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Numerical Simulation of the Atadei Geothermal Field: An Integrated Model Based on Updated Data

Muhammad Sholekan*, Sutopo , & Heru Berian Pratama

Geothermal Engineering Department, Institut Teknologi Bandung, Indonesia Jl. Ganesha No.10, Bandung, West Java, 40132, Indonesia
*Email: muhammad.sholekan@gmail.com

Abstract. Atadei geothermal system in southeastern Lembata remains unexploited due to insufficient subsurface constraints. This study formulates a calibrated three-dimensional reservoir model to address existing geological ambiguity and enable spatial delineation of productive zones. Multi-disciplinary inputs—comprising thermal logs, alteration mineralogy, resistivity cross-sections, and stratigraphic data—were synthesized and dynamically matched using VOLSUNG under natural-state conditions. The computational domain, exceeding 50 km², integrates deep convective boundaries, fault-aligned flow discontinuities, and phase transition indicators derived from synthetic wells. The simulation attained thermal convergence at $\log dt \geq 11$, reflecting hydrodynamic stabilization. Thermodynamic profiling indicates reservoir initiation at ~500 m depth, capped by a 600–1100 m thick low-permeability unit, with localized two-phase behavior observed at sub-vertical conduits. Peak reservoir temperatures exceed 240 °C, with steam saturation ranging from 0.2–0.65. Atypical vapor intrusion at shallow depth in ATS-4 indicates vertical migration through breached seal zones. The refined model reveals heterogeneity in phase distribution and offers a predictive basis for optimized well deployment.

Keywords: *Reservoir, Atadei, VOLSUNG, Saturation, Permeability*

1 Introduction

The Atadei geothermal field in Lembata, East Nusa Tenggara, Indonesia, is a high-temperature prospect with evident surface activity, including fumaroles and thermal springs aligned along structurally controlled zone. These features suggest a liquid-dominated system controlled by active faults. Despite early surveys estimating a 40 MW potential, the field remains undeveloped due to limited subsurface data and accessibility challenges. Although the presence of thermal anomalies is well documented, a comprehensive assessment of the reservoir's geometry, flow regime, and thermodynamic behavior remains incomplete. Addressing these gaps is essential for delineating productive zones and informing future exploration strategies.

The Atadei geothermal area is hosted within a Quaternary volcanic terrain, structurally influenced by active faulting, with prominent thermal indicators—such as fumaroles, acidic springs, and altered zones—suggesting the existence of a high-temperature system at depth. Elevated thermal activity concentrated in zones like Watuwawer and Lewokebingin points to structurally guided upflow pathways, consistent with previous findings (Aswin et al., 2001; Nanlohy et al., 2003; PLN, 2020). Geophysical interpretations, particularly from magnetotelluric surveys, reveal conductive caprock layers superimposed on more resistive structures interpreted as reservoir formations (Supijo et al., 2018, 2020; Arsyadipura et al., 2010). Subsurface temperature logs and alteration mineralogy from AT-1 and AT-2 corroborate the presence of ongoing geothermal circulation. While natural-state simulation has been successfully applied in other greenfields—e.g., Tulehu, Ulumbu, and Mataloko (Pradipta et al., 2019; Purba et al., 2016; Hamdani et al., 2021)—Atadei remains underdeveloped in this regard. Reservoir modeling efforts in Lahendong, Sokoria, and Wayang Windu have proven vital for project advancement (Saptadji et al., 2012; Sumintadireja et al., 2015; Sudarman et al., 2013), alongside international benchmarks such as Hengill and Los Azufres (O'Sullivan et al., 2015; Arellano et al., 2005). Recent methodological work by Pratama and Sutopo introduced experimental design and Box-Behnken approaches for probabilistic reservoir analysis in Atadei, enabling refined resource quantification (Supijo et al., 2020; Pratama et al., 2019). Comparable optimization frameworks were also adopted in Karaha–Talaga Bodas to address subsurface uncertainty and inform phased development scenarios (Sutopo et al., 2019). To advance Atadei, a calibrated 3D reservoir model is essential for reducing geological uncertainty and facilitate an integrated characterization of its geothermal system.

