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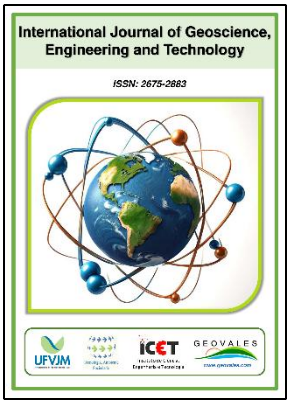

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Geothermal gradient of the Municipality of Teófilo Otoni in the Mucuri Valley based on well logging

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Abstract

In this study, geothermal gradient results were obtained from thermal profiling conducted in four wells located in the Municipality of Teófilo Otoni, in the Mucuri Valley, state of Minas Gerais. For the determination of geothermal gradients, we used ITL (interval temperature log) and CBT (conventional borehole temperature) methods. The ITL method was used in two wells, and CBT in the others. All wells were turned off for several months, allowing the means to remain undisturbed in the geological environment and yielding reliable results. The resulting temperature profiles indicate that geothermal gradients range from 10.7 to 19.2 ºC/km, with a mean of 18.3 ± 1.7 ºC/km in the city of Teofilo Otoni. The regional mapping data indicate that geothermal gradients are mostly below 20 ºC/km. The northern municipality has geothermal gradient values below 16 ºC/km, while the southern municipality has values between 16 and 20 ºC/km.

Keywords: Geothermal gradient, Temperature profile, Teófilo Otoni, Mucuri Valley.

1. Introduction

Thermal well logging provides a continuous record of subsurface temperature variations along the wellbore and represents an important source of information for characterizing thermal conditions and fluid-rock interactions (Jarzyna et al., 2021; Wang et al, 2019; Leary et al., 2017; Fuchs, 2013). Subsurface thermal data support the estimation of geothermal gradients, the identification of permeable intervals, the assessment of aquifer connectivity, and the recognition of vertical or lateral fluid movement within fractured or porous media (Cardoso and Hamza, 2014; Vieira, Gomes and Hamza, 2016; Vieira and Hamza, 2013; Keys, 1990). Temperature profiles also contribute to the evaluation of groundwater flow and heat transport processes (Patton, Cleall and Cuthbert, 2025; Jiménez-Valera, Alhama and Duque, 2024).

In geothermal systems, thermal logs help define feed zones, estimate heat exchange with surrounding formations, and improve conceptual models of reservoir circulation (Axelsson and Steingrímsson, 2012). In environmental and hydrogeological applications, thermal information supports the detection of flow paths, seepage zones, and interactions between shallow and deep groundwater systems (Wendland et al., 2022; Tirado-Conde et al., 2019; Vieira and Hamza, 2013; Bense et al., 2008). Therefore, thermal well logging offers a multipurpose subsurface measurement framework that integrates geological, hydrogeology, and thermal behavior, improving the interpretation of wellbore conditions and the spatial distribution of subsurface geothermal behavior (Shi et al., 2023; Williams and Paillet, 2023; Fahil et al., 2020; Vieira and Hamza, 2018).

Moreover, geothermal energy use involves the exploitation of heat derived from the interior of the Earth (Wang et al., 2019). This energy results from heat flow from deeper layers and from the natural radioactivity of rocks (Best, 2013; Gomes, 2003; Gomes and Hamza, 2005; Gomes, 2009; Alexandrino and Hamza, 2008). Furthermore, the development of geothermal maps at appropriate scales is often the best way to examine regional variations (Gomes, 2009).

As part of a geothermal energy research project in the state of Minas Gerais, entitled "geothermal gradient and heat flow with perspectives for geothermal energy exploitation in the Jequitinhonha and Mucuri valleys," the Jequitinhonha and Mucuri Valleys Geoscience and Engineering Study and Research Group (GEOVALES) and the Geothermal Laboratory of the National Observatory (LabGeot) of Rio de Janeiro, performed thermal logging in urban water-supply wells in the municipality of Teófilo Otoni. Moreover, the geothermal temperature measurements were conducted with support from LabGeot, which provided the thermal logging equipment for all wells.

The main objective of this work is to evaluate the geothermal gradient using well logs and to create the geothermal gradient map of the municipality of Teófilo Otoni.

The municipality of Teófilo Otoni is located in the state of Minas Gerais, in the Mucuri Valley region, as shown in Figure (1). The highlighted red outline corresponds to the region where geothermal measurements were performed, which is located in the northeastern region of the state of Minas Gerais).

