2D temperature cross sections, a horizontal slicing method was used to construct the 3D temperature model at various elevations from the top of reservoir (TOR) at 800 m asl to the deepest well data at -1300 m asl. Temperature was hand-contoured at specific elevations utilizing the well data. Away from wells, temperature was inferred from structural boundaries and low resistivity (value <5 ohm-m) as indicated from 3D magnetotelluric modeling. Thickening and draping of the conductor limited the probable reservoir extent in some areas.

The hand-contoured temperature polylines were used as an input to build and interpolate 3D temperature bodies in Leapfrog. From review of well permeability, lithology, and vein mineralogy, it was found that some parts of the high temperature body had low permeability, and that deep high permeability was associated with dike intrusions in the SW. These factors were considered along with temperature when the model was used for well targeting and planning as the 11-well development program progressed. Learnings about permeability were used to construct reservoir bodies where both high temperature and permeability were most likely to exist. The 3D temperature model was updated after drilling, enhanced by new information from geology to better portray the permeability character in Muara Laboh. This 3D model was one of the key inputs in updating the Muara Laboh conceptual model and numerical models.

1. FIELD OVERVIEW

Muara Laboh Geothermal Field is located in South Solok Regency, West Sumatra, Indonesia. The geothermal field is situated along the Great Sumatra Fault (GSF) within a pull-apart basin formed in a step-over between its Siulak (south) and Suliti (north) segments. Dilation accommodated prolonged intrusion at depth and overlying extension within the pull-apart basin (Baroek et al., 2018; Mussofan et. al, 2018; Figure 1). Based on Mussofan et al. (2018), the Muara Laboh basin filled with quaternary volcanics consisting mainly of andesitic to dacitic tuffs and debris flows. There is a significant difference between the western and eastern parts of the basin. Undifferentiated silicic volcanics (Qou, Qol) are widely distributed on the northwest, west and southwest, reaching 1000 m in thickness based on well data, while volcaniclastic rocks (Qyu) are dominant in the eastern basin, thinning towards the bounding fault on the northeast (Suliti Segment). Intrusion and volcanism occurred primarily along the southwestern fault segment (Siulak). Intrusive rocks consist of inferred Quaternary dikes as well as Middle Miocene to Mesozoic granitic to dioritic rocks (Tgdr, Tgd) are typical in the deeper parts of some wells. The Tertiary intrusions cut volcanic and volcaniclastic rocks of the Painan Formation (Tomp) and older formations (Figure 2).

Conceptual model interpretation utilizing data from six exploration wells suggested an upflow of approximately 300°C fluid from the deep permeable zone encountered in pad-H wells is outflowing toward the NNW through a narrow path to the shallow NE reservoir zone in pad-A (where steam cap occurs) and onward to Sapan Malulong hot spring as shown in Figure 3 (Situmorang et al., 2016). As new wells were drilled and data collected during the development drilling phase between 2017-2018, Muara Laboh update of the conceptual model has been undergoing. The new temperature modeling discussed in this paper is one of the key inputs in updating the conceptual model.

1.2 Temperature modeling history

The temperature modeling originally derived from numerical simulation built after exploration drilling in 2015. The most likely system extent and temperature distribution were implemented in a TOUGH2 numerical simulation of the field (Situmorang et al., 2016). They summarized an initial-state model, where hot geothermal fluid is upwelling from the deep part of the resource to the south, close to Patah Sembilan (PS) fumarole. The ascending fluid then flows to the northwest along the path almost parallel along NW-SE structures but turns to follow NE-SW permeable structures when the fluid reaches just north of pad-H, passing ML-A1 well to Idung Mancung (IM) fumarole, before it flows toward Sapan Malulong (SM) chloride spring along NNW-SSE permeable structures. The reservoir fluid experiences a temperature decrease from 310°C to 200°C along this path.

The temperature model from the simulation model was extracted into point attributes and imported to Leapfrog© to generate a 3D initial temperature model in 2016 (Figure 4). These temperatures were corrected for inferred steam migration in the wellbore and other non-reservoir effects. This model was used for initial targeting of development wells.

Development drilling in 2017-2018 added 11 wells (Figure 5) and new data allowing further revision of the 2016 temperature model. A different approach was used to revise the 2016 model using hand-contoured temperature on 2D horizontal slices. The 3D model was then built based on the revised 2D model, and combined with an updated 3D resistivity model and other revised geological features.

2. THE 2018 TEMPERATURE MODELING WORKFLOW

2.1 Introduction

The fundamental keynotes of the approach are to use all geoscience data as indicators of the 3D temperature distribution and relationship to fluid flow (e.g., Stimac and Mandeno, 2016). Hard data (well temperature data) is used as the main model basis and other soft data (resistivity pattern, faults) are interpreted in terms of temperature away from the area of hard constraints (Figure 6).

The model includes the area of the 17 drilled wells, important structures in the eastern part of the field, Patah Sembilan crater in the south and the extension of the conductive layer to west and southwest (Figure 7). The thickness of the model is 4.2 km, from 2400 to -1800 m asl. Focusing on geometry of the temperature anomaly and the permeable reservoir body were the main goals of this modeling especially when Supreme Energy needs to update its conceptual model.

2.2 Methodology

Well temperatures, faults and 1D TE resistivity maps are attributed in each 2D horizontal slice (Figures 8 and 9). Review and interpretation of horizontal slices was preferred due to limited data distribution and to better interpret the lateral temperature distribution using draping and thickening of the clay cap and potential marginal faults that were steeply dipping. At a first-pass, various elevations from the shallowest top of reservoir (TOR) at 800 m asl to the deepest well data at that time at -300 m asl were picked to draw isotherms by conventional hand-contouring.

