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Temperature Profile at Shallow Subsurface Depth of Warm Ground Geothermal Manifestations in Bukit Kasih Minahasa, North Sulawesi: Implications for SDG 7

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ABSTRACT

Objective: *To investigate the shallow subsurface temperature profile of warm ground geothermal manifestations in the Bukit Kasih area, Minahasa, North Sulawesi, Indonesia. Specifically, this study examined the relationship between temperature variation and subsurface depth to develop a preliminary thermal model of geothermal manifestations. The study contributes to geothermal resource assessment and supports sustainable renewable energy development in line with Sustainable Development Goal 7 (Affordable and Clean Energy).* ***Method:*** *The study employed a field-based quantitative approach through direct temperature measurements at warm ground geothermal manifestation sites. Temperature data were collected from several randomly selected measurement points at shallow subsurface depths ranging from 0 to 200 cm. The research was conducted over six months, consisting of field surveys, preparation of measurement equipment, geothermal manifestation observations, temperature data acquisition, laboratory analysis, and data processing. The temperature gradient and depth-temperature relationship were analyzed to determine the subsurface thermal characteristics and develop temperature distribution models.* ***Results:*** *The results showed that the shallow subsurface temperature gradient of warm ground manifestations in the Bukit Kasih geothermal area varied from 13.61 to 71 °C/m. The temperature-depth relationship demonstrated a linear pattern at shallow subsurface depths, indicating a consistent increase in temperature with increasing depth. Meanwhile, the temperature model at greater depths followed a logarithmic function pattern, reflecting changes in heat transfer behavior within the subsurface environment. These findings provide important information regarding shallow geothermal characteristics and potential indicators for further geothermal exploration.* ***Novelty:*** *The study provides new insights into the shallow subsurface thermal characteristics of warm ground geothermal manifestations in Bukit Kasih, Minahasa, North Sulawesi, by developing a temperature-depth model based on direct field measurements. The findings contribute to geothermal exploration strategies and the advancement of renewable energy utilization in accordance with SDG 7 (Affordable and Clean Energy).*

INTRODUCTION

The prospect of utilizing geothermal energy in Indonesia is quite promising, considering that geothermal energy as a renewable electricity source provides a sustainable alternative with low environmental impact compared to conventional fossil-based energy resources. The development of geothermal energy aligns with global efforts to achieve Sustainable Development Goal 7 (SDG 7), which emphasizes access to affordable, reliable, sustainable, and clean energy. Geothermal resources have significant potential to support the energy transition by reducing greenhouse gas emissions and promoting the utilization of environmentally friendly energy technologies (Alhamid et al., 2016; Suryani et al., 2025; Yudha et al., 2022). Therefore, comprehensive geological, geophysical, and geochemical investigations are required to improve the understanding of geothermal systems and support sustainable geothermal resource development.

North Sulawesi has abundant geothermal resources marked by the emergence of geothermal manifestations in several locations, including the Minahasa region (Mukti et al., 2022; Rauf et al., 2023). The occurrence of geothermal manifestations is commonly associated with volcanic fields, where heat sources, permeable structures, and hydrothermal circulation systems interact to form surface expressions (Stelling et al., 2016). Therefore, geoscience studies in volcanic geothermal fields are essential to characterize subsurface conditions. The material characteristics and subsurface structures controlling geothermal manifestations are important aspects to investigate in order to obtain geological, geophysical, and geochemical information, which subsequently becomes the foundation for geothermal exploration and sustainable energy utilization.

Surface manifestations in geothermal areas are closely related to rock fractures, faults, and contact zones between different rock units because these structures represent weak zones that control fluid movement and surface expression patterns (Tian et al., 2026; X. Zhang et al., 2026; Y. Zhang et al., 2026). Lineaments are commonly associated with geological structures such as bedding, fractures, faults, hot spring occurrences, river bends, and other structural features controlled by subsurface deformation processes (Gabrielsen & Olesen, 2024; Gani et al., 2026; Seelan, 2024). The identification of fault patterns and fracture zones is important because permeable structures generally act as pathways for geothermal fluids and represent potential targets in geothermal exploration (Gabrielsen & Olesen, 2024; Joji, 2025). Hot fluids primarily migrate through fracture and fault networks, where interactions between fluids and surrounding rocks influence the thermal characteristics observed at the surface (Feng et al., 2022; Gudmundsson, 2022; Sato & Ito, 2026).