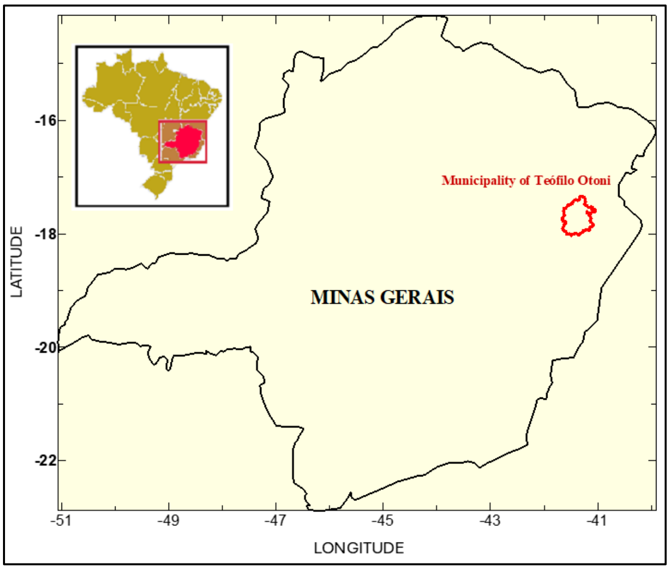

Figure 1 – Regional location of the municipality of Teófilo Otoni in the state of Minas Gerais.

2. Synthesis of the regional geology

The municipality of Teófilo Otoni is located mostly within the Juiz de Fora Complex (JF), which is predominantly Archean in age, situated in the northeastern region of the state of Minas Gerais, and includes part of the Araçuaí Belt and the Mantiqueira Province (Almeida, 1977; Almeida et al., 1978; Almeida and Hasui, 1984).

The current physicochemical characteristics of the Earth's crust are strongly linked to the way in which temperature distribution and thermal energy flow occur within its interior (Gomes e Hamza, 2004). Evidence indicates that the current thermal state of Earth plays a significant role in several planetary phenomena, both internal and external (Hamza and Muñoz, 1996; Gomes, 2009; Alexandrino and Hamza, 2008).

Furthermore, the JF unit in Figure (2) illustrates the Juiz de Fora Complex (Pedrosa-Soares et al, 1994). A section of the regional geology map of the eastern and northeastern region of the state of Minas Gerais is presented, highlighting that Teófilo Otoni is located within the Juiz de Fora Complex, as shown in Figure (2).

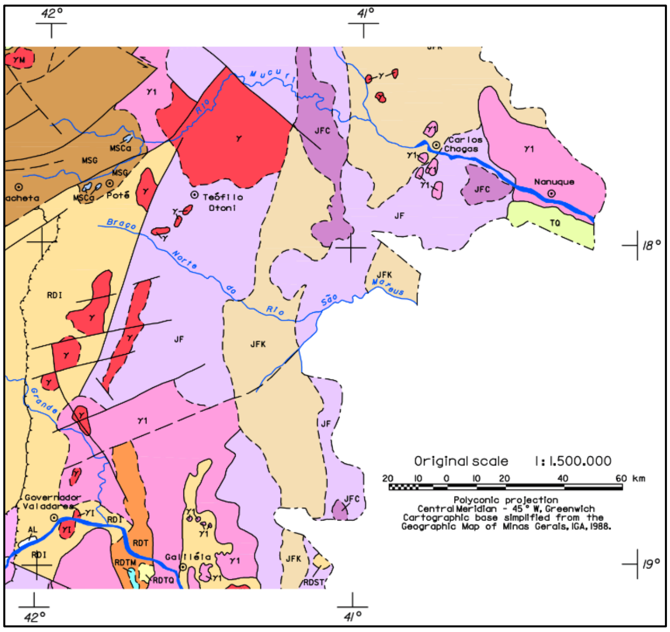

Figure 2 – Regional geology of the Teófilo Otoni region, where JF represents the Juiz de Fora Complex (Adapted from Pedrosa-Soares et al, 1994).

In this context, knowledge of the geology of a region is highly important, particularly for interpreting the physical characteristics of rocks and sediments. Moreover, two important geological formations occur within the municipality of Teófilo Otoni: (1) Tumiritinga Formation and (2) São Vitor Tonalite, both located within the Juiz de Fora Complex. The Tumiritinga Formation consists of a main lithotype composed of gray biotite gneiss, fine-grained or occasionally medium-grained, which occasionally shows mylonitic foliation, with marble occurring near Ladainha and close to Poté. The São Vitor Tonalite is composed of biotite tonalite, hornblende-biotite tonalite, and biotite granodiorite. It has a medium to coarse grain size and a gray coloration, with outcrops occurring along the Teófilo Otoni–Ladainha road (Gomes, 2020).

3. Methodology

The geothermal gradient is the rate at which the temperature of the Earth's interior varies with depth in the Earth's subsurface (Wang et al., 2019). It is a fundamental parameter derived from temperature logs obtained during well logging. It serves as a direct indicator of the thermal regime and heat flow characteristics of a given region (Keys, 1990).

Accurate determination of the geothermal gradient is essential for estimating subsurface temperatures at various depths, which in turn informs decisions regarding drilling, well design, energy extraction methods, environment, and groundwater studies. Moreover, variations in the geothermal gradient can reveal the presence of anomalous heat sources, such as magmatic intrusions or convective fluid flow, which are often targeted for enhanced geothermal systems (Trifonova et al., 2026).