Soft data interpretations used to infer temperature are summarized into three main points:

- A prominent NNW-SSE elongated draping of the conductor in the eastern part of the system is most likely not associated with the current geothermal system, thus it was interpreted to form the eastern boundary of the system.
- The SW extension of the conductive layer has been used to estimate the maximum extent of the reservoir to the west and southwest.
- The absence of a conductive layer inside the south crater of Patah Sembilan is likely caused by its removal by sector collapse. This is used as the southern boundary of the system, but there is a possibility the geothermal reservoir extends beneath the crater even after removal of its top seal.

Hand-contouring followed these rules:

- Contour spacing represents convective (widely spaced contour) and/or conductive conditions (dense contour)
- The NW-SE elongated conductor is considered the boundary (closed temperature contours) while the SW boundary is open (SW extension with open temperature contours).

2.3 Moving from 2D to 3D

The geo-referenced 2D maps of re-digitized temperature contours were imported to Leapfrog© using polylines. Prior to 3D interpolation, well temperature data were also incorporated together with the polylines. This data set was then interpolated using the Radial Basis Function (RBF) method, and the output was a 3D temperature iso-surfaces.

3D final iso-temperature result has mismatch with the first pass of 2D hand-contouring (Figure 10) due to the refinement process of adding polylines and/or eliminating any unreliable polylines, as we gained more data. During drilling these polylines had minor changes due to additional data acquired, so basically this method can be used for a quick model update. The result of the 3D temperature model is shown in Figure 11.

2.4 Results

From the latest model work, the model is evolving progressively as a result of getting new data from the early model. The 2015 model is well-constrained by exploration wells and already utilize geophysics, geology and geochemistry (Situmorang et al., 2016). The additional information from development and re-assessment of the interpreted reservoir boundary gives the latest model visible changes.

In the latest model, the sealed fault and NNW-SSE elongated conductive layer is the biggest concern for the eastern boundary. It is also strongly indicated by the temperature measurement of development wells in pad A. Closed temperature in pad A, indicating the extent of the shallow steam zone, is now well-delineated by well results.

In the early model, the southern area is assumed to have the highest potential for system extension, based on the highest temperature in H well at that time and PS fumarole in the crater. As a contrast, in the latest model, based on additional H wells, the highest measured temperature is found toward the SW, making the model extends towards SW rather than the SE. This is also consistent with extension of the conductive layer toward west and the occurrence of the young Anak Patah Sembilan/APS volcanic vent. However, it is still possible that the reservoir extends further south beneath the crater (Figure 12).

3. RESERVOIR BODY

Learnings about permeability were used to construct reservoir bodies where both high temperature and permeability were most likely to exist. From review of well permeability, lithology, and vein mineralogy, it was found that some parts of the high temperature body had low permeability, and that deep high permeability was associated with dike intrusions in the SW reservoir (Mussofan et al., 2018; Baroek et al., 2018). These factors were considered along with temperature when the model was used for well targeting and planning as the 11-well development program progressed.

The top of reservoir (TOR) surface is defined based on the top of convective temperature profile in each wellbore. The TOR is shallow in the NE reservoir with a liquid level at 650 m asl and a steam zone extending to 800 m asl. The TOR is observed to be plunging to the SW where deep liquid reservoir is observed in H wells at 300 m asl. It is observed in petrography analysis that there is a deposition of late-stage calcite, quartz and prehnite (Baroek et al., 2018) filling early epidote veins which likely caused local low permeability in the upper propylitic zone at H wells.

The base of reservoir (BOR) surface is defined based on the deepest feed zone occurrence with 500 meters extension to cover the uncertainty of the BOR. The elevations of the top of convective profile from each well were interpolated into the 3D meshes in the 3D model while BOR is flatten at a depth of -1800 m asl. The 3D reservoir body is overlaid with iso-temperature body in Figure 12.

4 CONCLUSION

Having a clear and efficient modeling workflow helps to update model elements quickly, giving more time to focus on the details that have the most impact for well targeting and understanding field characteristics. Updating conceptual model in 3D is the most favorable benefit while 2D has limitation with the dimension of the system.

Based on temperature and reservoir body modeling, An accurate temperature model clarifies the potential upflow area, fluid flow paths and its system boundaries, while the reservoir body represents the most likely confluence of both high temperature and permeability and is used for well targeting. However, additional data is needed to assess the connectivity between one area to another for a robust well targeting, but this will not be elaborated in this paper.