This study aims to construct a calibrated three-dimensional reservoir model of the Atadei geothermal system based on recent geological, geophysical, geochemical, and well data. The field is characterized by structurally aligned thermal manifestations concentrated in areas such as Watuwawer and Lewo Kebingin, which coincide with low-resistivity anomalies identified in MT surveys. Temperature logs from wells AT-1 and AT-2 show values exceeding 240°C below 1000 meters, supported by alteration of mineral assemblages. Despite these findings, development remains constrained due to the lack of an integrated model. Using the VOLSUNG simulator, this study replicates natural state conditions and defines key subsurface features, including thermal distribution, permeability contrasts, and fluid pathways. The resulting simulation reduces geological uncertainty and provides essential insight into future well targeting.

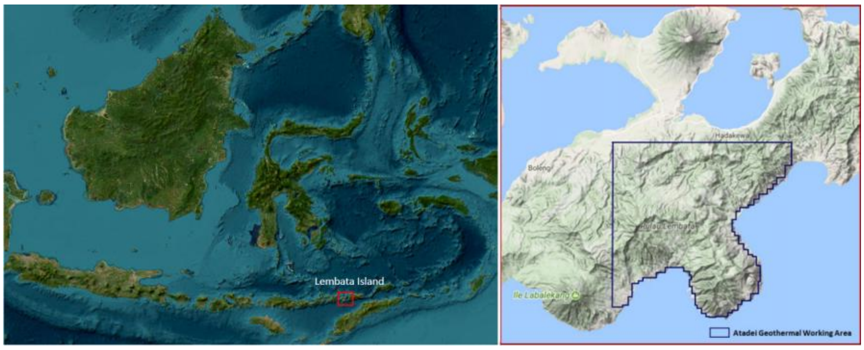


Figure 1 *Location of Atadei geothermal working area in lembata island*

2 Outline of Atadei Geothermal System

2.1 Geological, geochemical, and geophysical properties

The Atadei geothermal system lies within a Quaternary volcanic setting in southeastern Lembata Island, underlain by andesitic to dacitic volcanic formations. This includes lava flows, pyroclastic layers, and zones of pervasive hydrothermal alteration. Surface expressions—such as fumaroles and acid sulfate springs—are spatially linked to NE–SW faults like Lewo Kebingin and Watuwawer, which serve as deep fluid conduits. Stratigraphic interpretations indicate a volcanic cover of moderate thickness, enabling caprock development and supporting a structurally guided, liquid-dominated geothermal regime.

Geochemical and geophysical investigations have offered strong evidence of an active subsurface system. Fumarole gas ratios and acidic spring chemistry point to reservoir temperatures between 220°C and 250°C, with indications of magmatic influence. Isotope data suggests a mixing of meteoric and deep-sourced fluids. Magnetotelluric surveys have identified a conductive zone, likely a clay cap, between 500–1000 meters depth, overlying a more resistive reservoir. Fumaroles at Lewokebingin and Watuwawer suggest proximity to a high-temperature upflow zone with strong magmatic input, while Illewerung and Lewogowok reflect mixed-phase discharge. These findings collectively confirm the presence of a compartmentalized, high-enthalpy geothermal system.