Bukit Kasih is a geothermal manifestation area located in Kanonang Village, Minahasa Regency, North Sulawesi, and is included within the Tompaso geothermal prospect area. This region is characterized by hilly morphology, representing part of the slopes of Mount Rindengan and a volcanic chain trending southwest–northeast (SW–NE). Bukit Kasih has an elevation ranging from 800–900 m above sea level and consists predominantly of young volcanic rocks, including basaltic lava, volcanic bombs, lapilli, and ash deposits formed during the Quaternary period. Various geothermal manifestations can be observed in this area, including warm ground, steaming ground, hot springs, fumaroles, and hydrothermal alteration zones (Elders & Moore, 2025; Sary, 2024; Yadav et al., 2024). These manifestations are generated by heat transfer processes from subsurface geothermal systems to surface materials through conduction and fluid circulation mechanisms.

The occurrence of warm ground manifestations provides an opportunity to investigate shallow subsurface thermal characteristics through temperature gradient measurements. The geothermal gradient represents the rate of temperature increase with increasing depth within the Earth's subsurface and provides important information regarding thermal conditions and heat distribution in geothermal systems (Pierru et al., 2022; Xiao et al., 2023; Zaccagnino & Doglioni, 2022). Understanding shallow subsurface temperature distribution is an important preliminary step in geothermal resource assessment because it provides insights into heat sources, thermal anomalies, and potential areas for further exploration.

Previous research has been conducted in the same area with a different research focus, specifically on steaming ground manifestations. Measurements were conducted at two manifestation points, where the results indicated that the temperature gradient of steaming ground A varied between 16.21 and 75.5 °C/m, while steaming ground B ranged from 41 to 71.6 °C/m. Both manifestations showed a logarithmic relationship between temperature and depth. However, studies focusing on warm ground manifestations remain limited, even though these manifestations may provide valuable information regarding shallow geothermal heat distribution and subsurface thermal behavior.

This research aims to obtain a temperature-depth model of warm ground manifestations in the Bukit Kasih geothermal area and determine the corresponding temperature gradient characteristics. The obtained temperature gradient patterns are expected to provide an understanding of shallow subsurface thermal conditions and contribute to preliminary geothermal resource assessment. Furthermore, this study supports sustainable geothermal energy development by improving knowledge of geothermal manifestations, which is essential for advancing renewable energy utilization in accordance with SDG 7 (Affordable and Clean Energy).

RESEARCH METHOD

Field data collection and data processing

Field data collection was conducted based on the type of geothermal manifestation and adjusted according to the physical characteristics of each manifestation. The measured parameters were determined to characterize the thermal conditions, physical properties, and heat transfer mechanisms associated with geothermal manifestations in the Bukit Kasih area. For warm ground, steaming ground, and hydrothermal alteration manifestations, the main parameters measured included surface temperature, subsurface temperature at depths of 50, 100, 150, and 200 cm, and the area of the manifestation zone. Temperature measurements were performed using a digital thermometer equipped with a probe inserted into the soil. Initially, the probe was placed slightly below the ground surface, and measurements were conducted after the temperature reading reached a stable condition. The recorded temperature was obtained from at least three repeated measurements at each point to minimize measurement errors and improve data reliability.

After surface temperature measurements were completed, subsurface temperature measurements were carried out by creating a small borehole using a hand drill. The thermometer probe was inserted sequentially into the borehole at depths of 50, 100, 150, and 200 cm. At each depth interval, the measurement was performed after the temperature stabilized, and the data were recorded. Each measurement was repeated at least three times to obtain representative temperature values and evaluate the consistency of the thermal response at different depths.

For hot pool and hot spring manifestations, the measured parameters consisted of fluid temperature at the center of the manifestation, fluid discharge rate, and manifestation area (for hot springs). Fluid temperature measurements were conducted directly at the fluid emergence point or at the nearest accessible location representing the thermal condition of the manifestation. Similar to shallow ground temperature measurements, each temperature measurement was repeated at least three times to obtain reliable results.