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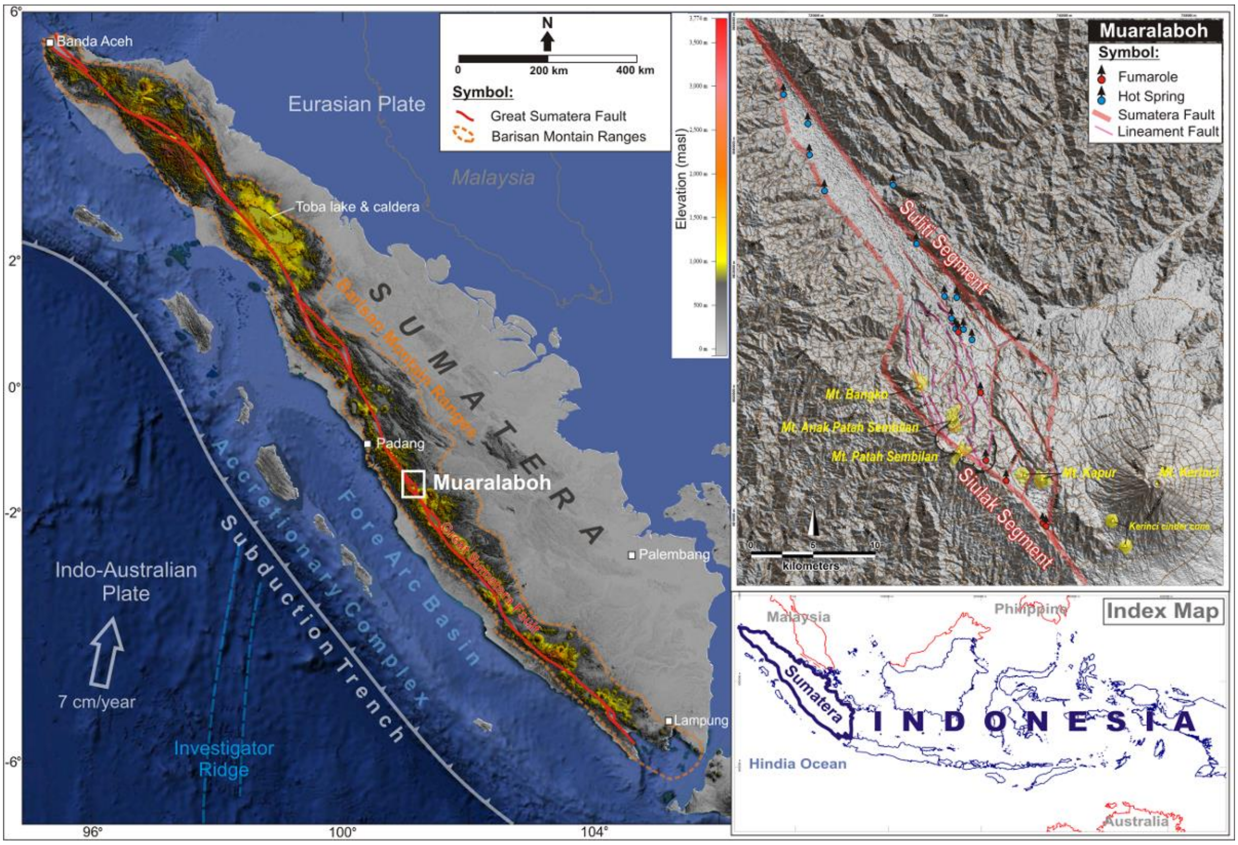
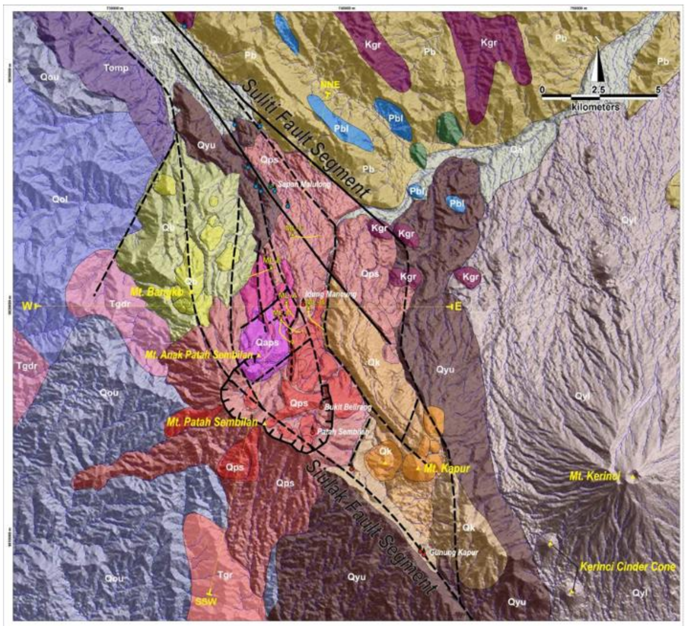


Figure 1: Left: Map of Sumatra island and the location of Muara Laboh field. Right top is a map showing Muara Laboh field located in between two segments of the Great Sumatran Fault (Baroek et al., 2018).



Reference Ages	Volcanic & Sediment	Intrusive	Formation/Product & Lithology	Geothermal System in Correlations to Stratigraphy
Quaternary (<*1.8 Ma*)	Qal, Qyl, Qaps, Qps, Qb, Qyu	Qk, Qou/i	Aluvium Mt. Kerinci, Mt. Kapur, Mt. Anak Patah Sembilan, Mt. Patah Sembilan, Mt. Bangko – **Andestic Volcanic Rocks** Undifferentiated silicic volcanic rocks Intercalation andesite & silicic volcanic rocks	**Hosts Reservoir Clay Cap** **Shallow Reservoir** **Intermediate Zone**
Tertiary (Oligocene to Miocene *33-5.3 Ma*)	Tomp	Tgdr, Tgr	**Granite & Granodiorite** **Painan Formation:** Volcanic (andesitic to silicic) & Sedimentary (shale to sandstone)	**Deep Reservoir**
Mesozoic (Cretaceous *144 Ma*)	Ps	Kgr	**Granitic Rocks** **Siguntur Formation:** Quarzite	**Outside Reservoir**
Paleozoic (Permian *248 Ma*)	Pbl, Pb		**Bukit Barisan Formation:** Phyllite, slate, limestone, metagreywacke	

Figure 2: Geologic map and simplified stratigraphy of Muara Laboh (Mussofan et al., 2018).