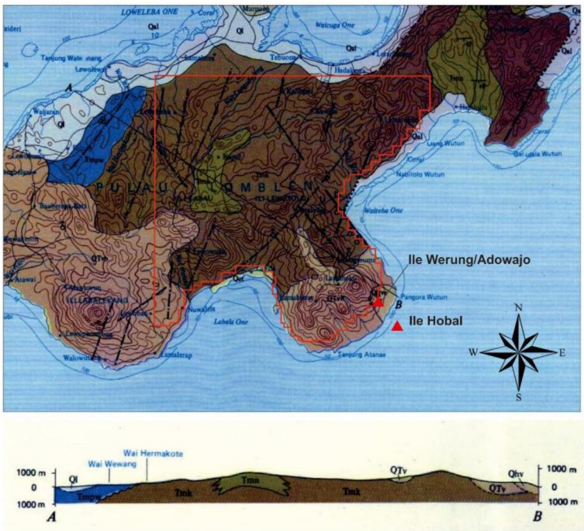
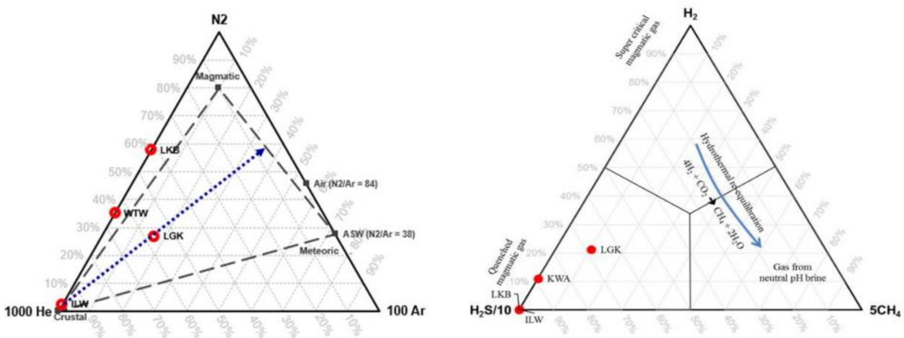


Figure 2 *Snapshot of Map and Geological Section of Lomblen Quadrangle, East Nusatenggara (Koesoemadinata & Noya, 1989). The red line is the boundary of Atadei Geothermal Working Area (Pre-Fs PLN 2020)*

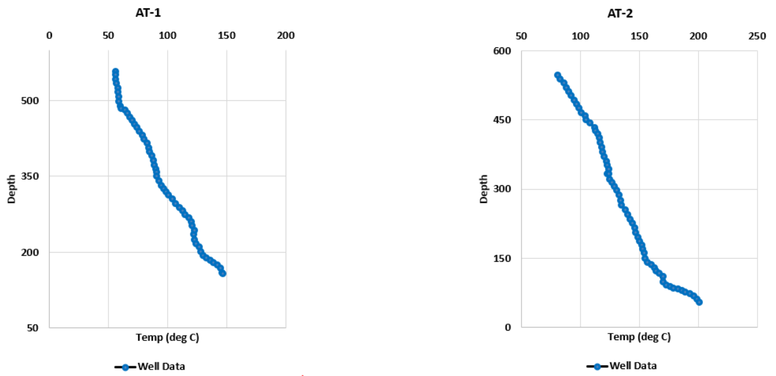


(a) (b)

Figure 3 *Geochemical diagram (a) Trilinear diagram of He-N2-Ar (b) Trilinear diagram of H2S-H2-CH4 gases of Atadei. (Pre-Fs PLN 2020)*

2.2 Well Data

AT-1 was drilled in the central portion of the Atadei geothermal prospect and reached a total depth of approximately 830 meters. Temperature measurements within the well revealed consistent gradient, with values approaching 200°C at its deepest section. Petrological analysis of drill cuttings showed the presence of argillic alteration in shallow intervals, shifting to propylitic assemblages—such as chlorite and epidote—below 500 meters. The stratigraphy comprises volcanic lava flows interlayered with tuffaceous deposits. It provided critical insights into the overlying caprock system and supported the refinement of the subsurface structural model.



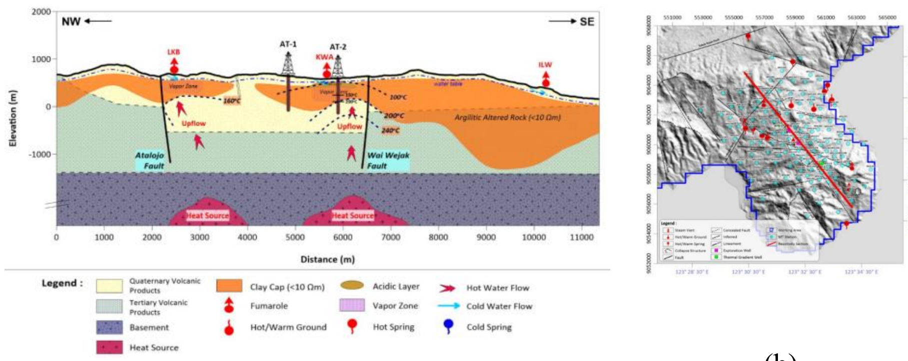
(a) (b)