The discharge rate measurements were conducted using three different approaches depending on the physical characteristics and flow conditions of each manifestation. The first method involved measuring the volume of discharged water within a specific time interval, which was applied to manifestations with relatively small discharge rates. The second method involved measuring the time required to fill a container with a known volume, which was also suitable for low-discharge manifestations. The third method was applied to manifestations with larger discharge rates by measuring the travel time of a floating object along a predetermined flow distance. This method considered the flow channel geometry, including flow depth and channel width, to estimate the water discharge rate.

For fumarole manifestations, measurements included fumarole temperature at the center of the gas emission point, ambient air temperature, manifestation surface area, and fluid flow velocity. The temperature measurement was performed directly at the fumarole outlet or the closest safe location accessible during field observations. The measurement process was repeated at least three times to ensure the accuracy and consistency of the obtained thermal data.

The collected field data were subsequently processed based on the dominant heat transfer mechanism occurring within geothermal manifestations. The temperature-depth relationship of warm ground manifestations was analyzed by constructing a temperature profile model using Microsoft Excel. The measured temperature data were first organized according to their corresponding depths. The temperature-depth curve was then fitted using a logarithmic model function:

$$T=k_1+k_2\ln(\ln(k_3x-k_4))$$

where T represents temperature, x represents subsurface depth, and k_1, k_2, k_3, and k_4 are model constants determined through curve fitting. The optimum model parameters were selected based on the minimum error value between the measured temperature data and calculated model temperature. Subsequently, a comparison graph between measured temperatures and modeled temperatures was generated to evaluate the accuracy of the proposed temperature-depth relationship.

RESULTS AND DISCUSSION

Results

For warm ground manifestations, the manifestation temperature was measured at 7 sample points, namely BK 17, BK 18. BK 19, BK 20, BK 21, BK 22, and BK 23. Field measurement results showed a variety of temperature gradients, namely 13.61 C/m up to 71 C. Most of the samples show that the temperature looks like a linear pattern but will look like a logarithmic pattern at deeper depths. The temperature at the sample points is lower than the temperature of the steamy ground, this is due to the heat that propagates to this manifestation away from the heat source and also propagates from the surrounding manifestations. The following is a model and discussion of each sample.

Sample BK17 with an elevation of 928 m (Fig 1). Physically, the sand-sized rocks are dark brown colors. The results of field research show that the increase in temperature with respect to depth follows a logarithmic function pattern y = 13.16 ln(x) + 123 with a refractive index of 4.74 C. near surface temperature decreased sharply presumably due to low rock conductivity. The high temperature at a depth of 200 cm is thought to be the conduction of heat from a heat source manifested by the steamy ground adjacent to this location. Assuming that at a depth of 200 cm the temperature gradient is stable, the temperature gradient obtained is 65.8 C/m.

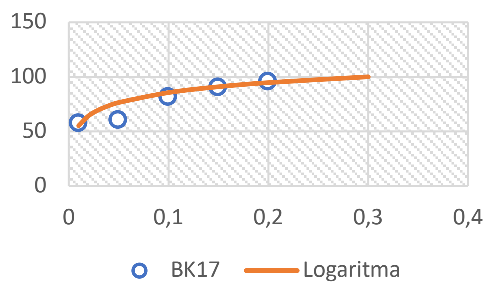

Figure 1. Temperature profile against depth of BK 17

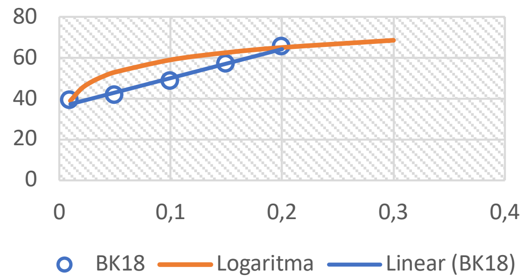

Figure 2. Temperature profile against depth of BK18

Sample BK18 with an elevation of 928 m (Fig 2). Physically, sand-sized rocks are dark brown on the surface. The results of field research show that the increase in temperature with respect to depth appears linear with a function of 141.46x + 35.89 but at a certain depth the temperature will be a logarithmic function. The low temperature is thought to be caused by a heat source that does not come directly from beneath the surface but propagates from another heat source. Assuming that at a depth of 200 cm the temperature gradient is stable, the temperature gradient obtained is 43.5 C/m.

