Regional geothermal studies in the state of Tocantins, north-central region of Brazil

Suze Nei Pereira Guimaraes[1], Fabio Pinto Vieira[1], Elizabeth Tavares Pimentel[1,2] and Valiya M. Hamza[1]

[1]Geothermal Laboratory, Department of Geophysics, National Observatory - ON/MCTI. [2]University Federal of Amazonas - UFAM. E-mail: sufisica@gmail.com, fabiovieira@on.br, elizabeth@on.br, hamza@on.br

Abstract

The Tocantins state is located in north-central region of Brazil. Its tectonic structure comprises the northern Tocantins Province and the western edge of the Parnaíba Basin. In this geological context, new geothermal data were acquired in 38 different locations, ranging from the southern to northern part of the area in two collection periods. Measurements were based on the conventional acquisition method, where we used a thermal probe that records temperature in depth. Mapping of the values of thermal gradient allowed the identification of a significant geothermal anomaly in the central region, whose average geothermal gradient is 22.2 ± 1°C/km. This is a low value for a region, whose probable geothermal resources wouldn't be able to be used for power generation, but geothermal resources contained in the geothermal anomaly could be developed for direct uses as tourism and spas, agribusiness, fish-farming and other. This anomalous region may be related with a directional trend of hot springs mapped in the southern region of the state and in neighboring regions with aligned structural directions along the Tocantins-Araguaia region.

Keywords: Geothermal gradient, direct uses, central-northern Brazil, thermal probes, exploration.

Estudios geotérmicos regionales en el estado de Tocantins, en la región centro-norte de Brasil

Resumen

El estado de Tocantins está situado en la región centro-norte de Brasil. Su estructura tectónica comprende la parte norte de la Provincia Estructural de Tocantins y el borde occidental de la Cuenca del Parnaíba. En este contexto geológico, se adquirieron nuevos datos geotérmicos en 38 lugares diferentes, que van desde el sur al norte de la zona en dos periodos de recolección. Las mediciones se basaron en el método de adquisición convencional, en el que se empleó una sonda térmica que registra la temperatura a profundidad. El mapeo de valores de los gradientes térmicos permitió identificar una anomalía geotérmica significativa en la región central, cuyo gradiente geotérmico promedio es 22.2 ± 1°C/km. Este es un valor bajo cuyos probables recursos geotérmicos no podrían utilizarse para generar energía eléctrica, pero los recursos contenidos dentro de la anomalía geotérmica sí podrían ser aprovechados para usos directos como turismo y spas, agricultura, piscicultura, y otros. Esta región anómala podría estar relacionada con un lineamiento de manantiales termales mapeados en la región sur del estado y en las regiones limítrofes, con direcciones estructurales alineadas a lo largo de la región de Tocantins-Araguaia.

Palabras clave: Gradiente geotérmico, usos directos, centro-norte de Brasil, sondas térmicas, exploración.

1. Introduction

According to surveys conducted by the Geothermal Laboratory of the National Observatory - ON/MCTI, the state of Tocantins, Brazil, is located in a region presenting abundant hot springs. Recent analysis of aeromagnetic data indicates the existence of typical features of a geothermal anomaly in the crust. At the beginning of the last decade, the Geothermal Laboratory of the National Observatory, in partnership with the Institute for Geothermal Research of Italy (IIRG), conducted a geochemical study on the hot springs in the state of Tocantins (Hamza et al., 2005). No data temperatures in depth from this region were acquired. This lack of data became an obstacle for determination of geothermal gradients and for more reliable assessments of the geothermal resources at local and regional scales. Therefore, it was proposed a new campaign to get additional data to characterize the crustal thermal field in this region.

2. Local geographical and geological characteristics

The state of Tocantins has an extension area of 277,620.914 km^2 (IBGE, 2002). Relief is mild and belongs to the central Brazilian highlands. Predominant climate is dry tropical with rainy seasons well characterized in certain seasons (October-April). According to meteorological data cited by the Brazilian Institute of Geography and Statistics (IBGE, 2002) the average annual temperature ranges from 24 to 26ºC. From a hydrographic view, the state is limited in the west by the Araguaia River and in the center by the Tocantins River. Both run from south to north and unite at the Esperantina city in the north region. Vegetation is quite diverse, but much of the region is covered by ‘cerrado’ vegetation.

Geologically, the region comprises three distinct structural tectonic units, called Tocantins, Parnaíba and São Francisco provinces (Figure 1; all figures after text). The Tocantins province is the largest in extent and predominates in the western part of the state. The Parnaíba province is the second largest and predominates in the northeast part, and the São Francisco province covers the southeastern region.

The Tocantins province is characterized by the union of the Araguaia belt and the northern part of the magmatic arc of the Mara Rosa, Goias Massif and Brasilia Belt. All present basements complexes with a predominance of Paleozoic-Proterozoic and Mesozoic-Proterozoic fold-belts intensely reworked during the Brasiliano event. The basement crops out in many places due to tectonic and/or erosional processes.

The Araguaia belt is composed of three formations, Estrondo, Couto Magalhães and Pequizeiro. The latter is of magmatic-sedimentary type related with the ophiolitic range (Hasui et al., 1977). The evolution of this fold-belt shows west polarity of various phenomena, with the exception of basic-ultrabasic magmatism. Structures of the Brasiliano cycle divided the Parnaíba basin during the Paleozoic and present a north-south orientation (Tocantins-Araguaia lineament). These structures have been mapped by Carozzi et al. (1975) and Cordani et al. (1984) among others.

