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Natural-State Reservoir Model of Sorik Marapi Geothermal Field

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ABSTRACT

The Sorik Marapi Geothermal Field is located west and northwest of Sorik Marapi, an active andesitic stratovolcano, on the western splay of the Sumatra Fault Zone (SFZ) and within the Panyabungan Graben. A conceptual model of the reservoir has been developed by integrating the geology, geophysics, geochemistry and well testing results obtained to date. The conceptual model is characterized by a primary upflow originating in the fractured basement rocks located near well T-09 in the drilled area with a temperature of >320°C. The conceptual model was used to develop a 3-D numerical natural state model; the model was calibrated by matching feedzone pressures and temperature profiles in wells. The calibrated natural state model will be used to history-match the available production data and to assess the production capacity of the drilled area. As geothermal development brings additional data from geoscientific studies, drilling and testing, the conceptual and numerical reservoir models will be updated and used to forecast the reservoir response to various development scenarios.

1. INTRODUCTION

Sorik Marapi Geothermal Power Ltd. (SMGP) is developing the Sorik Marapi Geothermal Field located west and northwest of Sorik Marapi, an active andesitic stratovolcano, on the western splay of the Sumatra Fault Zone (SFZ) and within the Panyabungan Graben. The license area covers an area of about 629 km^2; the initial development is focused on the area east of the stratovolcano (**Figure 1**). The geothermal field is currently supplying Phase 1, a 45 MWe geothermal power development that has been in operation since October 2019. In addition, SMGP is now completing drilling and testing the wells to support Phase 2 (45 MWe), which will come online in early 2021. To date, 22 wells have been drilled at the current resource area in the vicinity of Pads A, C, D, P, and T.

A conceptual model of the geothermal reservoir was developed by integrating available geological, geophysical, geochemical, and well test data. According to the conceptual model, the primary hot water upflow with a temperature greater than 320 °C originates in the fractured basement rocks located to the west of well T-09 (**Figure 2**).

The conceptual model was used as a point of departure for the 3-D numerical natural state model described in the following sections. The numerical model was calibrated by matching feedzone pressures and temperature profiles in wells. The calibrated natural state numerical model will be used to history match the available production data (November 2019 – October 2020) and to derive a preliminary estimate of the production capacity of the reservoir.

2. COMPUTATIONAL VOLUME, MODEL GRID, AND BOUNDARY CONDITIONS

The ground surface elevation in the Sorik Marapi area varies from less than 300 mASL (meters above sea-level) to over 2100 mASL. The bottom of the deepest well drilled to-date (T-07) is at 2362 mTVD (~ –1459 mASL). The bottom of the model grid is placed at 2500 m below sea-level; thus, the model grid extends more than 1000 m below the deepest well. The top of the model grid is placed at the assumed water level (1 bar surface). The computational domain has dimensions of 10 × 11 × 3.5 km; it is discretized into a three-dimensional structured grid with higher resolution within the well field. The origin is at 563,351.73 mE, 70,863.33 mN and –2,500 mASL The X-axis is rotated 32.71° north of east to be aligned with the orientation of the Great Sumatran Fault zone.

The geologic framework based on the conceptual model (developed within the LeapFrog framework and updated with new drilling and testing data through October 2020) is used as the basis for assigning lithological types to the elements of the numerical grid. The reservoir rocks in the center of the model consist of metasediments and Quaternary Tertiary intrusives. The reservoir is bounded by less permeable granites to the south, sediments to the east, and background sediments to the west. The major metasedimentary and intrusive formations hosting the geothermal reservoir are overlain by young volcanic rocks containing smectite clay, which form a cap over the reservoir. Major structures controlling the system boundaries are strands of the NNW-trending Great Sumatran Fault on the east and west, and the Bridge Fault on the north which intersects those two fault strands.

The numerical model is developed using an enhanced version of the TOUGH2 simulator (Pruess et al., 2012; Finsterle, 2020) as implemented in the iTOUGH2 simulation-optimization framework (Finsterle et al., 2017) using the EOS1sc equation-of-state module for supercritical water and steam (Magnusdottir and Finsterle, 2015). For the natural-state simulations described hereunder, a single-continuum model was used. However, for the simulation of the past production history as well as the forecasting runs, a dual-permeability model (Pruess and Narasimhan, 1982, 1985) will be developed.