Figure 4 *Well data of Atadei Geothermal Field (modified from Pre-Fs PLN 2020) (a) AT-1 (b) AT-2*

Well AT-2, located in the eastern sector of the prospect, was drilled to a depth of 750 meters and recorded a steeper thermal profile than AT-1, with temperatures exceeding 240°C in its lower section. Alteration of minerals such as illite, chlorite, and minor pyrite suggest the well penetrated an active hydrothermal zone. Lithological logs indicate fractured volcanic units with enhanced permeability along fault-aligned zones. Data from AT-2 were instrumental in calibrating the 3D reservoir simulation and are interpreted to represent the proximal upflow region.

2.3 Coceptual Model

The conceptual framework for the Atadei geothermal field has evolved from preliminary investigations conducted by the Volcanological Survey of Indonesia (VSI, 2000) and was subsequently enhanced through probabilistic reservoir assessments with Response Surface Methodology, as demonstrated by Supijo et al. (2020). Cross-section Line 8, oriented northwest–southeast, intersects major surface thermal expressions—LKB, KWA, LGK, and ILW—as well as exploratory wells AT-1 and AT-2. Subsurface upflow is interpreted to be structurally controlled by the Waiwejak fault, channeling convective fluid ascent from dual magmatic heat sources. Temperature logs confirm a high-enthalpy system, with AT-2 exceeding 240°C and AT-1 reaching 200°C. The reservoir is overlain by an argillic alteration zone and a clay-rich cap.



(a) (b)

Figure 5 *Conceptual Model of Atadei (a) NW-SE vertical cross section model (b) NW-SE Horizontal cross section of the Atadei (Pre-Fs PLN 2020)*

Based on the synthesis of geological, geochemical, and geophysical data along Line 8, a focused vertical upflow is delineated beneath the Watuwawer and Lewokebingi sectors. Fluid migration is structurally channeled by fault-induced permeability, while lateral flow is limited by lithological barriers. Subsurface logs suggest a liquid-dominated zone transitioning to a two-phase system upwards. Deep-seated intrusive bodies, inferred from anomalous geophysical responses, are interpreted as magmatic heat sources. Distinct gas and fluid compositions corroborate deep recharge and guide reservoir simulation and well-targeting strategies.

3 Numerical Model Development

3.1 Model Structure and Rock Properties

The numerical model covers an estimated area of 54 km², incorporating key subsurface components such as the geothermal reservoir, production and injection wells, as well as the interpreted upflow and outflow zones. It consists of 23 vertical layers, with the top layer following natural terrain and the deepest layer extending to approximately −2500 meters above mean sea level. Structural faults are modeled as internal boundaries to represent fluid flow discontinuities. The mesh comprises roughly 32,000 grid blocks, with horizontal dimensions ranging from 200 × 150 meters to 563 × 774 meters. To enhance geological alignment, the model rotated to 339 degrees.

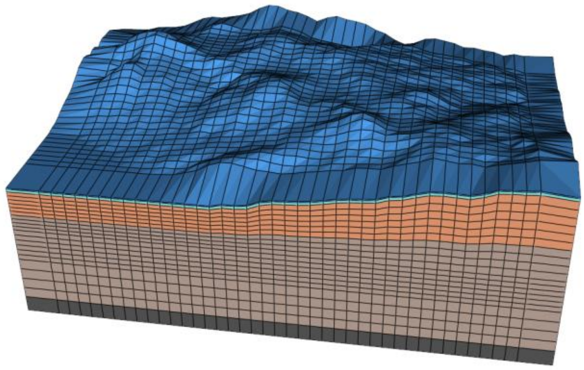
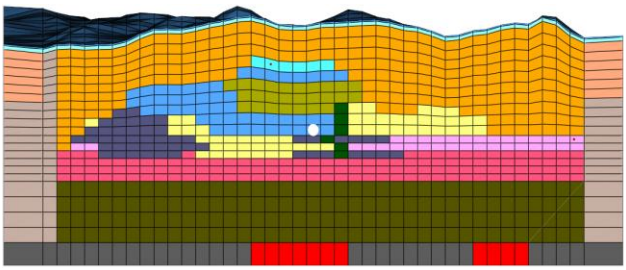