The Parnaíba province is marked by large deposits of sandstone covering the eastern region. Paleozoic sedimentary rocks ranging from Ordovician/Silurian to Permian are widely exposed across the Parnaíba Basin (Loboziak et al., 2000). They are outcropping along the east-west border in bending belts aligned NE-SW and N-S, respectively. The portion surrounded by the São Francisco province is known as the Jalapão region, characterized by lithological units of the São Francisco Craton. Main geological characteristics are shown in Figure 1.

3. Materials and methods

3.1. Database

The geothermal data acquisition was performed in two steps: one in October 2011 and other in August 2012. Contacts with the Sanitation Company of Tocantins (SANEATINS) allowed flexibility in planning the activities carried out under this project. In the first phase we obtained 25 temperature measurements, and in the second phase we obtained 13 more measurements in wells. Most wells had depths of less than 200 m. The map in Figure 2 shows the location of wells for which thermal profiles were prepared.

Temperature measurements in wells were realized using portable thermal equipment. This equipment includes a thermistor sensor previously calibrated. The sensor is coupled to an electronic circuit programmed for automatic data acquisition. Figure 3 shows some pictures of the equipment and operation of thermal profiling in the field.

3.2. Temperature profiles in wells

Thermal profiling consisted of temperature measurements along the depth of the well. In order to minimize thermal disturbances on the down-hole, measurements were performed during the lowering operation of the probe. Measurements were taken at depth-intervals of 4 meters for shallow depths (less than 100 m) and intervals of 5 meters for depths >100 m. The probe was stopped for 1 minute at each point of measurement, for the sensor to reach thermal equilibrium. During that minute the probe got 12 temperature measurements, since it was programmed to take measurements every 5 seconds.

Analyses of the dataset taken at each position allowed determine the thermal equilibrium temperature. As an illustrative example, Table 1 presents the data on the thermal profile data of well P21 in Nova Olinda city.

Depth (m)	T (°C)	Depth (m)	T (°C)
4	29.4142	64	29.7389
8	29.3015	68	29.8385
12	29.2267	72	29.9316
16	29.1815	76	30.0537
20	29.1865	80	30.1573
24	29.2503	84	30.2690
28	29.3555	88	30.3900
32	29.4192	92	30.4754
36	29.4586	96	30.5516
40	29.4855	100	30.6552
44	29.5083	105	30.7884
48	29.5283	110	30.8798

52	29.5529	115	30.9710
56	29.6018	120	30.9944
60	29.6758		

Table 1. Temperature data of well P21 located in Nova Olinda city.

Thermal profiles were analyzed to determine the geothermal gradient (Γ). Two techniques were used, the so called conventional method and the Conventional Bottom Temperature (CBT). In both methods the distribution of temperatures at shallow depths are determined based on considerations of annual mean ambient temperature and the temperature at the interface soil-rock. Values for the annual mean ambient temperature were obtained based on data from meteorological records in the region. In this work we used data of INMET, 2012.

Temperature at the interface soil-rock depends on the characteristics of the soil and the thickness of the weathered layer in place. It is common practice to consider that the temperature at the interface soil-rock is 1°C to 3°C higher than the ambient temperature (Turcotte et al., 2004).

3.3. Conventional Method (CVL)

The traditional method to determine the geothermal gradient is used in cases where geological layers are homogeneous, present a large thickness compared to ranges of dimensions, and thermal properties are constant. Implementation of this method usually consists of two distinct parts. The first part is to select the depth-range suitable for the determination of the gradient. The selected range should preferably be free of any disturbance that can affect the geothermal regime in the site. In the second part, the geothermal gradient value is determined by linear fitting method between depth data (z_i) and temperature (T_i) obtained in the thermal profiling.

Generally, the error in determining depth used in this method is small compared to the error in the temperature measurements. Thus, the depth can be considered as the independent variable and the temperature as dependent variable.

The least-square method allows determining the coefficients as estimates of errors associated with the linear fit. Figure 4 illustrates an example of applying the CVL method to data from borehole P04 in the Lagoa da Confusão municipality. In this figure, blue points indicate values of temperatures observed in the well. Red points define the interval chosen for calculating the geothermal gradient. The dashed line indicates temperature values interpolated to shallower depths. The upper limit chosen for interpolating is the depth of the interface soil-rock (the value estimated is five meters at this location). The temperature distribution in the gap between the surface and depth of five meters is indicated by the dotted line. It is assumed that at this location the temperature varies from 25 to 27°C in the first five meters.

It is assumed that this interpolation considers constant the thermal conductivity from the bottom of the interval up to the surface. Generally the soil layers and weathered rocks at shallow depths have lower thermal conductivities and therefore higher thermal gradients. It is important to note that differences with experimental values may also arise as a result of the actions of other disturbing processes. Most common effects are climate changes and heat transport by groundwater movement.

3.2.2. Conventional Bottom Temperature Method (CBT)

The principle of this method is based on the assumption that thermal disturbances produced by fluid movements induced in the well become practically absent at the bottom of the well (Ribeiro and Hamza, 1986). Consequently, measurements of stable temperatures in the down-hole can be used to determine the thermal gradient. In this case, the relationship between the temperature of the bottom (T_{CBT}) and surface (ambient) temperature (T_0) is determined by the relationship:

$$T_{CBT} - T_0 = \sum_{i=1}^{N} \left(\frac{dT}{dz} \right)_i h_i \tag{1}$$

Where $\frac{dT}{dz}$ is the thermal gradient in the layer i, h_i is the thickness of the layer, and N is the number of layers.