In this context, the heat measured near the surface arises from mantle convection generated by magma and also from other perturbing factors that affect the geothermal gradient and alter heat flow (Gomes, 2003; Hamza et al., 2005). In some cases, perturbations caused by hydrothermal movements, aquifers, natural water sources, fractures, geological faults, among other factors, are reported in the literature (Wang et al., 2019). These processes disturb the thermal gradient and affect the heat flow observed at the local surface (Hamza and Muñoz, 1996; Gomes, 2003; Hamza et al., 2005).

Moreover, temperature is measured using distinct methods, such as interval temperature logs (ITL), formerly known as the conventional method (CVL), underground mines (UMM), bottom-hole temperatures (BHT), stable bottom temperatures (SBT), and water wells (AQT) (Hamza et al., 2020). In the present study, two distinct methods were used to determine the geothermal gradients of the Teófilo Otoni region: the ITL and the BHT methods.

The ITL is used to determine the geothermal gradient by linearly fitting logging data using the least-squares method over a selected interval (Guimarães, Aguiar and Vieira, 2025; Gomes and Hamza, 2005). The interval should preferably be free from any perturbation process capable of affecting the local geothermal regime. Therefore, this method is adopted when the geological layers are laterally homogeneous, have constant thermal properties, and have well-defined physical dimensions relative to the measurement intervals. In general, the uncertainty in depth determination is small compared to that in temperature determination. Thus, depth was considered the independent variable and temperature the dependent variable (Bullard, 1947).

In this context, the conventional CVL method, according to Beardsmore and Cull (2001), shows that the thermal gradient is defined as follow:

$$dT/dz = (T2\text{-}T1)/Az \qquad (1)$$

Where T2 and T1 are the temperatures at two points separated by a distance Az. Moreover, dT/dz is expressed in terms of temperature per unit distance (Km), and is a vector quantity having both magnitude and direction.

The constant bottom-hole temperature (CBT) method is used when fluid flow within the well disrupts the conductive thermal regime, thereby preventing the ITL method from determining the thermal gradient. In such cases, the CBT method serves as a variation of the well-known Bottom-Hole Temperature (BHT) method. The CBT method was originally proposed by Carvalho and Vacquiers (1977) and was adapted to determine the thermal gradient.

The principle of the CBT method is based on the assumption that thermal perturbations generated by fluid movements induced by the well itself become practically negligible in the lower section of the well. Consequently, stable temperature measurements at the bottom of the well are used to determine the thermal gradient. For this purpose, the mean annual surface temperature must be known (Carvalho and Vacquiers, 1977).

In this case, the relationship between the bottom-hole temperature (T_{CBT}) and the surface temperature (T_0) is determined by Equation (2).

$$T_{CBT} = T_0 + q \sum_{i=1}^{N} R_i \, h_i \qquad (2)$$

Where R_i is the thermal resistivity of layer i. The summation term refers to the cumulative thermal resistance of the formations present down to the bottom of the well, where the temperature measurement was performed. The summation term refers to the cumulative thermal resistance of the formations present down to the bottom of the well, where the temperature measurements were performed. The variances of the fitted coefficients were estimated using the standard least-squares regression relationships, while the degree of linear correlation was assessed through the corresponding linear correlation coefficient (Gomes e Hamza, 2005). The variance values (σ^2) of T_0 and Γ are given by (Equations 3 and 4):

$$\sigma_{T_0}^2 = \frac{\left[\frac{1}{N-2}\sum(T_i - T_0 - \Gamma z_i^2)^2\right]\sum z_i^2}{N\sum z_i^2 - (\sum z_i)^2} \qquad (3)$$

$$\sigma_{\Gamma}^2 = \frac{N\left[\frac{1}{N-2}\sum(T_i - T_0 - \Gamma z_i^2)^2\right]}{N\sum z_i^2 - (\sum z_i)^2} \qquad (4)$$

3.1 Temperature well logging

This technique consists of lowering a thermal probe into the well, with a thermistor-type temperature sensor mounted at its tip. Thermistors are thermally sensitive resistors whose resistance changes significantly with small changes in body temperature. Moreover, this behavior arises from temperature-dependent variations in the concentration and mobility of charge carriers within the sensing material, resulting in a nonlinear, typically exponential, relationship between resistance and temperature (Gomes, 2003; Gomes and Hamza, 2005).

Consequently, thermistor-based probes offer high sensitivity for detecting thermal variations along the wellbore, making them suitable for identifying temperature anomalies associated with fluid movement, potential leakage pathways, climate change, and other factors. Thermistors are semiconductors whose electrical resistance (ER) decreases with increasing temperature (T), and their rate of change is approximately 4 times that of metals. The small thermal mass of the sensor results in shorter response times, thereby accelerating field measurements (Gomes and Hamza, 2003). Furthermore, the relationship between the resistance (R) of the thermistor and the absolute temperature (T) is generally given by Equation (5).

$$R = R_0 e^{\left[B\left(\frac{1}{T} - \frac{1}{T_0}\right)\right]} \qquad (5)$$

Figure (3) presents a map of the municipality of Teófilo Otoni and the georeferenced measurement sites where thermal logging was performed. Additionally, the geographic coordinates were measured using portable global positioning system (GPS) instruments, with an average accuracy of 15 m, and the World Geodetic System 1984 (WGS 84) was adopted.