Figure 6 *Griding and Layering system of Atadei*

Understanding the lithological framework and permeability architecture is essential for constructing a robust natural state model in geothermal systems. Achieving an accurate representation often demands numerous calibrations attempts through iterative simulations to reach natural state condition. These elements control subsurface fluid movement and heat distribution, significantly influencing model performance. The spatial arrangement of lithological units utilized in this study is illustrated in the accompanying figure 7.



Rock properties

Material	Colour	Ky(mD)	Kd(mD)	Kz(mD)
Atmosfer		10	10	10
Basement		3	3	3
Boundary		1.00E-05	1.00E-05	1.00E-05
Boundary 2		0.001	0.001	0.001
Cap Rock		1.00E-05	1.00E-05	1.00E-05
FAULT		60	60	70
FAULT 2		65	65	75
Ground Water		5	5	5
Heat Source		100	100	100
Reservoir 0		50	50	45
Reservoir 1		45	45	35
Reservoir 2		40	40	33
Reservoir 3		35	35	30
Reservoir 4		30	30	30
Reservoir 5		20	20	20
Reservoir 6		10	10	15

Figure 7 *Material Properties Distribution*

3.2 Initial and Boundary Conditions

The simulation domain was initialized with defined atmospheric and subsurface boundary conditions. A surface temperature of 25 °C and pressure of 1 bar were imposed at the top boundary to represent ambient conditions. No-flow constraints were applied along the lateral boundaries to simulate impermeable formations and restrict external flux. At the model base (−2500 m), three deep-seated heat sources were introduced to represent magmatic upflow. Each source was assigned an enthalpy of 1264 kJ/kg and associated with distinct upflow zones beneath

Watuwawer (6.94 kg/s), Lewokebingin (4.17 kg/s), and Lewogowok (2.78 kg/s). The spatial distribution of these heat sources is depicted in Figure 8.

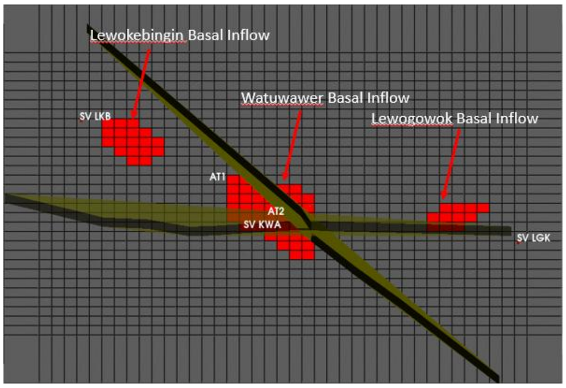


Figure 8 *Heat source location*

4 Result

The Atadei geothermal model reached thermal and hydraulic equilibrium during natural-state simulation, demonstrated by a time step advancement of log dt ≥ 11 (Figure 9). This indicates long-term dynamic stability of the reservoir. Simulated temperature distributions closely align with measurements from wells AT-1 and AT-2 (Figure 10), validating the model's representation of subsurface conditions. The consistency supports the credibility of the applied boundary conditions, geological layering, and fault structures. The alignment enhances confidence in the defined boundaries, stratigraphy, and structural framework. Subsurface thermal data indicates reservoir onset near 500 m depth, with temperatures surpassing 230 °C beneath existing wells.