Figure 5 shows an example of using the CBT method for calculating the thermal gradient in the well P10, localized in Palmas city. This well is 330 m deep. Note that the thermal profile of this well makes it difficult the application of the conventional method CVL to calculate geothermal gradient. The bends are indicative of thermal disorders arising from advective transport of heat inside the well. In the absence of appropriate data, the only option is to use the down-hole temperature least disturbed to determine the thermal gradient. According to this interpretation, the temperature distribution in the absence of advective groundwater movements inside the well would be along the line that connects the down-hole temperature and the temperature about the interface soil-rock. In Figure 5 the temperature distribution is indicated by the green dashed line. The value of the calculated thermal gradient in this case is 27.52°C km^{-1}. Linear trends can be identified in restricted sections where the disruptive effect of the advective heat becomes constant.

In well with no groundwater movements, values for geothermal gradient obtained by CVL and CBT methods produced nearly identical results. An example of this case is illustrated in Figure 6 for the well P18 in the Santa Maria city.

4. Results

Values calculated based on both the CVL and the CBT methods are shown in Table 2 for purposes of comparison and analysis. In general, values from the CBT method are considered as being more reliable. Then, the assessment of the regional distribution of geothermal gradients in the area of Tocantins state is based on gradients calculated by the CBT method.

No.	Longitude	Latitude	Depth (m)	Locality	Γ (°C/km)	
					CVL	CBT
1	-49.15	-11.89	84	Cariri	7.65	15.46
2	-49.15	-11.89	105	Cariri	10.88	12.78
3	-49.27	-11.34	96	Dueré	22.61	23.95
4	-49.61	-10.78	140	Lagoa da Confusão	13.01	13.17
5	-49.20	-10.59	88	Cristalândia	8.05	19.54
6	-48.92	-10.56	135	Nova Rosalândia	13.50	17.84
7	-48.90	-10.18	110	Paraiso	20.45	22.92

8	-48.39	-10.74	96	Porto Nacional	35.78	30.83
9	-48.31	-10.18	80	Palmas	1.69	16.11
10	-48.33	-10.35	330	Palmas	30.45	27.51
11	-47.71	-10.28	120	Barra da Aroeira	35.05	32.64
12	-49.21	-9.80	115	Divinópolis	16.50	24.73
13	-49.05	-9.26	44	Dois Irmãos	7.98	20.24
14	-49.37	-8.74	140	Araguacema / Tarumã	17.41	18.28
15	-49.56	-8.82	72	Araguacema	8.29	17.34
16	-48.93	-8.76	72	Goianorte	10.44	12.82
17	-48.92	-8.76	48	Goianorte-B	2.30	8.19
18	-47.75	-8.77	210	Santa Maria	42.09	42.86
19	-48.51	-8.54	180	Presidente Kennedy	54.18	38.00
20	-48.48	-8.04	56	Colinas	30.30	30.24
21	-48.42	-7+.63	120	Nova Olinda	20.19	25.66
22	-48.25	-7.21	110	Araguaína	15.78	13.34
23	-47.85	-6.19	96	Luzinópolis	4.65	6.15
24	-47.81	-5.40	130	Praia Norte	31.57	30.82
25	-47.92	-6.03	115	São Bento	34.15	33.48
26	-47.75	-11.61	115	Chapada de Natividade	26.08	26.35
27	-47.29	-12.23	100	Conceição do Tocantins	20.70	24.04
28	-47.72	-11.71	96	Natividade	13.83	13.87
29	-47.72	-11.72	115	Natividade	26.46	26.53
30	-47.93	-7.86	325	Palmeirante	7.12	6.54
31	-48.92	-8.59	92	Pequizeiro	13.65	13.89
32	-47.05	-11.61	92	Porto Alegre do Tocantins	14.15	14.39
33	-48.24	-11.97	96	São Valério da Natividade	12.60	12.69
34	-49.15	-7.97	105	Juarina / Tancredo	28.21	29.03
35	-48.53	-6.42	64	Xambioá	14.75	15.08
36	-49.37	-6.11	88	Eldorado dos Carajás	5.75	5.91
37	-50.03	-8.04	115	Redençao	8.62	9.06
38	-50.04	-7.33	155	Rio Maria	16.44	16.83

Table 2. Relation of localities and values of geothermal gradients calculated by both the CVL and CBT methods.

According to data presented in Table 2, it is easy to note that there are significant variations in the thermal field of crustal layers in the Tocantins state. It was considered that all values above 30°C/km were anomalous values. According to this limit, results obtained in this study can be considered as indicative of thermal anomalies in the cities Porto Nacional, Barra de Aroeira, Santa Maria, President Kennedy, Colinas, Praia Norte and São Bento. On the other end, values below 15°C/km were considered as indicative of negative anomalies. These low values were found in the cities of Cariri, Lagoa da Confusão, Goianorte, Araguaína and Luzinópolis cities. The average geothermal gradient throughout the Tocantins state is 22.2 ± 1°Ckm^{-1}.

The geothermal gradient map of the state is shown in Figure 7. To prepare this map, we used the method of interpolation 'kigrid' with spacing of 250 km.

It can be seen in Figure 7 a significant geothermal anomaly with direction north-south in the central region. There is evidence that this anomaly extends to the local occurrences of hot springs in the state of Goiás.