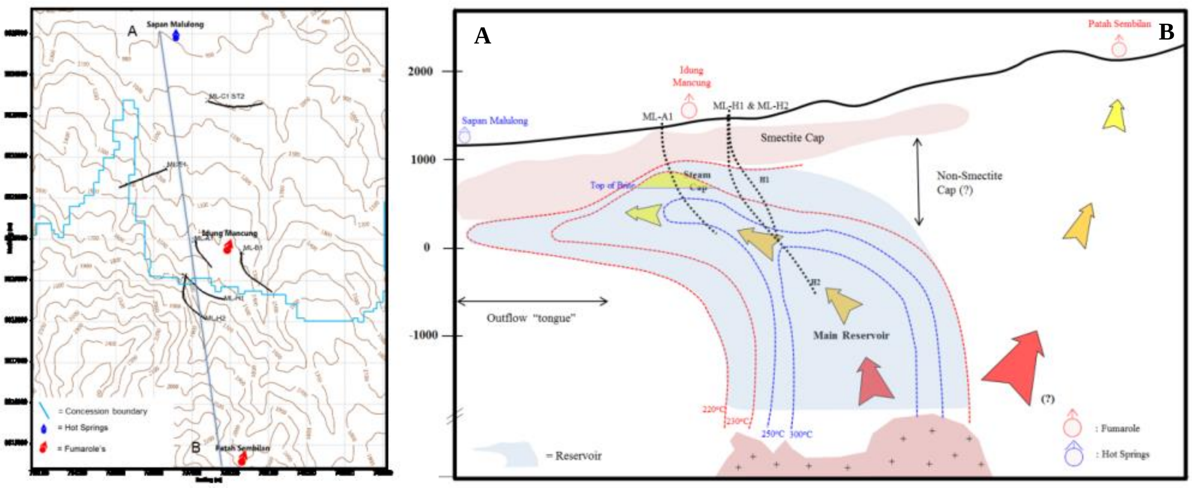


Figure 3: Left: Map showing of six exploration wells drilled in Muara Laboh. Right: N-S cross section showing the conceptual model developed after exploration drilling (Situmorang et al., 2016).

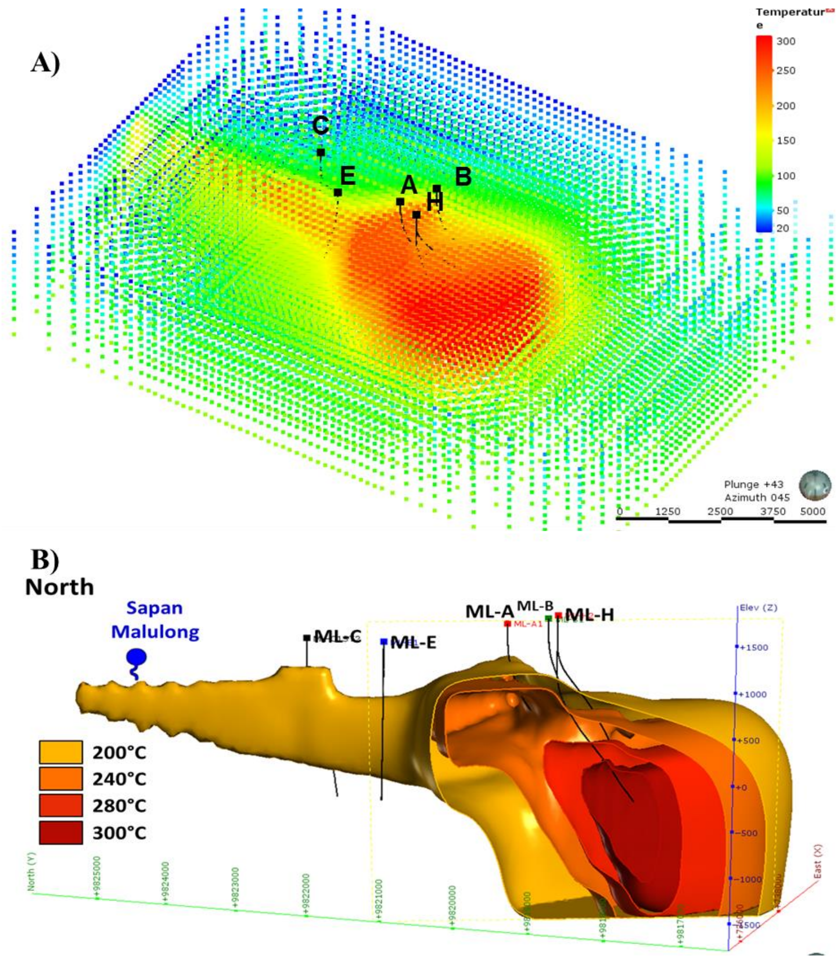


Figure 4: 2016 3D model includes geology model and temperature model, independently, then it is combined for well targeting. A) Point attributes data of initial temperature model is extracted from 2015 numerical simulation B) interpolated initial temperature data result.

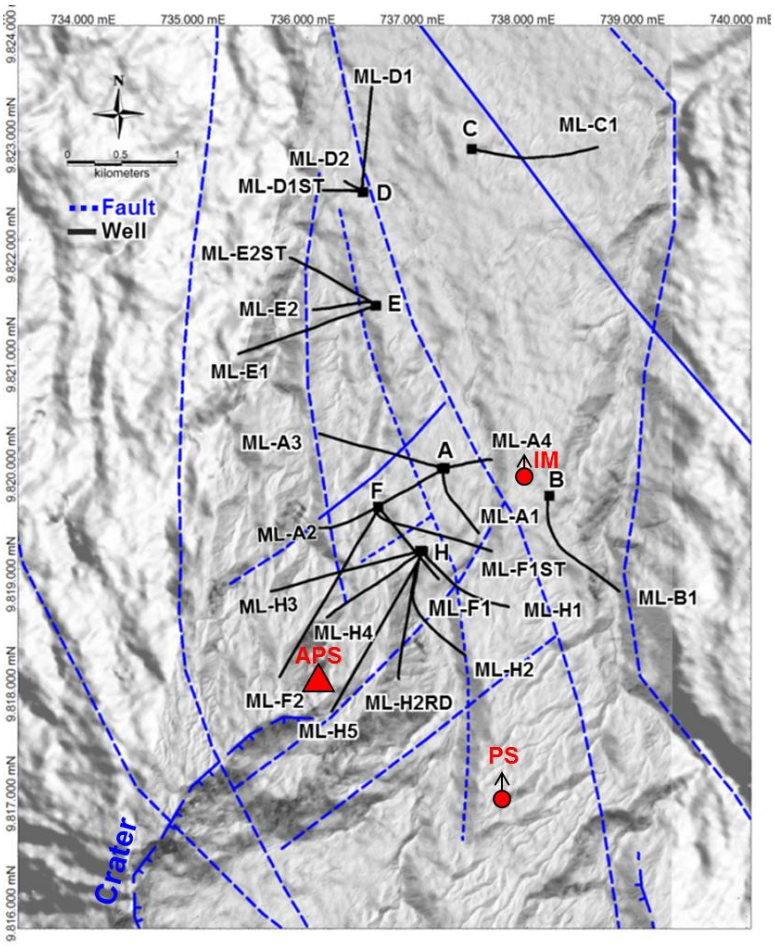


Figure 5: The map of Muara Laboh field, with 17 wells as total drilled wells until 2018 (SEML, 2018).