Sample BK 19 with an elevation of 928 m (Fig 3). Physically, sand-sized rocks are dark brown on the surface. The results of field research showed that the increase in temperature with respect to depth appeared linear with a function of 164.72x + 61.5 from the surface to a depth of 0.15 m and then tended to be stable to a depth of 200 cm with a function of 8.3425 ln(x) + 101.9. The less stable temperature near the surface is thought to be caused by the low rock conductivity so that heat cannot be transferred properly. Assuming that at a depth of 200 cm the temperature gradient is stable, the temperature gradient obtained is 41.71 C/m.

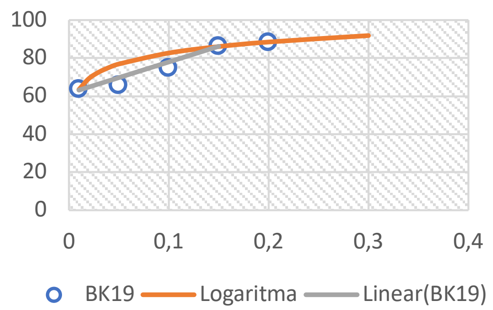

Figure 3. Temperature profile against depth of BK19

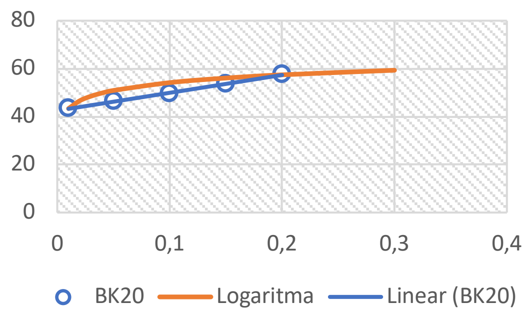

Figure 4. Temperature profile against depth of BK20

Sample BK20 with an elevation of 928 m (Fig 4). Physically, the rock has a hard and dense texture, blackish gray in color. The results of field research show that the increase in temperature with respect to depth appears linear with a function of 74.23x + 42.51 but at a certain depth the temperature will be a logarithmic function. The low temperature is thought to be caused by a heat source that does not come directly from beneath the surface but propagates from another heat source. Assuming that at a depth of 200 cm the temperature gradient is stable, the temperature gradient obtained is 23.5 C/m.

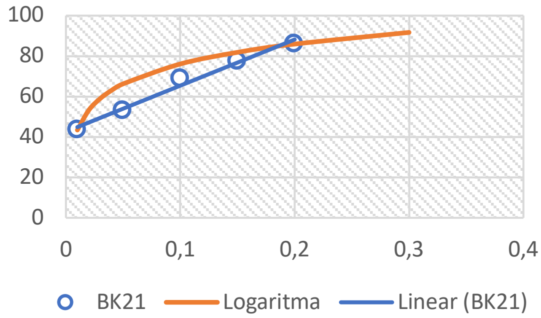

Figure 5. Temperature profile against depth of BK 21

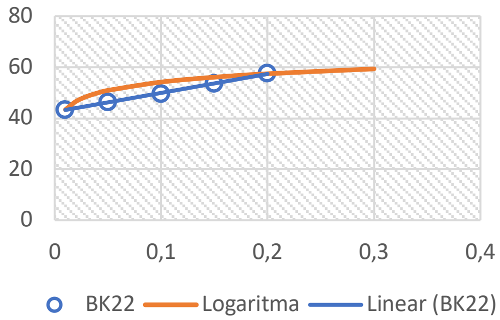

Figure 6. Temperature profile against depth of BK 22

Sample BK21 with an elevation of 922 m (Fig 5). Physically, sand-sized rocks are dark brown on the surface. The results of field research show that the increase in temperature with depth appears linear with a function of 227.97x + 42.59 but at a certain depth the temperature will tend to be stable following the logarithmic function. The low temperature near the surface is thought to be caused by the low conductivity of the rock so that heat cannot be transferred properly. The high temperature at a depth of 200 cm is thought to be the conduction of heat from a heat source manifested by the steaming ground adjacent to this cation. Assuming that at a depth of 200 cm the temperature gradient is stable, the temperature gradient obtained is 71 C/m.