Considering the lithological diversity of the region, we used 2.5 $Wm^{-1}K^{-1}$ as the average value for thermal conductivity (Alexandrino and Hamza, 2008). Thus, the calculated heat flow in the state is shown in Figure 8.

5. Conclusions

Results achieved in this work contributed to the realization of pioneering measures in determining geothermal gradients in 25 locations in the Tocantins state. Mapping of the geothermal gradients seems to indicate a significant geothermal anomaly in the central region. This region is marked by the boundary between the Tocantins and the Parnaiba structural provinces (Goés and Feijoo, 1994).

The structural features seem to be related with the geothermal anomaly zone, since the hot springs previously mapped are aligned in the same direction. This direction is due to processes occurred in the end of the Brasiliano cycle (Cambric-Ordovician), where grabens formed by thermo-mechanical subsidence were filled by progressive subsidence along tectonically unstable tracks (Caputo and Lima, 1984).

The average geothermal gradient obtained for the Tocantins state was 22.2 ± 1°Ckm^{-1}. This value is considered low for geothermal-electric projects, but inside the anomalous regions it could be possible to exploit geothermal resources for direct uses in agriculture, tourism, fish-farming, etc.

Acknowledgements

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References

Alexandrino, H., and V.M. Hamza, 2008. Estimates of heat flow and heat production and a thermal model of the São Francisco Craton. *International Journal of Earth Sciences*. Vol. 97(2), pp. 289-306.

Caputo, M.V., e E.C. Lima, 1984. Estratigrafia, idade e correlação do Grupo Serra Grande - Bacia do Parnaíba. Anais Congresso Brasileiro de Geologia, 33, Vol. 2, pp. 740-753.

Carozzi, A.V., F.U.H. Falkenhein, R.G. Carneiro, F.R. Esteves, e C.J.A. Contreiras, 1975. *Análise Ambiental e Evolução Tectônica Sinsedimentar da Seção Siluro-Carbonífera da Bacia do Maranhão.* PETROBRÁS/CENPES. Vol. l, 49 pp.

Cordani, U.G., B.B.B. Neves, R.A. Fuck, A. Thomaz, e F.M.B. Cunha, 1984. *Estudo preliminar de integração do Pré-Cambriano com os eventos tectônicos das bacias sedimentares brasileiras.* PETROBRÁS, 70 pp.

Goés, A.M.O., e F.J. Feijó, 1994. Bacia do Parnaíba. *Bol. Geociencias*. PETROBRAS, Vol. 8(1), pp. 57-68.

Hamza, V.M., F.J.S. Silva, A.J. de L. Gomes, and Z.D. Terceros, 2005. Numerical and Functional Representation of Regional Heat Flow in South America. *Physics of the Earth and Planetary Interiors*, Vol. 152, No.4, pp. 223-256.

Hasui, Y., F.A.M. Abreu, and J.M.R.S. Silva, 1977. Estratigrafia da faixa de dobramentos Paraguai-Araguaia no Centro-Norte do Brasil. *Boletim IG, Instituto de Geociências*, USP, Vol. 8, pp. 107-118.

IBGE, 2002. Data about Brazilian population. *PNAD* (National Survey of Households). http://www.ibge.gov.br. Access on 27 Julho, 2002.

INMET, 2012. Climatologia. http://www.inmet.gov.br. Access on 2 de setembro de 2012.

Loboziak, S., M.V. Caputo, and J.H.G. Melo, 2000. Middle Devonian-Tournaisian miospore biostratigraphy in the southwestern outcrop belt of the Parnaiba Basin, North-central Brazil. *Revue de Micropaleontologie.* Vol. 43, No. 4, pp. 301-318.

Ribeiro, F., and V.M. Hamza, 1986. Modeling thermal disturbances induced by drilling activity: Advances in theory and practice. *Rev. Bras. Geofisica*, Vol. 4, pp. 91-106.

Turcotte, C.S., J.M. Thérialt and D.R.D.C.Valcatier, 2004. An analysis of air-soil temperature differences at five locations: Application to passive standoff chemical detection. *Defence R&D Canada – Valcartier - Technical Memorandum* - DRDC Valcartier TM 2004, 127pp.