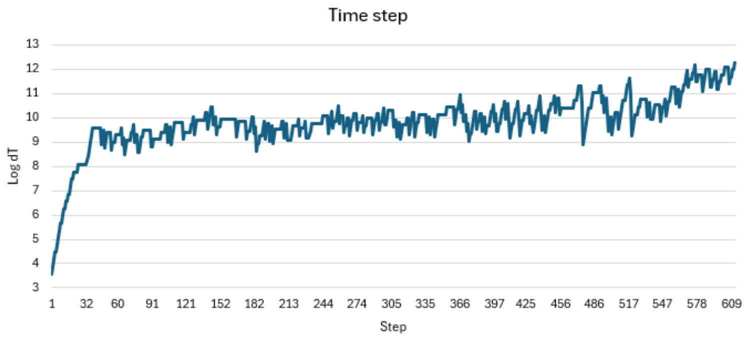


Figure 9 *Time step system*

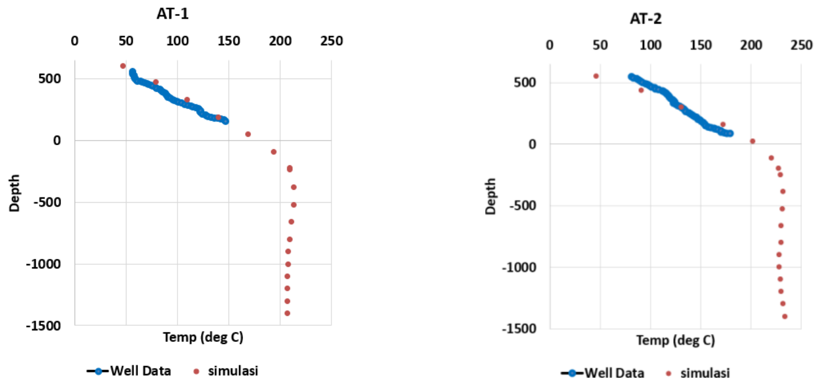


Figure 10 *Well temperature matching*

Figure X displays a vertical section illustrating subsurface temperature gradients and fluid flow pathways. Dominant upward flow is concentrated beneath KWA and LGK, whereas discharge predominantly occurs southward of the LKB sector.

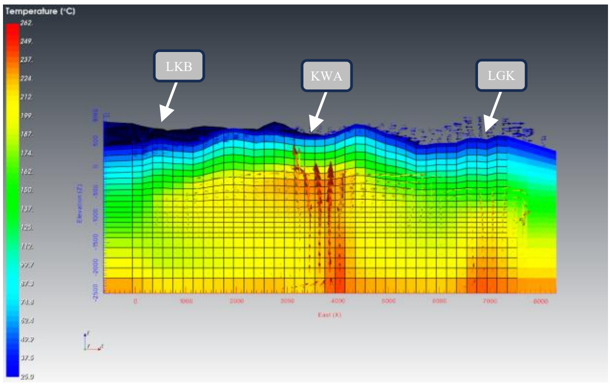


Figure 1 *Vertical slice of numerical model*

5 Discussion

Through natural-state simulation, the spatial distribution of thermodynamic conditions within the reservoir was effectively identified. To simulate and evaluate the subsurface characteristics, four non-physical (dummy) wells were incorporated into the model. These wells were positioned near key surface manifestations, including the steam discharge areas at Watuwawer (KWA), Lewokebingin (LKB), and Lewogowok (LGK) (see Figure 11), enabling a representative assessment of reservoir dynamics associated with the upflow region.