Sample BK22 with an elevation of 928 m (Fig 6). Physically, the hard texture rock is blackish gray in color. The results of field research show that the increase in temperature with depth appears linear with a function of 74.229x + 42.51 but at a certain depth, the temperature will tend to be stable following the logarithmic function. The low temperature is thought to be caused by a heat source that does not come directly from beneath the surface but propagates from another heat source that is far away. Assuming that at a depth of 200 cm the temperature gradient is stable, the temperature gradient obtained is 23.5 C/m.

Sample BK23 with an elevation of 923 m (Fig 7). Physically, the hard texture rock is blackish gray in color. The results of field research show that the increase in temperature with respect to depth appears linear with a function of 141.46x + 35.892 but at a certain depth the temperature will be a logarithmic function. The low temperature is thought to be caused by a heat source that does not come directly from beneath the surface but propagates from another heat source. Assuming that at a depth of 200 cm the temperature gradient is stable, the temperature gradient obtained is 13.62 C/m. The temperature gradient below the surface increases with increasing depth. However, in geothermal areas anomalies can occur due to the presence of heat sources at shallow depths. Heat transmission pattern almost linear with the geothermal gradient. Surface heat flow signatures and anomaly scales are diagnostic of heat transfer mechanisms and of the scale of the processes involved.

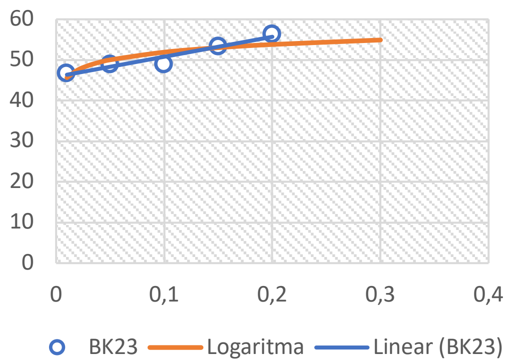

Figure 7. Temperature profile against depth of BK 23

Discussion

The temperature characteristics of warm ground manifestations in the Bukit Kasih geothermal area were investigated through shallow subsurface temperature measurements at seven observation points, namely BK17, BK18, BK19, BK20, BK21, BK22, and BK23. The obtained temperature gradients ranged from 13.61 to 71 °C/m, indicating significant variations in subsurface thermal conditions among the investigated locations. The variation of temperature gradients reflects differences in heat transfer efficiency, lithological characteristics, distance from the main heat source, and possible influence of adjacent geothermal manifestations. Generally, the temperature-depth profiles show an initial linear increase at shallow depths, followed by a logarithmic trend at greater depths. This pattern indicates that heat transfer in the shallow subsurface is mainly controlled by conductive processes, while temperature stabilization at greater depths is associated with reduced thermal variation as the system approaches thermal equilibrium.

Compared with steaming ground manifestations previously studied in the same geothermal area, the warm ground manifestations exhibit relatively lower temperature gradients. This condition is related to the mechanism of heat propagation. Steaming ground manifestations are generally located closer to the upflow zone where high-temperature fluids directly reach the surface, while warm ground manifestations are commonly formed through conductive heat transfer from deeper sources and lateral heat propagation from surrounding manifestations. Therefore, the measured temperatures in warm ground locations represent the residual thermal effect of the geothermal system rather than direct discharge from the main heat source.

At sample point BK17 (elevation 928 m), the temperature-depth relationship follows a logarithmic function expressed as $y = 13.16 \ln(x) + 123$, with a fitting error of 4.74 °C. The calculated temperature gradient at 200 cm depth reaches 65.8 °C/m, representing one of the highest gradients among the investigated warm ground locations. The relatively high gradient suggests that BK17 is strongly influenced by nearby heat sources. The increase in temperature at deeper levels is interpreted as the result of conductive heat transfer from an adjacent steaming ground manifestation. Meanwhile, the relatively unstable temperature near the surface may be associated with variations in soil moisture content and low thermal conductivity of unconsolidated sandy materials, which reduce the efficiency of heat transmission from the subsurface.