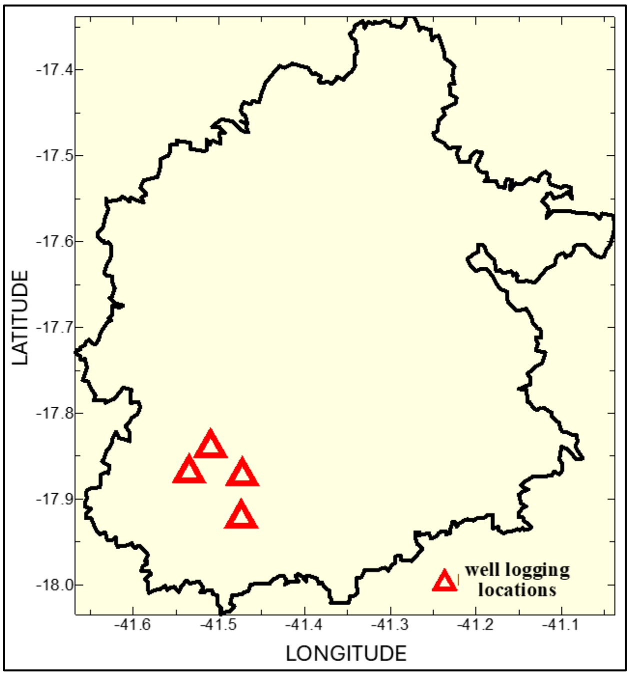

Figure 3 – Measurement locations where geothermal profiles were performed in the Municipality of Teófilo Otoni.

4 Results and discussion

The well logs used for the analysis and determination of the geothermal gradient were based on experimental data measured in water-supply wells at four sites located within the Municipality of Teófilo Otoni.

Moreover, the geothermal logs for each well were compiled from temperature measurements taken at their respective depths. The results obtained, including the final gradient values for each well are presented in Table (2). Additionally, all thermal profiles obtained were compiled, analyzed, and subsequently properly interpreted.

Furthermore, the individual results are presented in Figures (4), (5), (6), and (7), which contain the complete set of thermal logs obtained. Figure (4) shows the profile of well C03, located in the Póton area. Figure (5) shows the profile of well C05, located in the São José neighborhood.

Table 2 – Results of the geothermal gradients obtained.

Well	Geothermal Gradient (°C/km)		
	Type	Value	Standard Deviation
C03-COPASA-TEO	CBT	17.2	0.17
C05-COPASA-TEO	CVL	19.2	0.71
C11-COPASA-TEO	CVL	10.7	1.29
P01-JBS-TEO	CBT(CVL)	18.6	0.48

Figure (6) shows the profile of well C11, located in the Bela Vista neighborhood, and Figure (7) presents the profile of well P01 from JBS, located in the Santa Clara neighborhood. In this matter, well C11 presented the lowest thermal gradient with a value of 10.7 °C/km, and is interpreted as an indicator of a recharge zone, mainly because it is located very close to the Santo Antônio stream, one of the tributaries of the Todos os Santos River. In turn, the Todos os Santos River is a tributary of the Mucuri River (Gomes, 2020, Pinto, Pacheco and Almeida, 2019), the main river in the region, which extends to southern Bahia and discharges into the Atlantic Ocean.

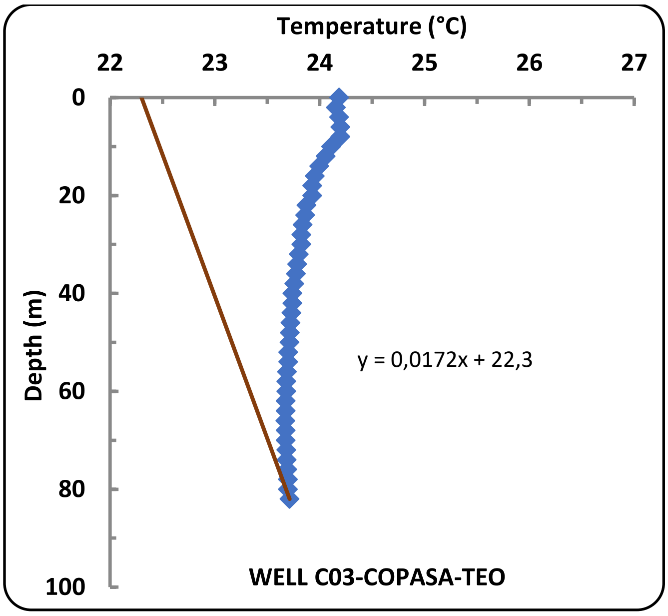

Figure 4 – Geothermal gradient profile of well C03, located in the Póton area.

Regarding the Well C03, a geothermal gradient of 17.2 ± 0.17 °C/km was presented. A similar result was obtained for well C05, with a value of 19.2 ± 0.71 °C/km.

Although these two wells are separated by several kilometers, the results obtained by the CBT method showed similar values and the same regional geothermal behavior. Furthermore, the geothermal gradient of well C05 was determined using the CVL method and showed the highest value among all wells measured in Teófilo Otoni, resulting in a value of 19.2 ± 0.71 °C/km.