FIGURES IN THE FOLLOWING PAGES

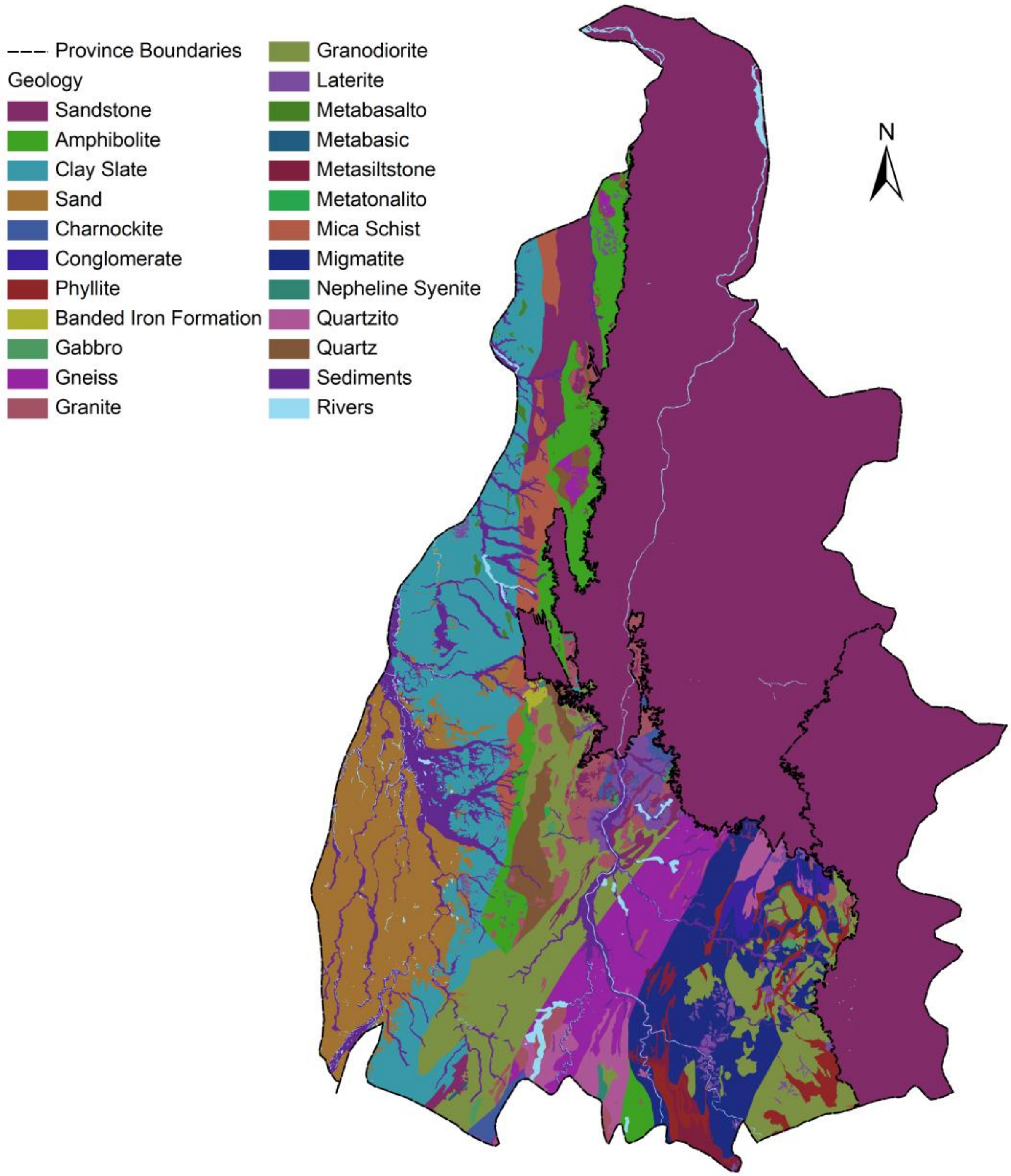

Figure 1. Simplified geologic map of the Tocantins state.