At BK18 (elevation 928 m), the temperature profile initially demonstrates a linear relationship represented by y = 141.46x + 35.89, before transitioning into a logarithmic trend at greater depths. The calculated temperature gradient is 43.5 °C/m, indicating moderate thermal influence compared with BK17. The lower gradient suggests that the heat source is not located directly beneath this point but is likely controlled by lateral heat propagation from surrounding geothermal manifestations. The absence of a strong shallow thermal anomaly indicates that heat transfer at this location is dominated by conductive diffusion rather than direct upward movement of geothermal fluids.

The temperature profile at BK19 (elevation 928 m) exhibits two distinct thermal behaviors. From the surface to approximately 15 cm depth, the temperature increase follows a linear function (y = 164.72x + 61.5), while deeper measurements follow a logarithmic function (y = 8.3425 ln(x) + 101.9). The calculated temperature gradient reaches 41.71 °C/m. The rapid temperature variation in the shallow zone is likely related to heterogeneous thermal conductivity caused by variations in surface material properties. At greater depths, the temperature becomes more stable due to the dominant influence of conductive heat transfer from the geothermal system.

At BK20 (elevation 928 m), the measured temperature-depth relationship follows a linear trend (y = 74.23x + 42.51) before approaching a logarithmic pattern at greater depths. The calculated temperature gradient is 23.5 °C/m, which is significantly lower than BK17, BK18, and BK19. This lower value may be associated with the physical characteristics of the host rock, which consists of hard and dense blackish-gray volcanic material. The dense lithology may reduce heat propagation due to differences in thermal conductivity and permeability, resulting in weaker shallow thermal anomalies.

The highest temperature gradient was observed at BK21 (elevation 922 m), reaching 71 °C/m. The temperature-depth profile initially follows a linear function (y = 227.97x + 42.59) and gradually changes into a logarithmic pattern at greater depths. The high gradient indicates a strong thermal anomaly beneath this location. Similar to BK17, this condition is interpreted as the influence of conductive heat transfer from nearby steaming ground manifestations. The high temperature response at 200 cm depth suggests that BK21 is located within a zone affected by shallow geothermal heat accumulation. However, the lower surface temperature indicates that surface conditions and rock thermal properties control the near-surface heat response.

At BK22 (elevation 928 m), the obtained temperature gradient is 23.5 °C/m, similar to BK20. The temperature-depth relationship follows a linear function (y = 74.229x + 42.51) and gradually develops into a logarithmic pattern. The relatively low gradient compared with BK17 and BK21 suggests that BK22 is located farther from the main heat source. The hard blackish-gray rock observed at this location may also influence heat distribution by limiting fluid circulation and reducing thermal anomaly intensity.

The lowest temperature gradient was observed at BK23 (elevation 923 m), with a value of 13.62 °C/m. The temperature profile follows a linear relationship (y = 141.46x + 35.892) and transitions into a logarithmic pattern at deeper levels. The low gradient indicates weaker geothermal influence compared with other measurement points. This condition suggests that BK23 may represent a peripheral zone of the geothermal manifestation system where heat has undergone significant attenuation during lateral propagation from the main thermal source.

The spatial variation of temperature gradients among the seven warm ground locations demonstrates that shallow geothermal heat distribution in Bukit Kasih is heterogeneous. The gradient differences, ranging from 13.61 °C/m at BK23 to 71 °C/m at BK21, indicate variations in the intensity of subsurface heat transfer. Locations with higher gradients, such as BK17 and BK21, are likely influenced by shallow heat sources or proximity to active geothermal pathways, while locations with lower gradients, such as BK20, BK22, and BK23, represent areas where heat has been reduced through lateral conduction and distance from the main source.

The observed temperature depth behavior also confirms that shallow geothermal systems are controlled by complex interactions between heat source distribution, lithological properties, and conductive heat transfer mechanisms. Although the temperature increase generally follows the geothermal gradient, localized anomalies may occur due to shallow heat accumulation associated with geothermal manifestations. Therefore, shallow temperature profiling of warm ground manifestations provides valuable preliminary information for identifying thermal anomalies and supporting geothermal resource assessment in the Bukit Kasih area.