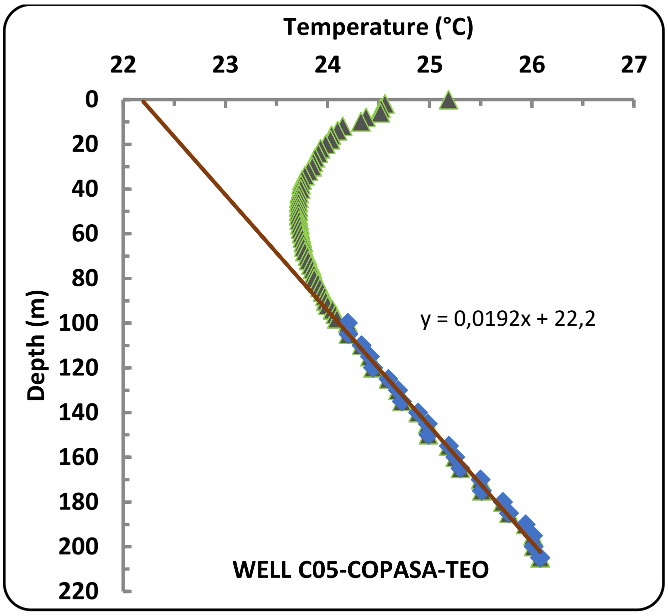

Figure 5 – Geothermal gradient profile of well C05 in the São José neighborhood.

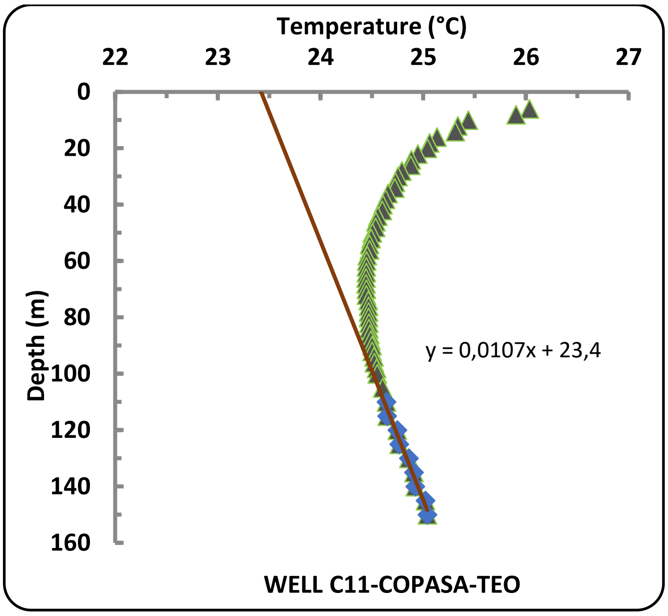

Figure 6 – Geothermal gradient profile of well C11 located in the Bela Vista neighborhood.

The profile of well C11 showed the lowest geothermal gradient among all wells logged in Teófilo Otoni, with a result of 10.7 °C/km. This result indicates a possible recharge zone, as the well is located very close to the Santo Antônio stream, which is a tributary of the Todos os Santos River.

Based on the depth analysis, well C05 was logged down to 205 m and was the deepest well.

The CVL method was used for the determination, indicating that this is the most reliable geothermal gradient in the region, approximately 19.2 ± 0.71 °C/km.

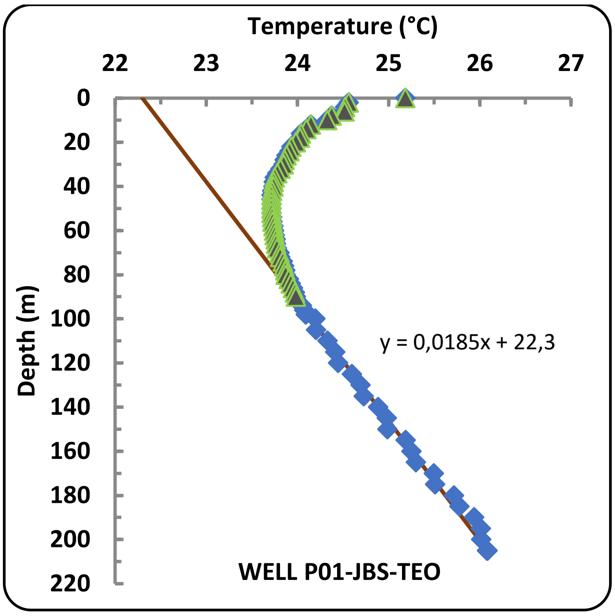

Figure 7 – Geothermal gradient profile of well P01 of JBS, located in the Santa Clara neighborhood.

The maps with the geothermal gradients obtained in Teófilo Otoni are presented in Figure (8) for the data obtained using the CVL method and in Figure (9) for the complete dataset.

6. Conclusion

Despite the low data density, the present study showed that the obtained values indicate that this region is characterized by relatively low geothermal gradients, lower than 20 °C/km.