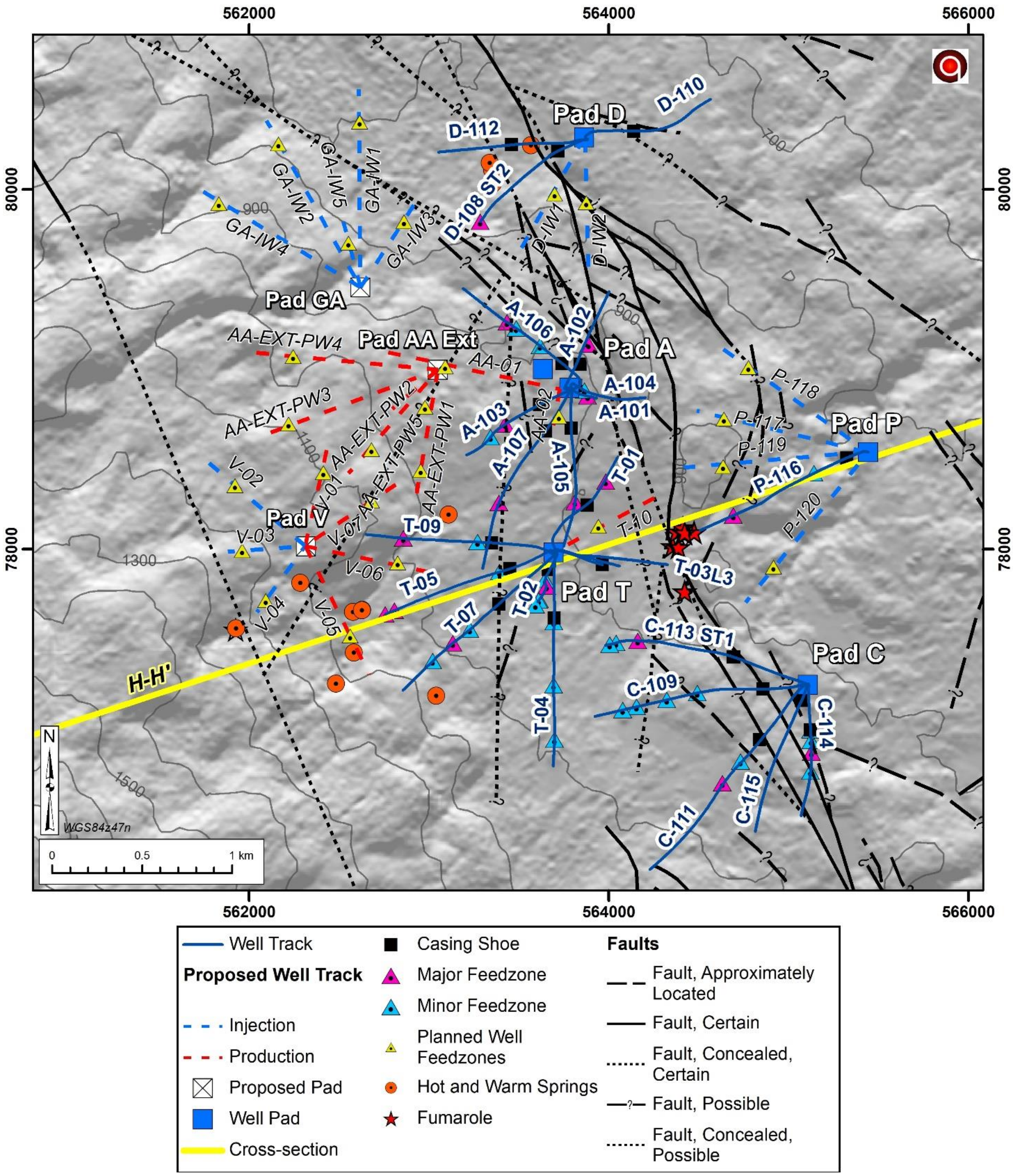

Figure 1: Plan view of the Sorik Marapi geothermal field with current and proposed well tracks.

