Revista Brasileira de Geofísica; 1988, Vol. 6 (2), 33-42

doi: 10.22564/brjg.v6i1-2.1069

THE USE OF CHEMICAL GEOTHERMOMETRY AND HEAT LOSS MODELS IN ESTIMATING TERRESTRIAL HEAT FLOW FOR LOW-TEMPERATURE HYDROTHERMAL SYSTEMS

SUZANNE J. HURTER
Instituto Astronômico e Geofísico - USP
Departamento de Geofísica
Caixa Postal 30627, 01051 - São Paulo, SP, Brasil

Attempts to use chemical thermometric data of thermal waters of estimating heat flow density values are usually based on statistical methods for determining the depth of the reservoir. This is a serious limitation and the results are often found to be of limited validity. In the present work a new method is proposed for estimating heat flow density which makes use of not only geochemical thermometric data but also readily available information on mass flow rate and geological information on conduit geometry and applied heat-loss models for determining the depth of circulation. The method was used for estimating heat flow density for thermal spring systems at Águas de Lindóia, Monte Alegre do Sul, Amparo and Serra Negra situated in the northeastern region of the State of São Paulo. Reservoir temperatures were calculated using quartz, chalcedony and Na-K-Ca (Mg corrected) chemical geothermometers. Assuming that the drop from reservoir to spring temperature is caused by conductive heat loss along the conduit, two heat loss models (cylindrical and vertical plane conduits) were used for determining reservoir depth. The results obtained show fairly good agreement with conventional heat flow measurements in the same region. Experience in applying this method however indicates that model calculations on the reservoir depth are sensitive to the value of mass flow rate. Hence special attention must be paid to the geological setting of the springs for determining the total mass flow rate for each spring system. Contribution of shallower meteoric waters as well as subsurface loss of thermal waters to aquifers at depth are factors that can contribute to substantial errors in heat flow estimates.

As tentativas de uso de geotermômetros químicos para estimar a densidade de fluxo térmico em sistemas hidrotermais se baseiam geralmente em métodos estatísticos para a determinação da profundidade de reservatório. Isto constitui uma limitação séria e os resultados têm se mostrado frequentemente de validade restrita. No presente trabalho propõe-se um novo método de estimar a densidade de fluxo térmico que se utiliza da geotermometria química, além de informações como a vazão em massa das fontes, seu contexto geológico e de modelos de perda de calor. Este método é aplicado para estimar a densidade de fluxo térmico na região dos sistemas de fontes de Águas de Lindóia, Monte Alegre do Sul, Amparo e Serra Negra, situados na parte nordeste do Estado de São Paulo. As temperaturas de reservatório também foram calculadas a partir dos geotermômetros de quartzo, calcedônia e Na-K-Ca (Mg). Assumindo-se que a queda de temperatura desde o reservatório até a surgência se deve à perda de calor condutivo ao longo do trajeto das águas, foram utilizados dois modelos de perda de calor (para condutos cilíndricos e planares). Os valores de densidade de fluxo térmico resultantes foram comparados a medidas convencionais existentes na mesma região e mostram razoável concordância. A experiência na aplicação deste novo método indica, no entanto, uma alta sensibilidade com relação ao valor da vazão utilizada. Cuidados especiais são necessários para determinar a vazão em massa total dos sistemas de fontes. A contribuição de águas meteóricas rasas como também possíveis perdas de vazão para aquíferos profundos, são fatores que podem provocar erros substanciais na estimativa de fluxo térmico.

INTRODUCTION

In areas of thermal springs the geochemical method has been proposed as a convenient mean of estimating heat flow density. This silica-heat flow interpretation technique proposed by Swanberg and Morgan (1978, 1980) consists of applying the quartz geothermometer of Truesdell (1976) to spring and well water samples. In this method silica geotemperatures are converted to heat flow density values by the expression,

$$q = \frac{T_{SiO_2} - To}{m} \tag{1}$$

where T_{SiO_2} is the quartz geotemperature, To the mean annual air temperature, "q" the heat flow density and "m" is a parameter obtained statistically by linear regression of data of a large number (about 70,000) of groundwater silica analyses in USA. This parameter may be written as

$$m = Z/k \tag{2}$$

where k is the mean rock thermal conductivity and Z the minimum mean circulation or reservoir depth. The value of "m" given by Swanberg and Morgan (1978) is $680 \pm 67\ {}^{o}C\ m^{2}\ W^{-1}$ which implies rock thermal conductivities of $2.1\ Wm^{-1}\ {}^{o}C^{-1}$ (sediments) and $3.0\ Wm^{-1}\ {}^{o}C^{-1}$ (crystalline rocks) which are representative of circulation depths of 1.4 km and 2.0 km, respectively. Although these estimates are not unreasonable, the use of a universally constant value for the parameter m implies in fixed values of k and Z. This imposes serious restrictions on the validity of heat flow data obtained by this technique, especially if a statistically significant and regional representative set of data is not available.