The obtained geothermal gradient values ranged from 10.7 to 19.2 °C/km and resulted in a mean value of 18.3 ± 1.7 °C/km for the municipality of Teófilo Otoni.

Moreover, Well C05 presented the highest geothermal gradient value, equal to 19.2 ± 0.71 °C/km. This was also the deepest logging well, for which the CVL method was used. Furthermore, the lowest geothermal gradient value was obtained in well C11, with an observed result of 10.7 ± 1.9 °C/km.

The observed result for the complete set of geothermal gradient values obtained in this study yielded a mean value of 18.3 ± 1.7 °C/km in the municipality of Teófilo Otoni.

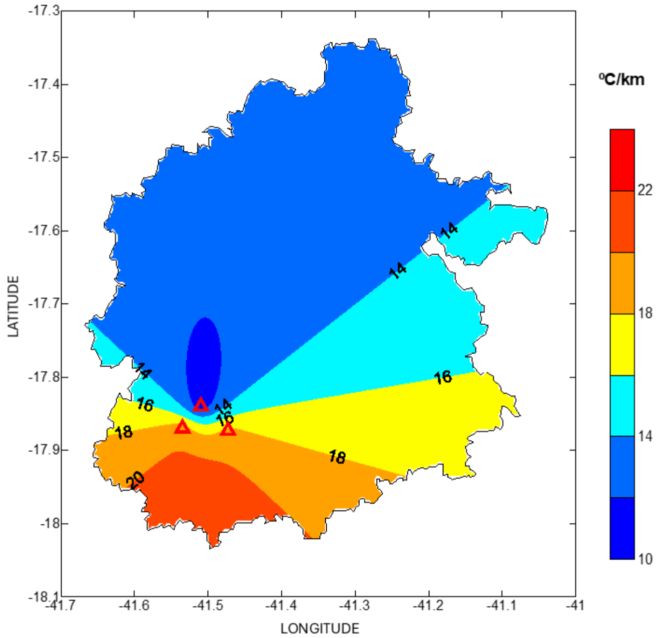

Figure 8 – Geothermal Gradient Map of Teófilo Otoni showing only CVL gradients.

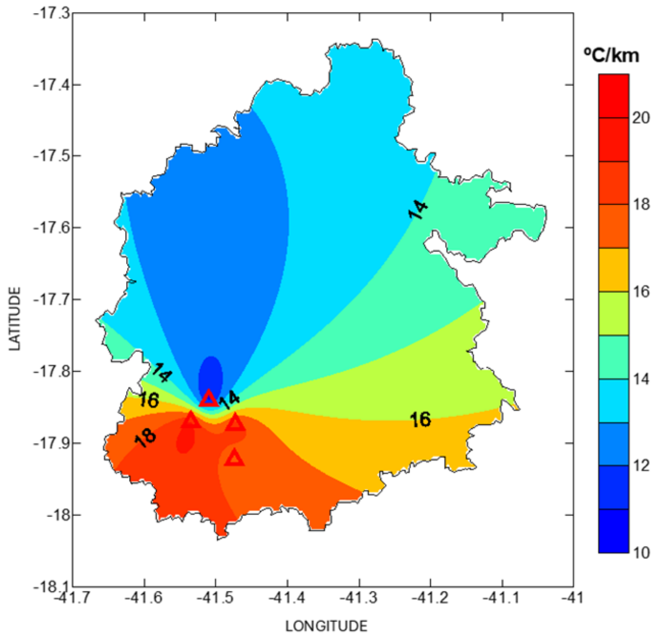

Figure 9 – Geothermal Gradient Map of Teófilo Otoni including all gradients.

The results observed for the set of geothermal gradient values from Teófilo Otoni are considered normal and correspond to geologically stable regions, which is common in all Precambrian regions. The results obtained in this study are included within this context.

Additional thermal logging is required in the region to obtain a more comprehensive regional geothermal interpretation, because the low data density allowed only the identification of long-wavelength features, that is, regional trends.

7. Acknowledgments

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References

Alexandrino, C.H. and Hamza, V.M., 2008. *Estimates of heat flow and heat production and a thermal model of the São Francisco craton*. International Journal of Earth Sciences, 97(2), pp. 289-306. https://doi.org/10.1007/s00531-007-0291-y

Almeida, F.F.M., 1997. *O Cráton do São Francisco*. Revista Brasileira de Geociências, 7(4), pp.349-364. https://doi.org/10.25249/0375-7536.1977349364

Almeida, F.F.M., Hasui, Y., Rodrigues, E.P. and Yamamoto, J., 1978. *A Faixa de Dobramentos Araçuaí na região do Rio Pardo*. In: Congresso Brasileiro de Geologia, 30, Recife. SBG, 1, pp. 270-283. Available at: <https://repositorio.usp.br/directbitstream/c245aeea-301a-420a-b79a-09392d9f9033/1477682.pdf> [Accessed 10 January 2026]

Almeida, F.F.M. and Hasui, Y., 1984. *O Pré-Cambriano do Brasil*. São Paulo: Edgard Blücher.