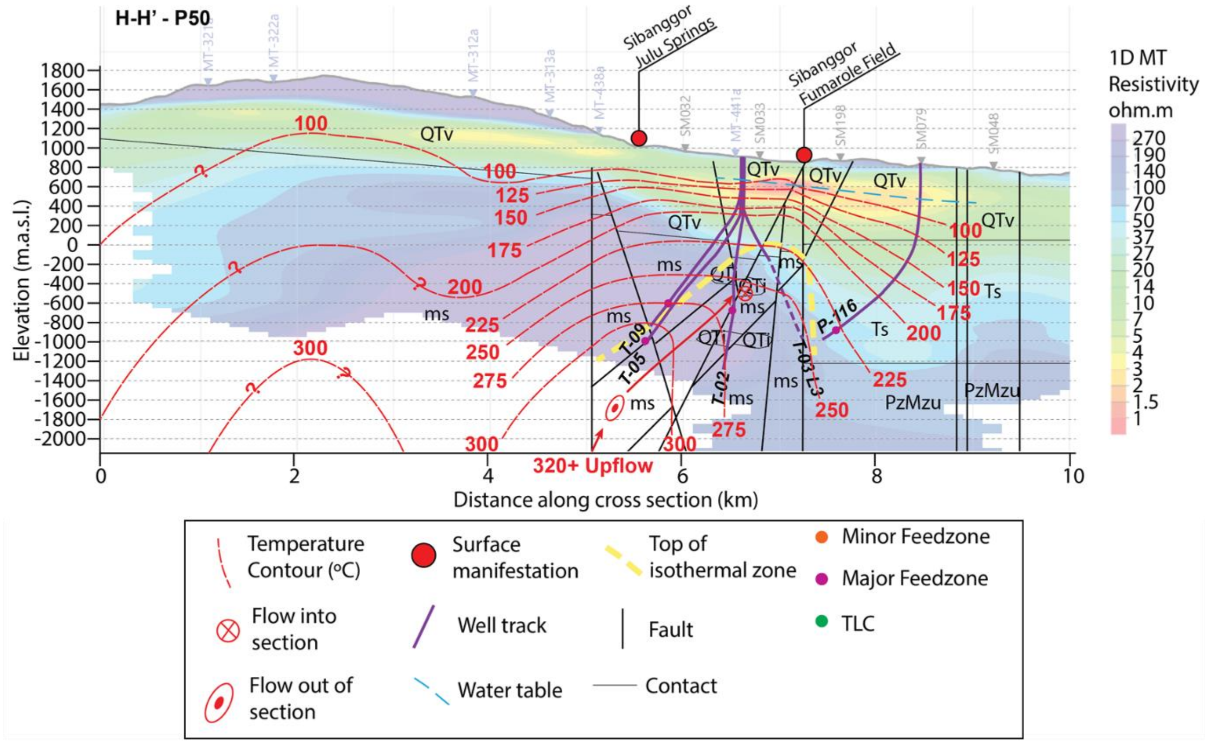

Figure 2: Resistivity and inferred temperature distribution along cross section H-H' from plan view of the Sorik Marapi geothermal field (Figure 1). Inclined (outward-facing) upflow of hot water is sourced from the fractured basement rocks located to the west of well T-09.

The computational grid in the X-Y plane and a three-dimensional visualization of the model domain with the major reservoir rocks exposed are shown in **Figure 3**. The mesh consists of 38,329 elements and 104,297 connections between them. Constant pressure and constant temperature boundary conditions are specified at both the top and the bottom of the model domain at elevations of 550 and –2,500 mASL, respectively. The uniform pressure and temperature values at these boundaries are determined as part of automatic model calibration. Note that heat flux across these boundaries is conduction-dominated. In addition, a high-enthalpy mass upflow within a relatively narrow high-permeability chimney west of well T-09 is specified, with the rate and enthalpy determined during model calibration. All vertical side boundaries are impermeable and thermally insulated, with the exception of two outflow windows that allow for lateral flow from the center of the reservoir along the orientation of the Great Sumatran Fault to the southeast and northwest. The pressures and temperatures at these two outflow windows are adjustable parameters to be determined during model calibration.