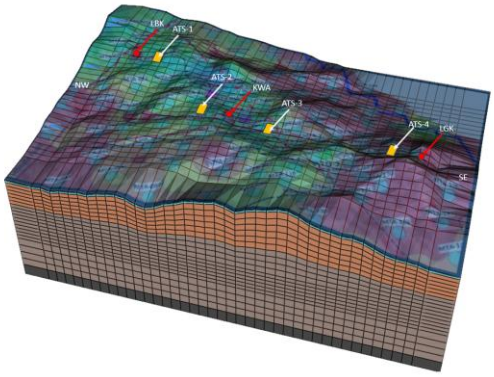


Figure 2 *Location of dummy wells*

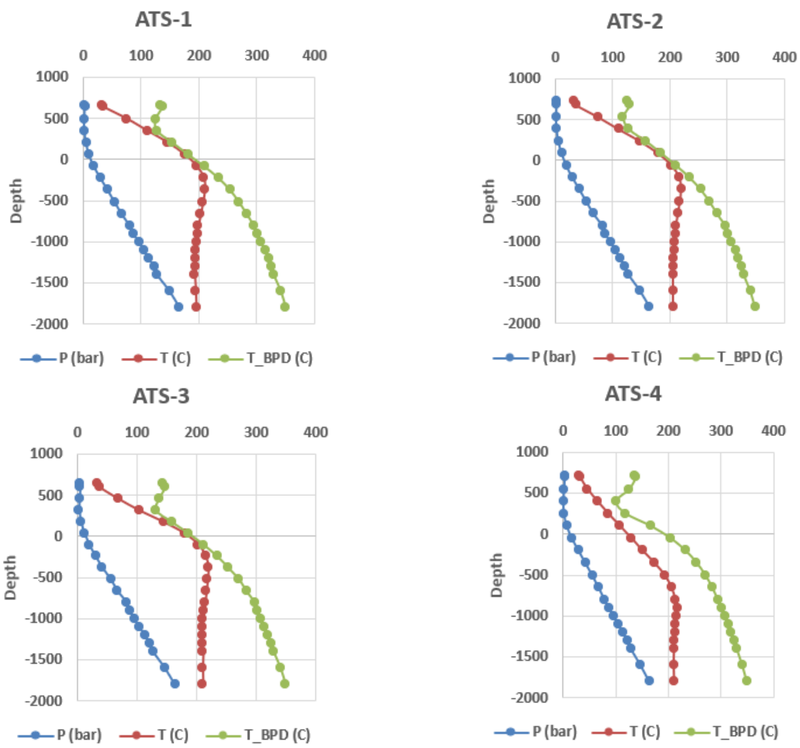


Figure 3 *Temperature and pressure data logging (dummy wells)*

ranging from 600 to 700 m thick. ATS-1 exhibits boiling behavior between 600–1000 m, indicated by gas saturation levels of 0.1–0.43 and temperatures exceeding 200 °C. ATS-2 presents a similar profile, with the two-phase transition occurring at 700–1100 m, supported by BPD trends and SG values between 0.2–0.65, suggesting steam cap formation. In ATS-3, the caprock is slightly thinner; temperature exceeds 220 °C at 1100 m, with reduced SG implying liquid-dominated conditions below 1000 m.

ATS-4 differs notably with a much thicker caprock, approximately 1100 m, overlaying a reservoir where temperatures reach 220–230 °C beyond 1200 m depth. A significant anomaly is observed at 450 m, where SG reaches 0.5 despite temperatures remaining below 100 °C. This suggests the presence of vapor migrating from deeper zones through a fault system, resulting in steam entrapment at shallow levels, implying structural breach of the caprock and vertical transport of deep-seated geothermal gases.

The Atadei reservoir displays a liquid-dominated system with temperatures ranging from 220°C to above 230°C and caprock thickness between 600–1100 m. Wells ATS-1 to ATS-3 reveal boiling conditions below 700 m, with maximum gas saturations of 0.43, 0.65, and 0.38 respectively, indicating steam accumulation near the upper reservoir. ATS-4, though sealed by a thicker caprock, shows a notable SG of 0.5 at just 450 m depth, suggesting vapor migration through a fault. These patterns reflect structurally influenced phase distribution within the system.

6 Conclusions

A three-dimensional reservoir simulation of the Atadei geothermal system achieved equilibrium under natural-state conditions, indicated by a stable log dt ≥ 11. The modeled temperatures align with field measurements, confirming subsurface temperatures between 220°C and above 240°C. The reservoir lies beneath a 600–1100 m thick clay-rich seal, consistent with geophysical interpretations. The system is predominantly liquid dominated, although localized boiling occurs below 700 m, especially near KWA and LGK. Range steam saturation reaches 0.2-0.65, pointing to the presence of transitional two-phase zones. In ATS-4, steam appears unusually shallow, suggesting vertical migration through faulted caprock. This integrated modeling supports Atadei's classification as a high-temperature geothermal system and informs future well placement for exploration and development.

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