Axelsson, G. and Steingrímsson, B., 2012. *Logging, Testing and Monitoring Geothermal Wells*. In: Short Course on Geothermal Development and Geothermal Wells. United Nations University Geothermal Training Programme. UNU, p. 20.

Beardsmore, G.R. and Cull, J.P., 2001. *Crustal Heat Flow A Guide to Measurement and Modeling*. Cambridge University Press, Cambridge.

Bense, V.F., Person, M.A., Chaudhary, K., You, Y., Cremer, N. and Simon, S., 2008. *Thermal anomalies indicate preferential flow along faults in unconsolidated sedimentary aquifers*. Geophysical Research Letters, 35(24), L24406 https://doi.org/10.1029/2008GL036017

Best, D.M., 2013. *Heat sources and heat flow*. EBSCO Research Starters. Available at: <https://www.ebsco.com/research-starters/earth-and-atmospheric-sciences/heat-sources-and-heat-flow> [Accessed 10 may 2026].

Bullard, E.C., 1947. *The time necessary for a bore hole to attain temperature equilibrium*. Geophysical Supplements to the Monthly Notices of the Royal Astronomical Society, 5(5), pp. 127-130. https://doi.org/10.1111/j.1365-246X.1947.tb00348.x

Carvalho, H.S. and Vacquiers, V., 1977. *Method for determining terrestrial heat flow in oil fields*. Geophysics, 42(3), pp. 584-593. https://doi.org/10.1190/1.1440729

Cardoso, R.A. and Hamza, V.M.,2014. *Heat Flow in the Campos Sedimentary Basin and Thermal History of the Continental Margin of Southeast Brazil*, International Scholarly Research Notices, 384752. https://doi.org/10.1155/2014/384752

Fahil, A.S., Ghoneim, E., Noweir, M.A. and Masoud, A., 2020. *Integration of Well Logging and Remote Sensing Data for Detecting Potential Geothermal Sites along the Gulf of Suez, Egypt*. Resources, 9(9), 109. https://doi.org/10.3390/resources9090109

Fuchs, S., 2013. *Well-log based determination of rock thermal conductivity in the North German Basin*. PhD Thesis (Scientific Technical Report; 13/11), Universität Potsdam.

Gomes, A.J.L., 2003. *Avaliação de Recursos Geotermais do Estado do Rio de Janeiro*. Master dissertation. National Observatory, Rio de Janeiro.

Gomes, A.J.L. and Hamza, V.M., 2003. *Avaliação de Recursos Geotermais do Estado do Rio de Janeiro*. In: International Congress of the Brazilian Geophysical Society, 8. Rio de Janeiro. https://doi.org/10.3997/2214-4609-pdb.168.arq_981

Gomes, A.J.L. and Hamza, V.M., 2004. *Mapeamento de gradientes geotérmicos no Estado de São Paulo*. In: Simpósio da Sociedade Brasileira de Geofísica, 1. São. Paulo. https://doi.org/10.22564/1simbgf2004.029

Gomes, A.J.L. and Hamza, V.M., 2005. *Geothermal gradient and heat flow in the state of Rio de Janeiro*. Revista Brasileira de Geofísica, 23(4), pp. 325-347. https://doi.org/10.1590/S0102-261X2005000400001

Gomes, A.J.L., 2009. *Avaliação de Recursos Geotermais da Bacia do Paraná*. Thesis. National Observatory, Rio de Janeiro.

Gomes, A.J.L., 2020. *Geological formations of the Mucuri river path in the State of Minas Gerais*. International Journal of Geoscience, Engineering and Technology, 1(1), pp. 7-16. https://doi.org/10.70597/ijget.v1i1.362

Gomes, J.L.S., 2020. *Morphometric characterization of the Todos os Santos river basin in Minas Gerais – Brazil*. International Journal of Geoscience, Engineering and Technology, 1(1), pp.1-6. https://doi.org/10.70597/ijget.v1i1.361

Guimarães, S., Aguiar, F. and Vieira, F.P., 2025. *Recent climate change variations in the state of Rio de Janeiro in southeastern Brazil, as determined by the geothermal method*. In: Congress of the Brazilian Geophysical Society, 19. https://doi.org/10.22564/19cisbgf2025.315

Hamza, V.M. and Muñoz, M., 1996. *Heat flow map of South America*. Geothermics, 25(6), pp. 599-646. https://doi.org/10.1016/S0375-6505(96)00025-9

Hamza, V.M., Dias, F.J.S.S., Gomes, A.J.L. and Terceros, Z.G.D., 2005. *Numerical and functional representations of regional heat flow in South America*. Physics of the Earth and Planetary Interiors, 152(4), p. 223256. https://doi.org/10.1016/j.pepi.2005.04.009

Hamza, V.M., Vieira, F., Gomes, J.L.G, Guimarães, S., Alexandrino, C.H. and Gomes, A.J.L., 2020. *Update of Brazilian Heat Flow Data, within the framework of a multiprong referencing system*. International Journal of Terrestrial Heat Flow and Applied Geothermics, 3(1), pp. 45-72. https://doi.org/10.31214/ijthfa.v3i1.42