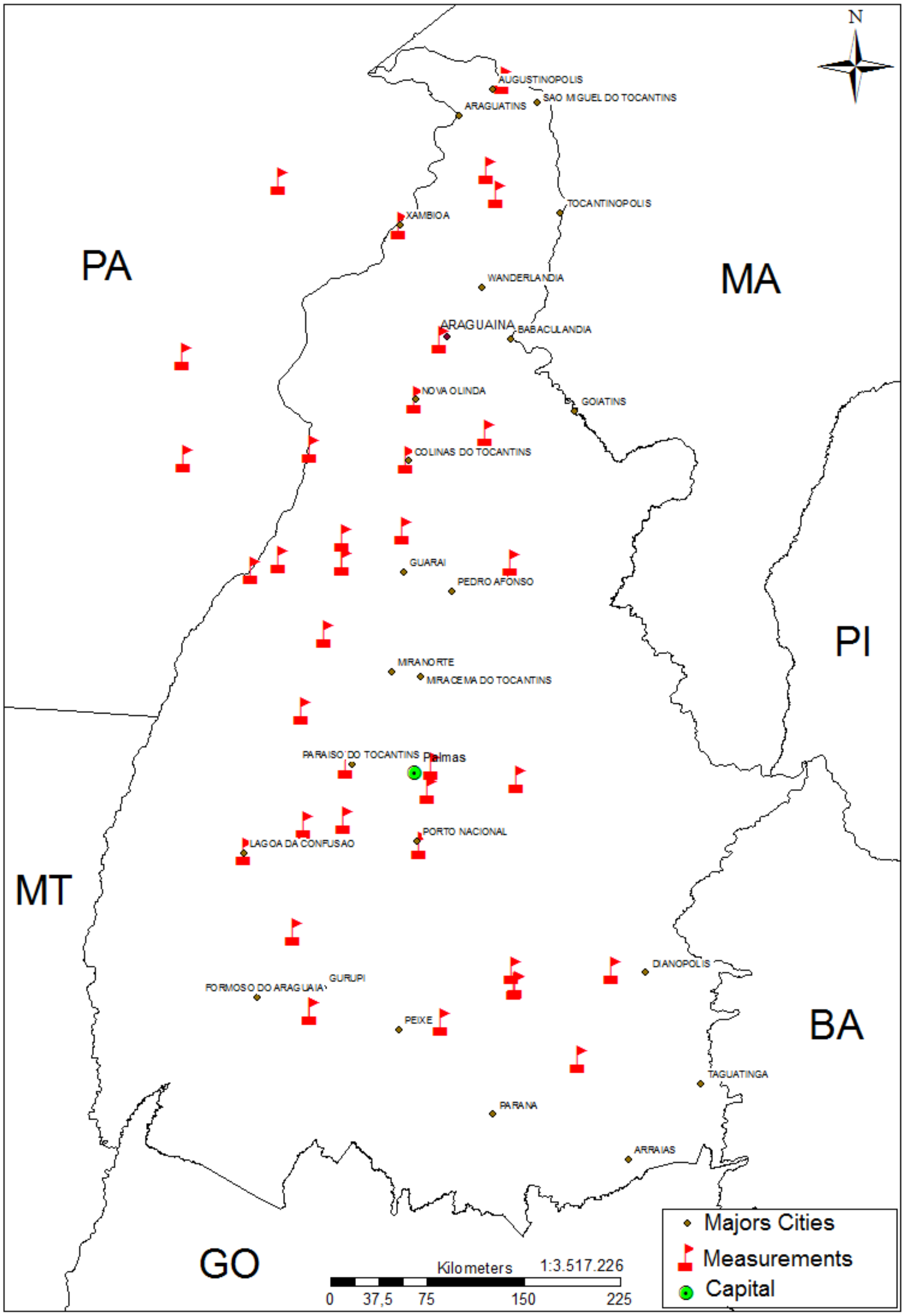

Figure 2. Location of wells used for geothermal measurements.

Figure 3. Parts of the used equipment and tools.

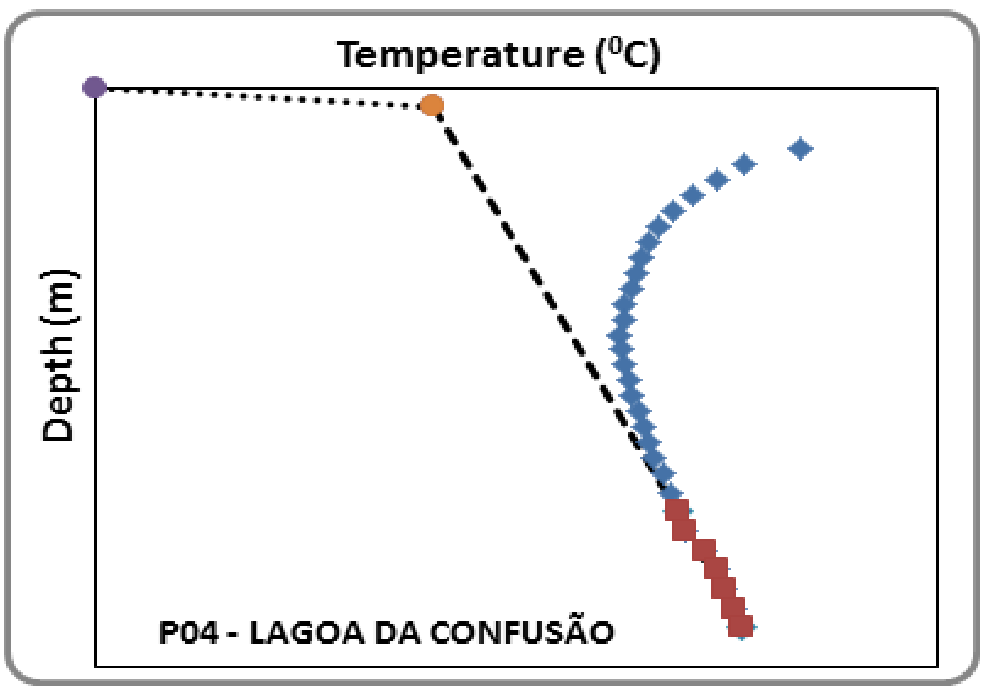

Figure 4. Temperature variation with depth in the well P04 in the Lagoa da Confusão municipality.

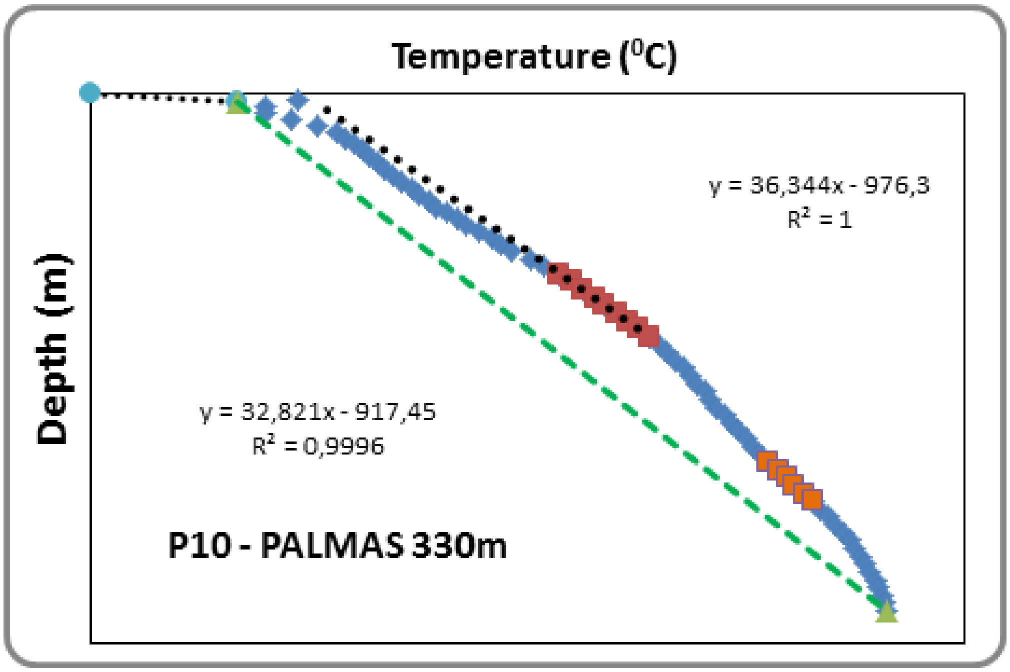

Figure 5. Example of the CBT method applied for determining the geothermal gradient in the well P10 in Palmas municipality.