We propose an independent way of estimating circulation or reservoir depth and an attempt to develop a new method of using geochemical data for estimating heat flow density.

THE CHEMICAL GEOTHERMOMETRY-HEAT LOSS-METHOD

Estimation of reservoir depth

The temperature drop during flow from reservoir to spring outlet is due to heat loss by the fluid along the path from the reservoir to the surface. We shall assume that this heat loss occurs by conduction of heat from the water to the surrounding rocks. Two models of conduit geometry for heat loss (see Fig. 1) are considered.

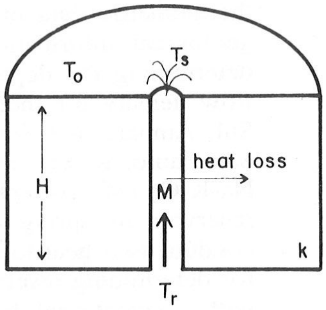
The first model (Fig. 1a) assumes that the water flows from the reservoir to the surface through a narrow vertical cylindrical conduit. Conductive heat loss occurs radially from the cylinder. Truesdell et al. (1977) have shown that reservoir temperature (Tr), spring temperature (Ts) and the mean annual air temperature (To) are related to the spring mass flow rate (M) by the relation,

$$\tau = \frac{Ts - To}{Tr - To} = M^{*}\ Rc^{*}\ [1 - \exp(-1/M^{*}\ Rc^{*})] \tag{3a}$$

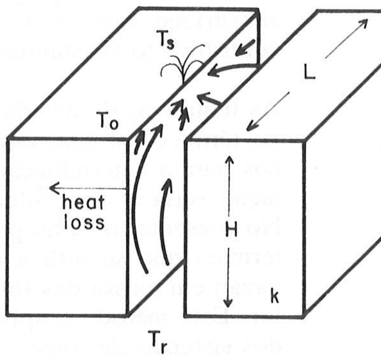
$$M^{*} = \frac{Mc}{2kH} \tag{3b}$$

$$Rc^{*} = \frac{4}{\pi} \tag{3c}$$

where τ is the dimensionless spring temperature, M^{*} the dimensionless mass flow rate, with M the mass flow rate, c the specific heat of water, k the rock thermal conductivity and H the reservoir depth. The constant Rc^{*} given by (3c) ties the approximate solution (3a) of Truesdell et al. (op. cit.) with the numerical solution of Sorey (1975).



CYLINDRICAL MODEL
(a)



PLANE MODEL
(b)

Figure 1. Geometry of the cylindrical (a) and the plane (b) heat loss models.

The second model (Fig. 1b) considers the flow of water up a vertical plane conduit of length L and depth H, converging near the surface to the spring. Lateral conductive heat loss across the plane is responsible for the temperature drop from reservoir to spring temperature. The approximate solution for this model has been developed by Nathenson et al. (1979) and Nathenson (1981), and may be written as,

$$\tau = \frac{M^{*}\ Rp^{*}}{L^{*}}\ [1 - \exp(-L^{*}/M^{*}\ Rp^{*})] \tag{4a}$$

$$L^* = l/H \qquad (4b)$$

$$Rp^* = 0.15 \qquad (4c)$$

where τ is the dimensionless spring temperature, M^* is given by (3a), L is the plane conduit length and H the reservoir depth. Rp^* ties equation (4a) to the numerical calculations of Sorey (1975).

Fig. 2 shows an example of the dimensionless temperature (τ) as a function of mass flow rate (M) for both models. For the cylindrical model, curves for reservoir depths of 1 km, 2 km and 3 km are shown. For the plane model, the curves correspond to square planes of 2 x 2, 3 x 3 and 4 x 4 km^2.

We propose to use these curves for estimating the reservoir depth (H) by assuming that the conduit geometry of the model is representative of subsurface circulation paths and that the reservoir temperature may be predicted by direct application of chemical geothermometry. Since data on spring temperature Ts, mean annual air temperature To and mass flow rate M can be readily obtained, it is fairly straightforward to calculate the dimensionless spring temperature ratio. By plotting the value of τ and the corresponding value of M upon these curves, an estimate of H can be obtained. For example, for point P, in Fig. 2, the estimated reservoir depth H, would be approximately 1 km for the cylindrical model.