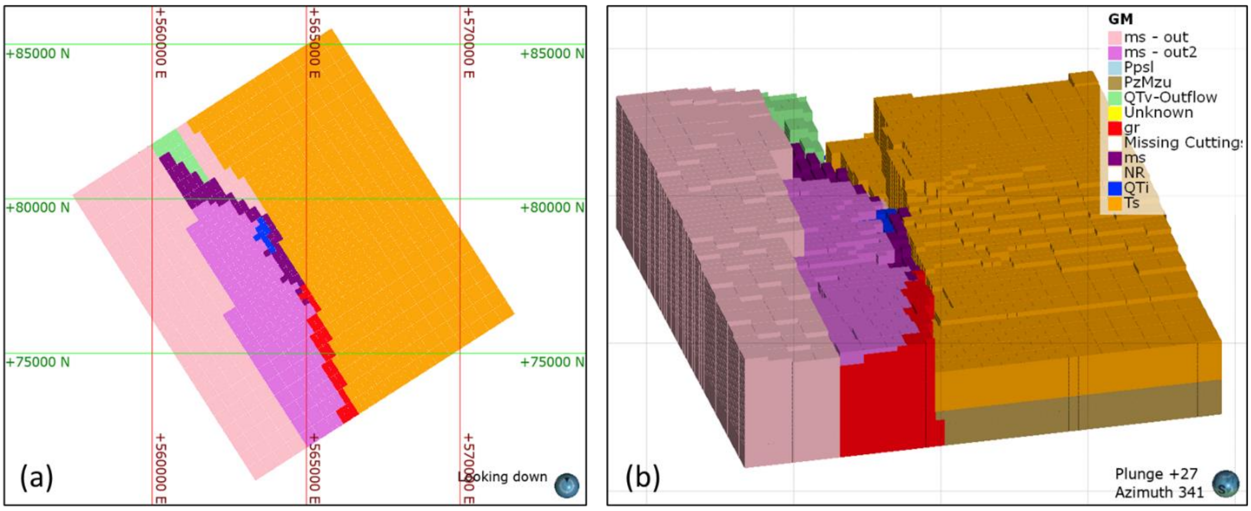

Figure 3: (a) Model grid in X-Y plane, and (b) three-dimensional visualization of model domain with main material types exposed from under the young volcanics cover.

3. MODEL CALIBRATION

Starting from an essentially arbitrary initial state, the computation is run to steady state, and the resulting temperature distribution is compared to measured profiles in wells that are considered to have stabilized and are representing natural-state conditions. Moreover, static downhole pressures at known feedzones monitored in some of the wells are also available for natural-state calibration. A total of 47 parameters are automatically adjusted to minimize a least-squares objective function of appropriately weighted residuals between measured and calculated temperatures and pressures. Estimates of rock property values that are considered reasonable are added as “prior information” to the estimation framework to stabilize the inversion. Adjustable parameters included the thermal conductivities as well as the horizontal and vertical permeabilities of the 12 different materials defined in the model. In addition, boundary pressures and temperatures at the top, bottom, and two outflow windows are estimated, along with the conductive heat flux, enthalpy and mass flow rate of the fluid in the upflow zone.

Figure 4 shows the comparison between measured (blue lines) and calculated (red lines) temperature profiles, where the calibration occurred at the discrete points corresponding to the element coordinates of the numerical grid (indicated by yellow squares). The match to the natural-state downhole pressure data is visualized in **Figure 5**. The model is considered to represent the observed natural state reasonably well given uncertainties in the conceptual model and the data.