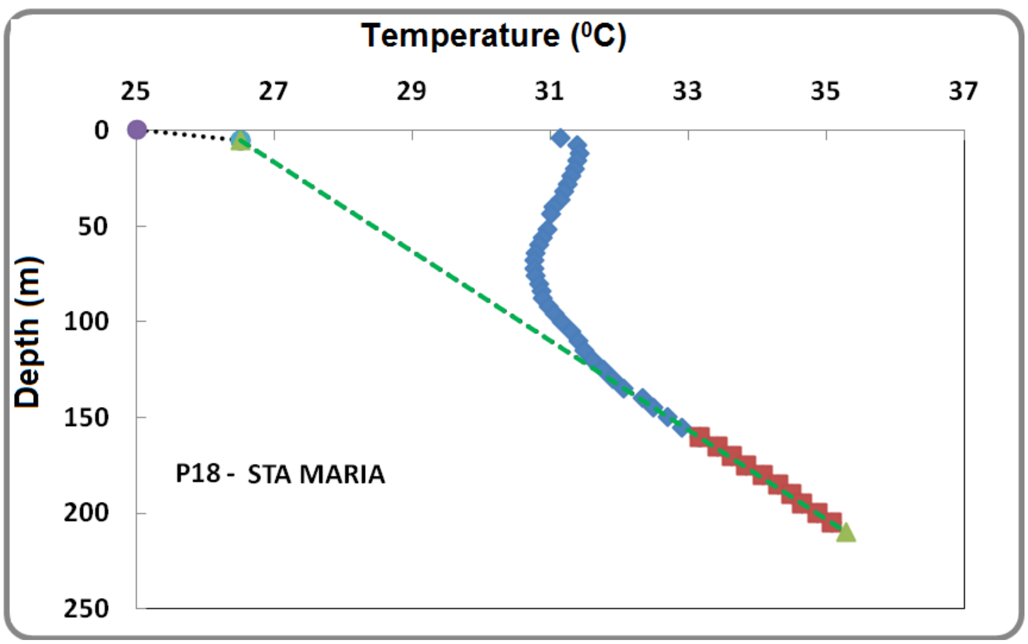

Figure 6. Example the CBT and CVL methods applied for determining the geothermal gradient in the well P18 in the Santa Maria municipality.