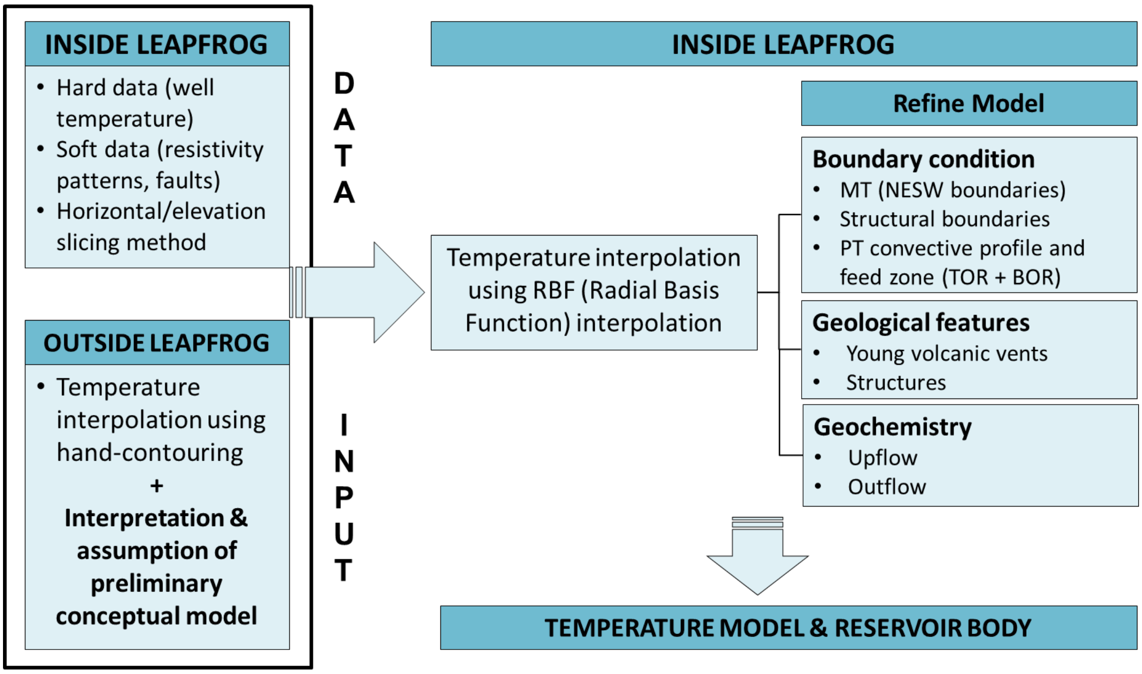


Figure 6: 2017-2018 Muara Laboh modeling workflow.