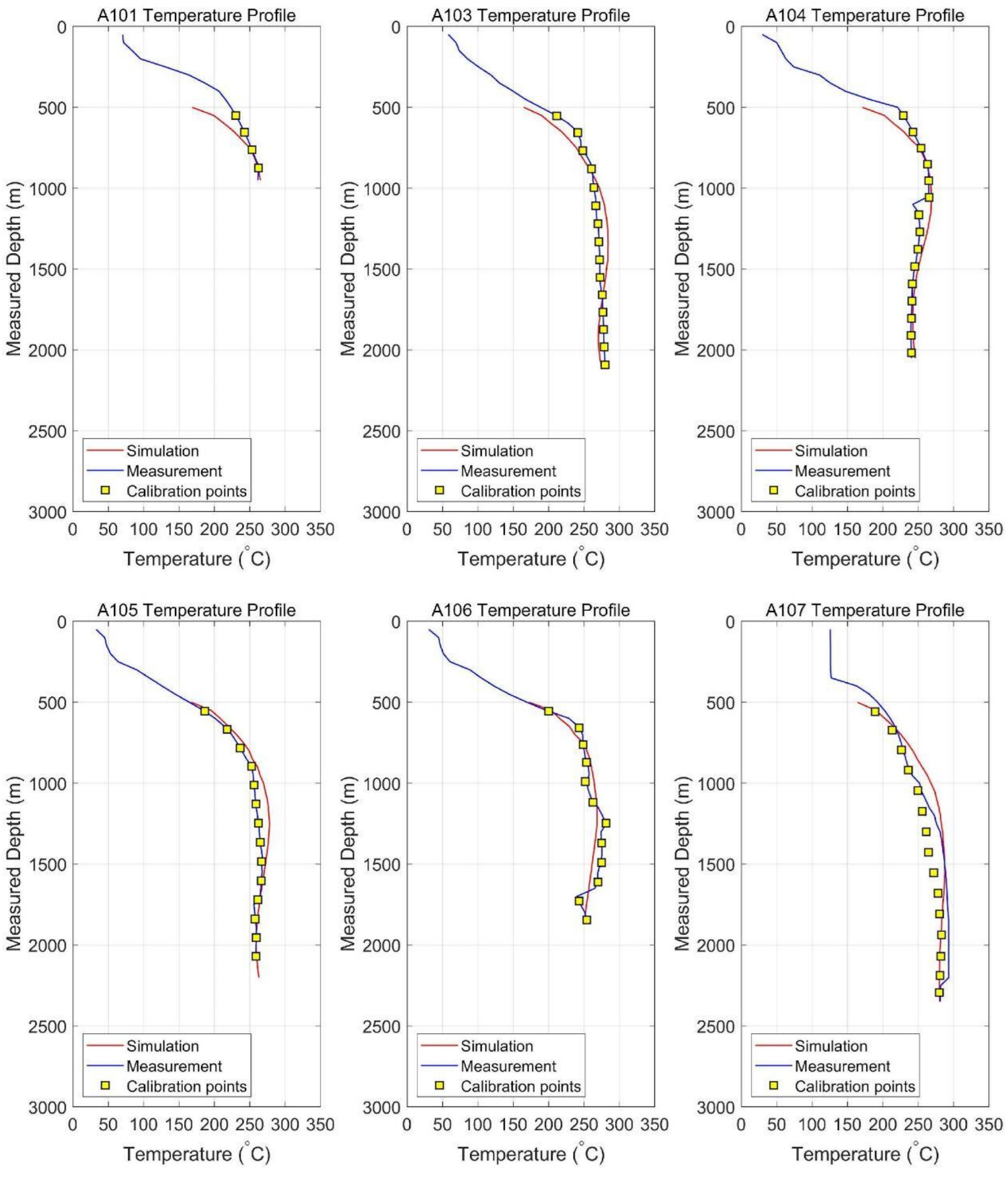

Figure 4: Comparison between measured and calculated temperature profiles along the wells.