CONCLUSION

Fundamental Finding: This study demonstrates the characteristics of shallow subsurface temperature distribution in warm ground geothermal manifestations at Bukit Kasih, Minahasa, North Sulawesi. The results indicate that the temperature gradient of warm ground manifestations varies from 13.61 to 71 °C/m across seven measurement points (BK17–BK23), reflecting variations in subsurface thermal conditions and heat transfer processes. The highest temperature gradient was observed at BK21 (71 °C/m), followed by BK17 (65.8 °C/m), while the lowest gradient was recorded at BK23 (13.62 °C/m). These variations indicate that the intensity of geothermal heat transfer is not uniform and is strongly influenced by the distance from the heat source, geological conditions, and thermal conductivity characteristics of subsurface materials. The temperature depth profiles generally show a linear increase pattern at shallow depths, indicating that heat transfer is mainly controlled by conductive processes. However, at greater depths, the temperature profiles gradually follow a logarithmic function pattern, suggesting that the rate of temperature increase decreases as the system approaches thermal equilibrium. The occurrence of higher temperature anomalies at deeper measurement intervals indicates the presence of a shallow geothermal heat source beneath the warm ground manifestations. The temperature distribution pattern confirms that warm ground manifestations are influenced by conductive heat propagation from deeper geothermal systems and lateral heat transfer from surrounding manifestations. **Implication:** The findings provide important insights into the shallow thermal characteristics of the Bukit Kasih geothermal system and demonstrate the potential of shallow temperature profiling as a preliminary method for geothermal resource assessment. The identified temperature gradients and temperature-depth models can be used as supporting information for understanding subsurface heat distribution, identifying thermal anomalies, and determining areas with higher geothermal potential. This study contributes to sustainable geothermal energy development by improving the understanding of near-surface geothermal processes, supporting the objectives of Sustainable Development Goal 7 (Affordable and Clean Energy). The characterization of shallow geothermal manifestations can assist future exploration strategies by providing initial information regarding heat transfer mechanisms and possible locations associated with geothermal activity. Furthermore, the results highlight the importance of integrating shallow thermal measurements with geological, geophysical, and geochemical investigations to obtain a more comprehensive understanding of geothermal systems. **Limitation:** This study has several limitations that should be considered. First, the temperature measurements were conducted only at shallow depths up to 200 cm, which limits the interpretation of deeper geothermal structures and the direct identification of the main heat source. Second, the study focused only on warm ground manifestations at seven measurement points (BK17–BK23), while other geothermal manifestations such as steaming ground, fumaroles, and hot springs require further investigation to provide a complete thermal characterization of the Bukit Kasih geothermal system. Third, the temperature-depth models were developed primarily based on thermal measurements and have not yet been integrated with detailed geological, geophysical, and geochemical datasets. **Future Research:** Future studies are recommended to conduct deeper temperature measurements and expand observations to various types of geothermal manifestations in the Bukit Kasih area. Integration with geophysical methods, such as electrical resistivity tomography, magnetotelluric surveys, and seismic analysis, is suggested to identify subsurface structures controlling geothermal fluid movement. In addition, geochemical analysis of geothermal fluids can provide further information regarding reservoir characteristics, fluid origin, and geothermal system evolution. Further research combining shallow thermal profiling, geological mapping, and subsurface modeling may improve the understanding of geothermal heat distribution and support more accurate geothermal resource assessment. These investigations will contribute to the development of sustainable geothermal energy utilization and strengthen the role of geothermal resources in supporting clean energy transition.

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AUTHOR CONTRIBUTIONS
Cyrke Adfie Netty Bujung: Conceptualization, methodology, investigation, data curation, formal analysis, writing original draft preparation, and visualization.
Donny Royke Wenas: Supervision, validation, writing review and editing, project administration, resources, and research support.

CONFLICT OF INTEREST STATEMENT
The authors declare no conflicts of interest.

STATEMENT ON THE USE OF AI OR DIGITAL TOOLS IN WRITING
AI tools were used only for language editing, grammar improvement, and discussion support. The authors take full responsibility for all aspects of the research and the final content of the manuscript.

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