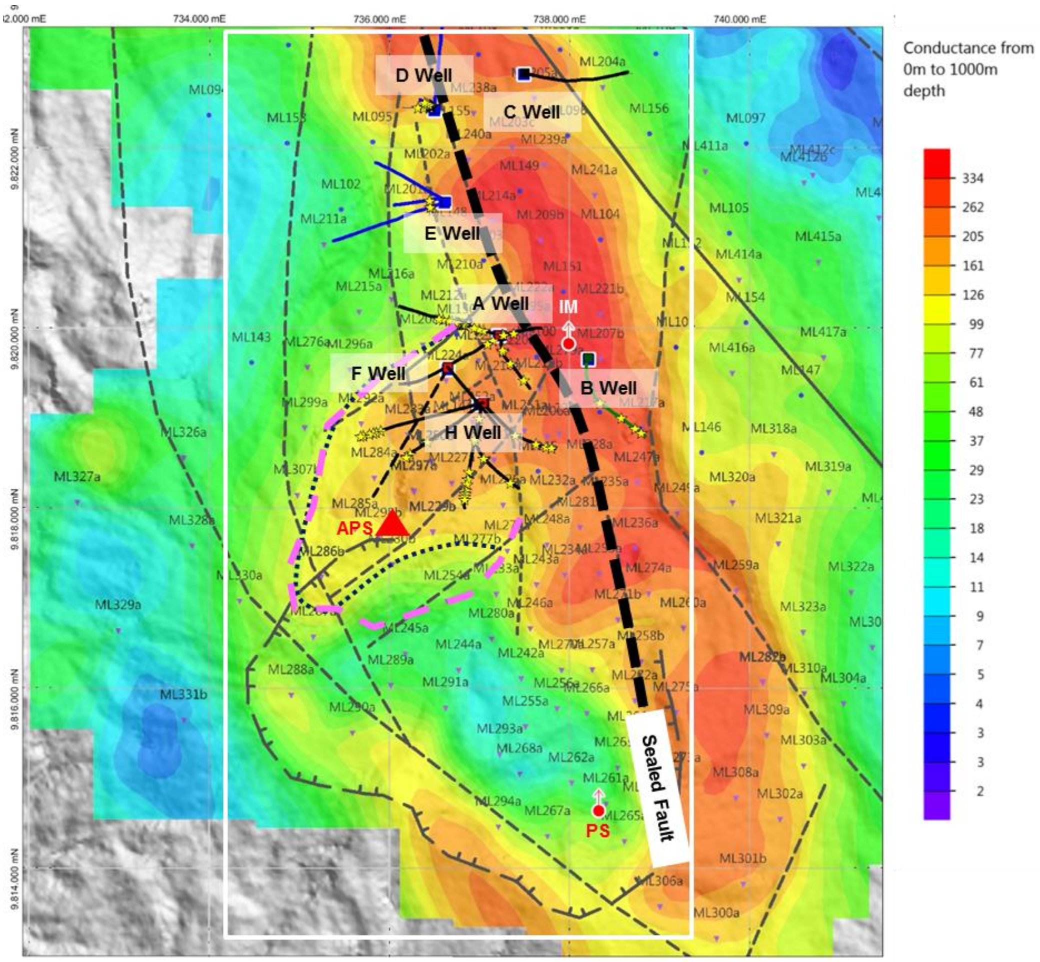


Figure 7: Map of total conductance (at 1000 m asl), conductive layer extension in western area (magenta lines), elongated conductive layer in the eastern of sealed fault, and model boundary marked by white rectangle (modified from SEML, 2018).

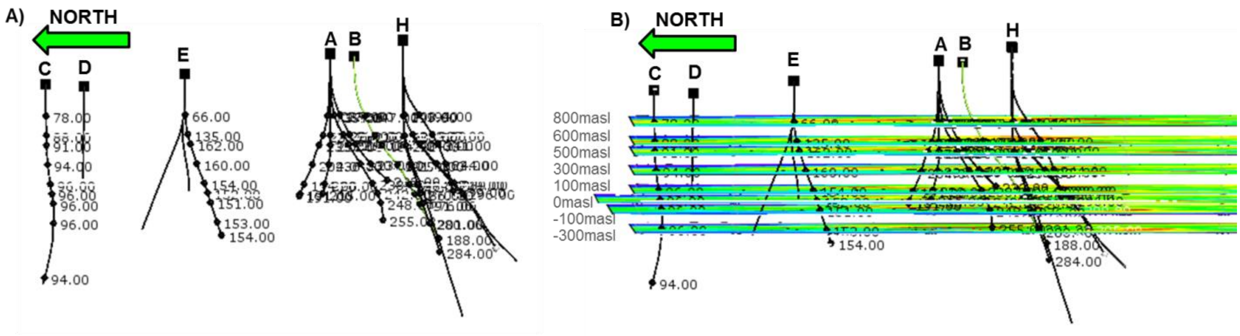


Figure 8: A) Re-sampled well temperature to fit 2D horizontal slices B) 2D horizontal slices at depth (800 m asl to -300 m asl).

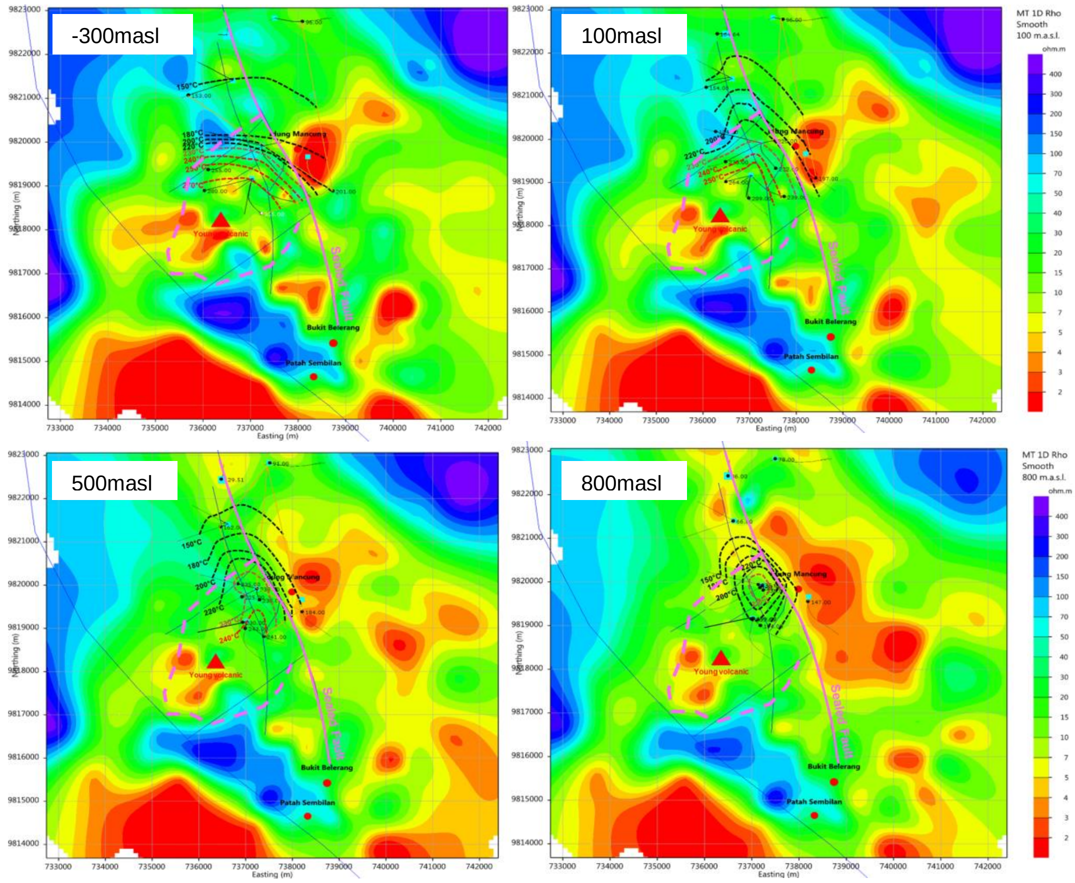


Figure 9: Hand-contoured temperatures are overlaid with 1D TE MT slices at depth and reservoir boundaries.