Jarzyna, J.A., Baudzis, S., Janowski, M., and Puskarczyk, E., 2021. *Geothermal Resources Recognition and Characterization on the Basis of Well Logging and Petrophysical Laboratory Data, Polish Case Studies*. Energies, 14(4), p.850. https://doi.org/10.3390/en14040850

Jiménez-Valera, J.A. Alhama, I. and Duque, C., 2024 *Advanced type curves for vertical groundwater flow estimation from temperature profiles. Applications to real scenario,* Journal of Hydrology, 631. https://doi.org/10.1016/j.jhydrol.2024.130860

Keys, W.S., 1990. *Borehole Geophysics Applied to Ground-water Investigations*. U.S. Geological Survey Techniques of Water-Resources Investigations, 02-E2. https://doi.org/10.3133/twri02E2

Leary, P., Malin, P., Saarno, T., and Kukkonen, I., 2017. *Prospects for Assessing Enhanced Geothermal System (EGS) Basement Rock Flow Stimulation by Wellbore Temperature Data*. Energies, 10(12), 1979. https://doi.org/10.3390/en10121979

Patton, A.M., Cleall, P.J. and Cuthbert, M.O., 2025. *Using groundwater temperature time-series to reveal subsurface thermal and hydraulic processes*. Hydrogeology Journal, 33, pp.1259-1277. https://doi.org/10.1007/s10040-025-02930-2

Pedrosa-Soares, A.C., Dardenne, M.A., Hasui, Y., Castro, F.D.C., Carvalho, M.V.A. and Reis, A.C., 2003. *Geologic Map of Minas Gerais*. Map at a scale of 1:1,100,000. Mining Company of Minas Gerais (COMIG) and the Government of Minas Gerais.

Pinto, D.B F., Pacheco, P.H.V.V. and Almeida, R.A., 2019. *Caracterização hidrológica da bacia hidrográfica do Rio Todos os Santos*. Revista Vozes dos Vales, 8(16), pp. 1-19. https://doi.org/10.70597/vozes.v8i16.1534

Shi, W., Ma, L., Huang, Z., Wang, G., Wang, C., Li, L., Ji, Y., Liu, L. and Xiao, C., 2023. *Application of well logging technology in geothermal resource evaluation: A case study of geothermal water wells in the Qianjiang sag, Jianghan Basin. Science progress*, *106*(2). https://doi.org/10.1177/00368504231183587

Vieira, F.P., Gomes, J.L.S. and Hamza, V.M., 2016. *Estudos do Campo Geotérmico Raso em Jenipapo de Minas - Implicações para escolha de sítios para barragens subterrâneas na região de "polígonos de seca"*. In: Proceedings of Simpósio Brasileiro de Geofísica, 7. p. 1. https://doi.org/10.22564/7simbgf2016.088

Vieira, F.P. and Hamza, V.M., 2013. *Indications of Spatial Associations between Deep-seated Groundwater Flow systems and Thermal Springs in Paleozoic Sedimentary Basins of Brazil*. In: Proceedings of the International Congress of the Brazilian Geophysical Society & EXPOGEF, 13. pp. 578-582. https://doi.org/10.1190/sbgf2013-120

Vieira, F.P. and Hamza, V.M., 2018. *Global Heat Flow: New Estimates Using Digital Maps and GIS Techniques*. International Journal of Terrestrial Heat Flow and Applications, 1(1), pp.6-13. https://doi.org/10.31214/ijthfa.v1i1.6

Tirado-Conde, J., Engesgaard, P., Karan, S., Müller, S. and Duque, C., 2019. *Evaluation of Temperature Profiling and Seepage Meter Methods for Quantifying Submarine Groundwater Discharge to Coastal Lagoons: Impacts of Saltwater Intrusion and the Associated Thermal Regime*. Water, 11(8), 1648. https://doi.org/10.3390/w11081648

Trifonova, P., Metodiev, M., Hristova, D. and Kolcheva, K., 2026. *Geothermal Sources Detected by Magnetic Anomalies and their Relation with Hot Springs and Geology: A Case Study from Bulgaria*. Earth Systems and Environment, 10, pp. 3439-3453. https://doi.org/10.1007/s41748-025-00814-9

Wang, J., Nitschke, F., Korzani, M.G. and Kohl, T., 2019. *Temperature log simulations in high-enthalpy boreholes*. Geotherm Energy 7(32). https://doi.org/10.1186/s40517-019-0149-0

Wendland, E.C., Reis, A., Anache, J.A.A., Rosa, D.M.S., Alcântara, G. de M., Lowry, C.S. and Lin, Y.-F.F., 2022. *Identifying stream-aquifer exchange by temperature gradient in a Guarani Aquifer system outcrop zone*. Brazilian Journal of Water Resources (RBRH), 27(23). https://doi.org/10.1590/2318-0331.272220220058

Williams, J.H. and Paillet, F.L., 2023. *Geophysical Logging for Hydrogeology*. The Groundwater Project. https://doi.org/10.21083/UQGA6966