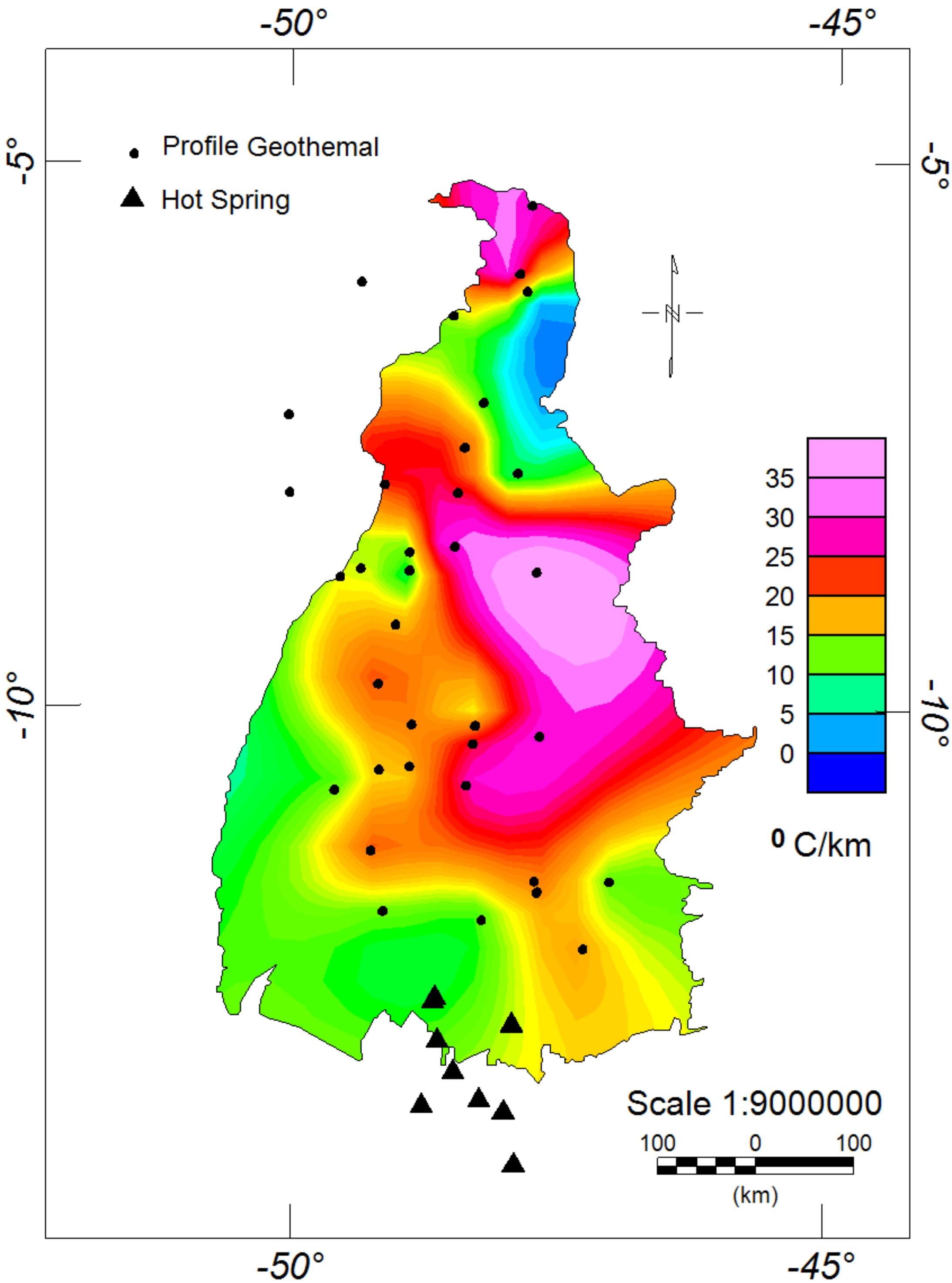

Figure 7. Geothermal gradient map of the State of Tocantins.

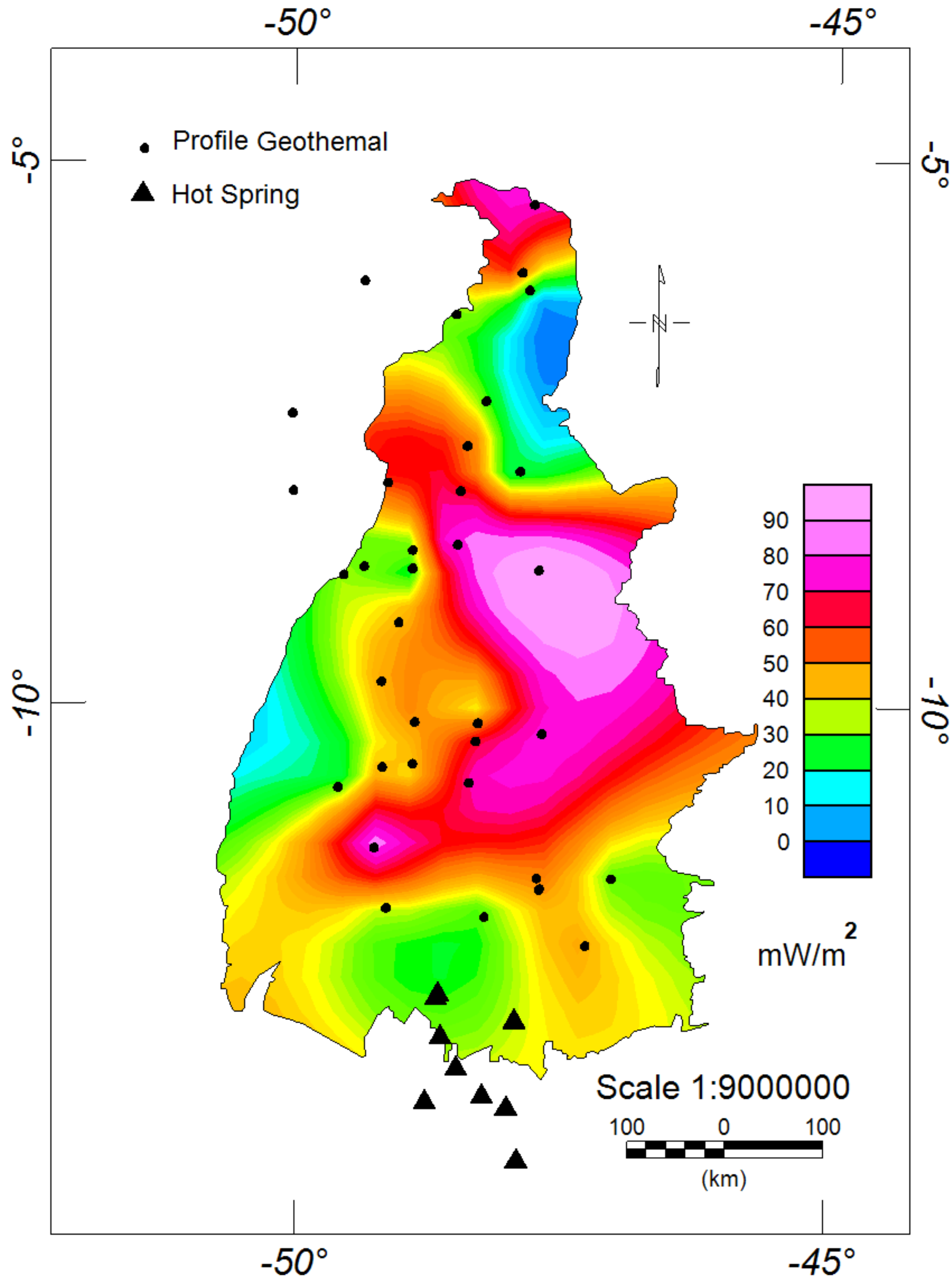

Figure 8. Heat flow map of the State of Tocantins.