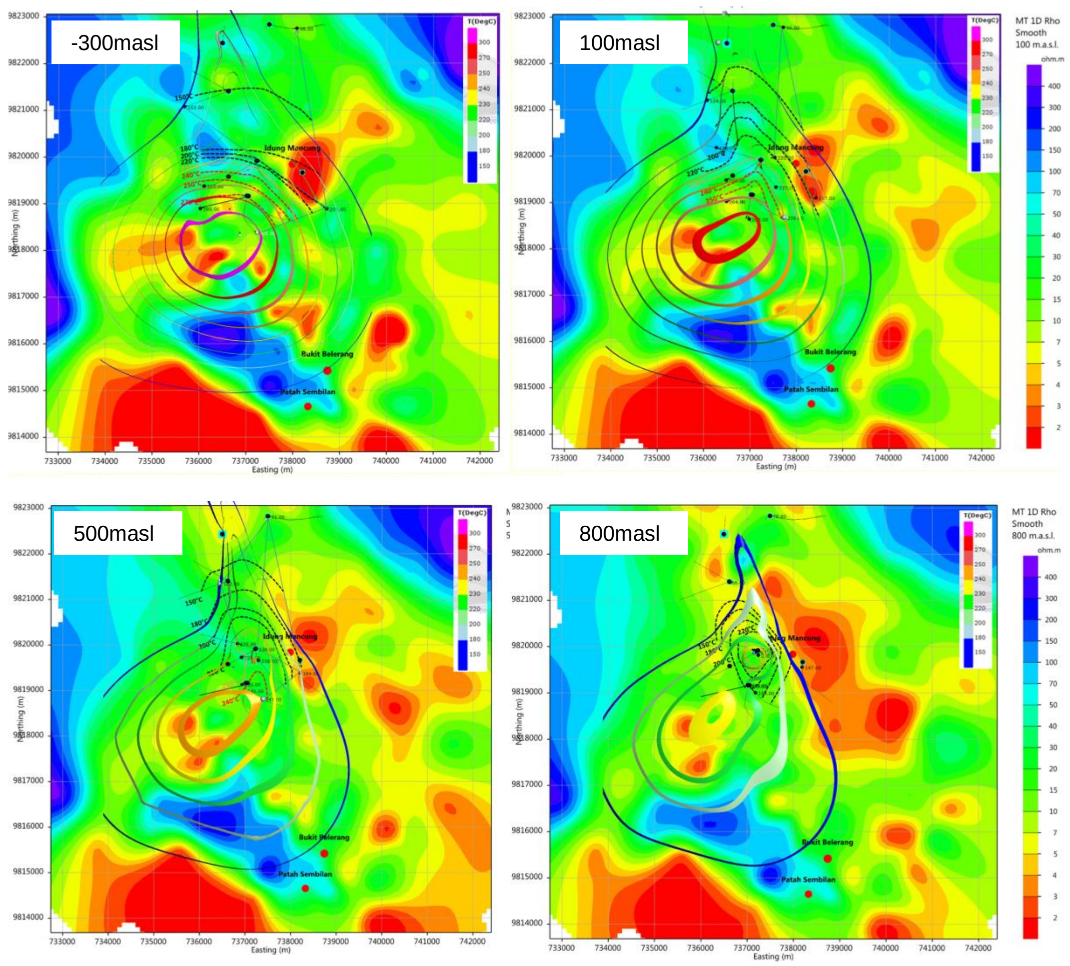


Figure 10: Iso-temperature 3D body result compare to 2D hand-contoured.

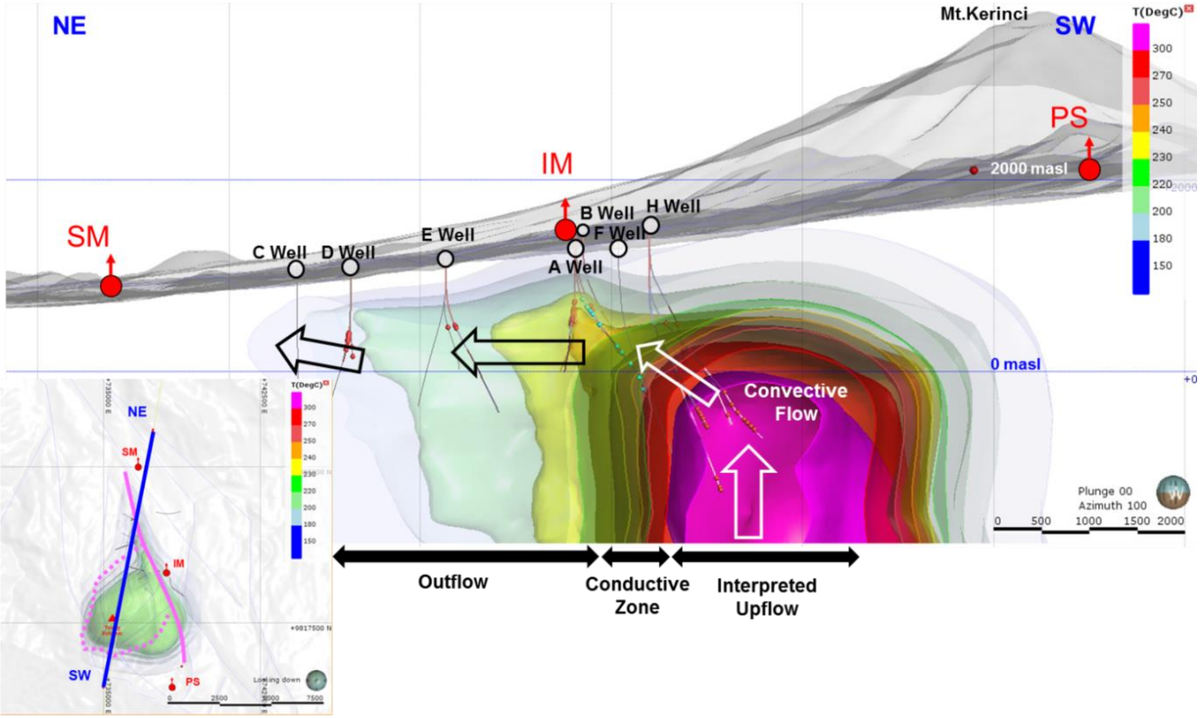


Figure 11: On NE-SW cross-section is a 3D temperature body result represents the hottest part of the system and outflow direction, interpreted convective and conductive flow path (modified after SEML, 2018).