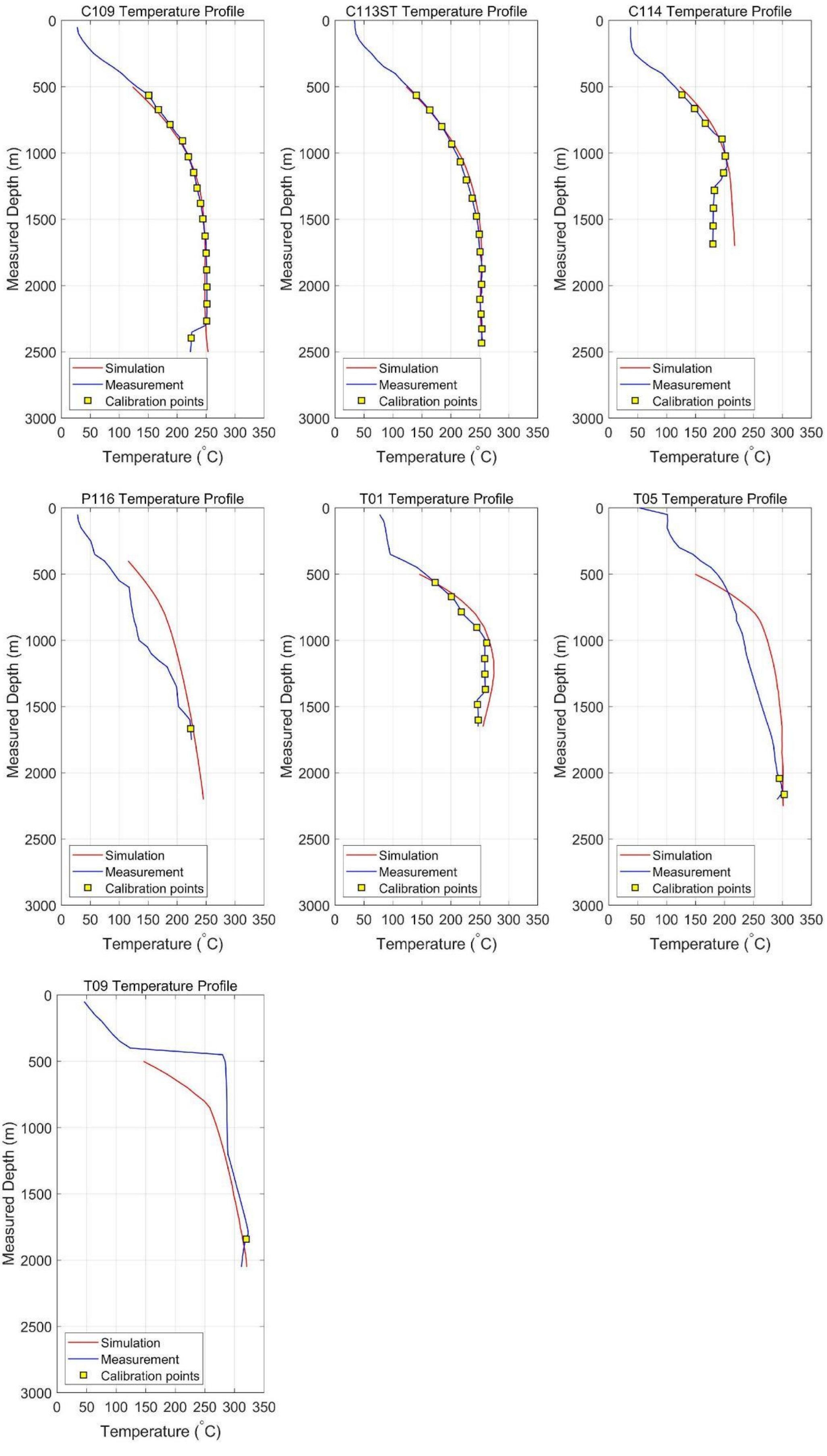

Figure 4: (cont.) Comparison between measured and calculated temperature profiles along the wells.