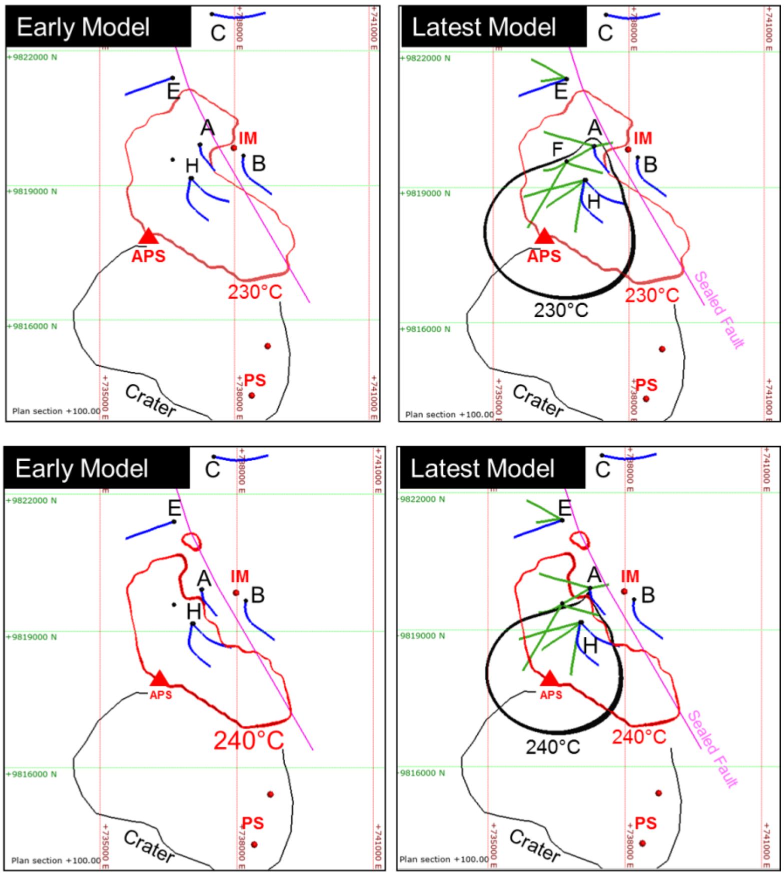


Figure 12: Temperature comparison between 2016 and 2018 temperature models showing a body of iso-temperature of 230°C and 240°C at 100 m asl.

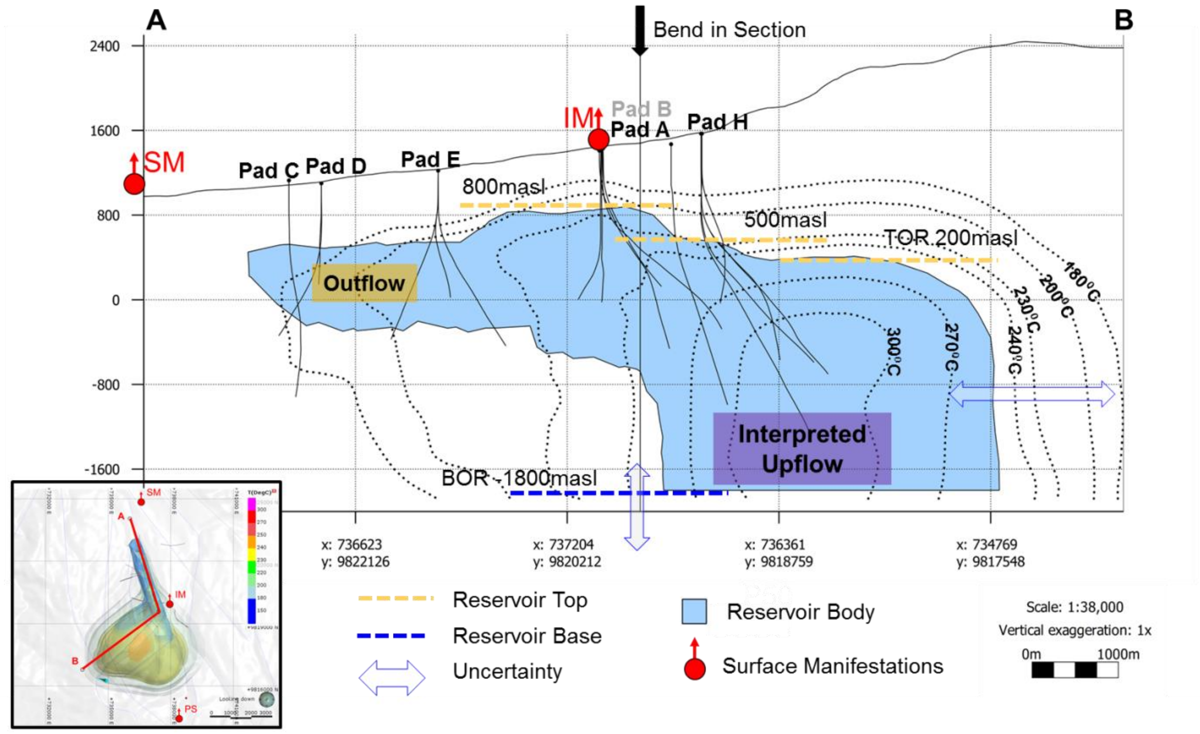


Figure 13: Reservoir geometry where it is most likely to be the potential drilling target (modified after SEML, 2018).