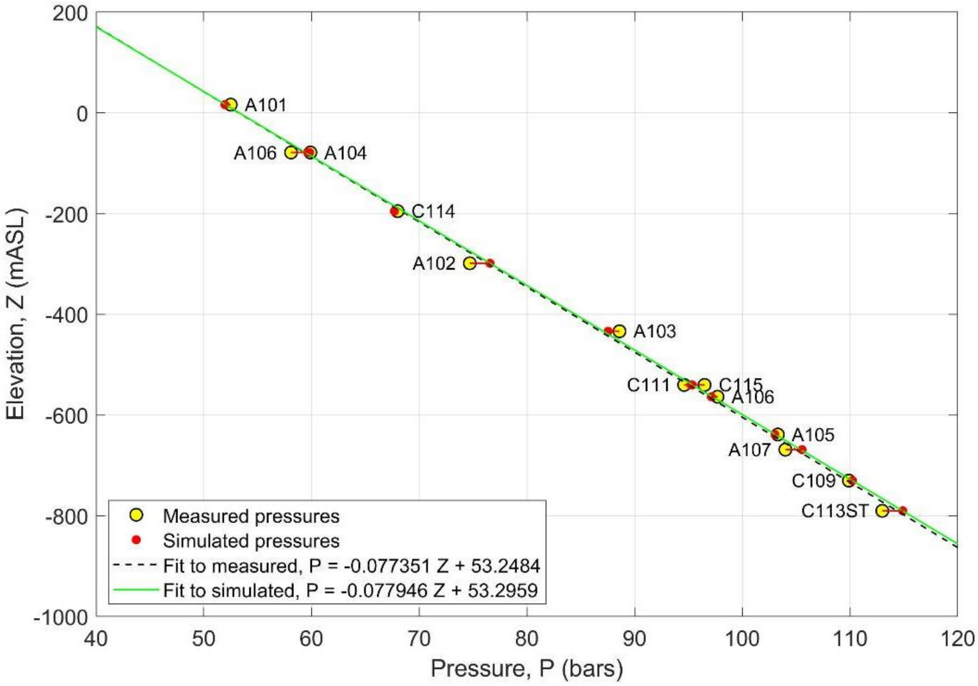

Figure 5: Comparison between measured and calculated static feedzone pressures for A- and C-pad wells.

4. DISCUSSION

Calibration of a geothermal reservoir model against natural-state data is an essential first step in the development of a computational tool to be used for resource assessment and reservoir management. Typically, only limited, spatially sparse data are available to determine the initial pressure, temperature, and steam saturation distributions throughout the reservoir and the extended model domain. Moreover, the available temperature and pressure data may be affected by drilling and well completion operations. The assumption that the system is at steady state prior to exploitation—while reasonable—may not be readily justifiable, with the results crucially affected by the boundary conditions imposed at great depths or at lateral model boundaries, where little information about the geological and hydrothermal conditions are available. Finally, hydrological and thermal reservoir properties—if available—often refer to a scale that is drastically different from the one relevant for large-scale reservoir modeling; the values are therefore conceptually and numerically different from model-related input parameters.

The temperature profiles and pressure data available at Sorik Marapi are suitable for the calibration of an initial, relatively coarse natural-state model. More importantly, the additional information available and used for the development of the geological model was included by a direct mapping of the lithological structures onto the TOUGH2 numerical grid. The ease with which the LeapFrog conceptual model can be updated and consistently transferred to the numerical model is a key advantage of the approach, specifically when new information about the reservoir becomes available during the production period. Moreover, iTOUGH2's automatic calibration and history matching capabilities, which supports a joint inversion of steady-state, natural-state data and transient production data, allows for an efficient and consistent updating of the reservoir model. It is also essential that boundary conditions can be subjected to the estimation process, along with reservoir properties.

As demonstrated in **Figures 4** and **5** above, the model matches the available natural-state data reasonably well. Nevertheless, the conceptual model appears too simplistic to accurately capture some of the temperature inversions. The need to include a high-permeability upflow region (which was not clearly identified in the initial geological model) to match the high temperatures encountered at depth in Wells T-05 and T-09 indicates the iterative nature of the model development process. Finally, while the estimated permeabilities, thermal conductivities and boundary conditions are reasonable, the available natural-state data are insufficient to adequately constrain the model. As a result, the uncertainties in the estimated parameter values remain large due to strong overall parameter correlations. The solution is non-unique, i.e., multiple parameter combinations would be able to yield similar matches to the observed pressures and temperature profiles. This is clearly indicated by the error analysis and composite sensitivity measures calculated by iTOUGH2. This outcome must be expected, also when using a manual trial-and-error method for model calibration.

5. CONCLUDING REMARKS AND FUTURE WORK

An initial conceptual and numerical model of the Sorik Marapi geothermal field was developed and calibrated against natural state pressure and temperature data. This model can be interpreted as a plausible representation of the Sorik Marapi geothermal field, given the current knowledge and information available about the reservoir. However, additional data (mainly from the production phase) need to be included in the model to make it a reliable tool for resource assessment and reservoir management. The current natural-state model is considered a suitable basis for a continually maintained and updated reservoir model of Sorik Marapi.

The calibrated single-continuum natural state model is being used as the basis of a dual-permeability model for history-matching the available production data. The actual production and injection rates will be provided as sink and source terms in the dual-permeability model. If multiple feedzones exist in a given well, the total rate is distributed to the feedzones according to the ratios of the estimated productivity or injectivity indices. This model is being calibrated using (a) the natural-state temperature and pressure data, and (b) production enthalpy data measured between April 2019 and September 2020. Fracture-continuum porosities are added to the set of adjustable parameters, which are determined using automatic history matching techniques of a model that connects a steady-state run preceding each transient simulation of the production period. The history-matched dual-permeability model will be used to assess the production capacity of the Sorik Marapi Geothermal Field.

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