Estimation of heat flow density

Heat flow density (q) may be estimated using the following expression,

$$q = \frac{k}{H} (Tr - To) \qquad (5)$$

where Tr is the reservoir temperature obtained from chemical geothermometry, To is the mean annual air temperature of the region considered, H the reservoir depth estimated from the heat loss curves and k is a mean rock thermal conductivity. Note that To is controlled by the surface heat budget, while Tr is determined by the basal heat flux. Hence q, as defined by equation(5), provides an estimative of heat flux from below the reservoir at depth H. It is also necessary to note that equation (5) does not define the form of temperature distribution as well as of heat transfer within the depth interval between the surface and the reservoir.

APPLICATION TO LOW-TEMPERATURE SPRING SYSTEMS IN THE NORTHEASTERN PART OF THE STATE OF SÃO PAULO

The chemical geothermometry heat-loss method of estimating terrestrial heat flow, hereafter referred to as the CGHL method, was applied to the spring systems of Águas de Lindóia, Amparo, Monte Alegre do Sul and Serra Negra, all situated in the northeastern part of the State of São Paulo.

The geological setting of this area (shown in Fig. 3) consists of a crystalline complex of metamorphic rocks known as Amparo gneisses, limited in the east by the granitic body of Socorro, as described by Wernick (1967). The Amparo Complex includes biotite gneisses with subordinated biotite schists and quartzites. The contact between the gneiss facies and

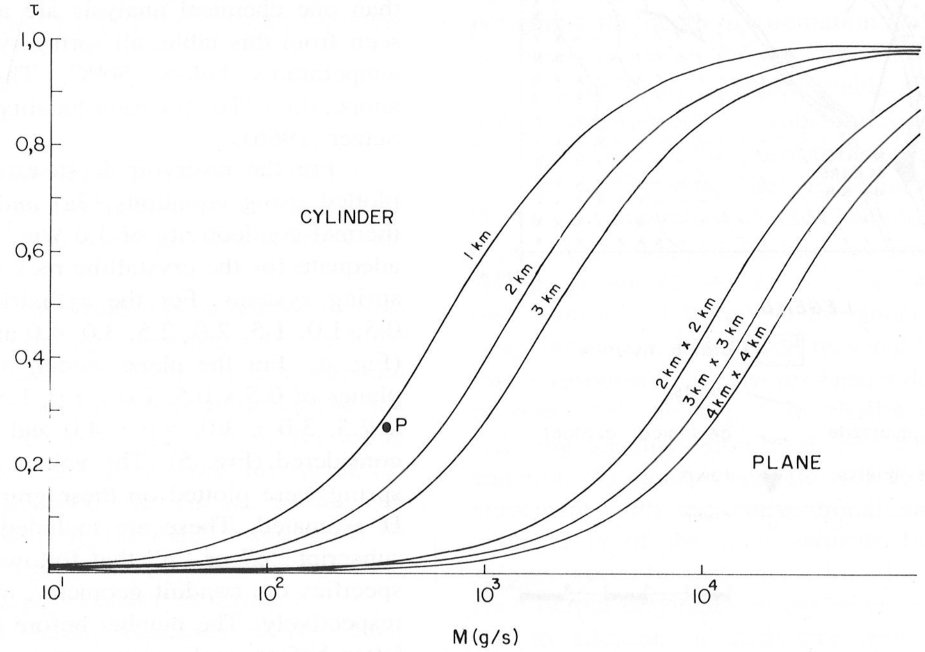


Figure 2. Dimensionless spring temperature (τ) plotted as a function of the spring mass flow (M) for the cylindrical and the plane models.

the migmatite facies is gradual. The fault systems are usually oriented to NE. Mylonites and other cataclastic rocks are also present.

Table 1 provides the geochemical data regarding concentrations of SiO_2, Na, Ca, K and Mg for spring systems in the four localities.

All data have been compiled from literature. A comment must be made on the discrepancies in the SiO_2 data base. CETESB (1978) and Szikszay and Teissedre (1978) claim to have used the molybdosilicate method for determining silica, in accordance with the procedures recommended in "Standard Methods for the Examination of Water and Wastewater" (A.P.H.A., 1976), Gonsalves (1932) and Teixeira (1946) do not specify the method of analysis used. It is therefore possible to attribute the discrepancy in SiO_2 data to different methods of analysis, as the detailed procedures followed are not known. This means that considerable care must be taken in interpreting results and these can only be considered as a very preliminary attempt to establish the method.

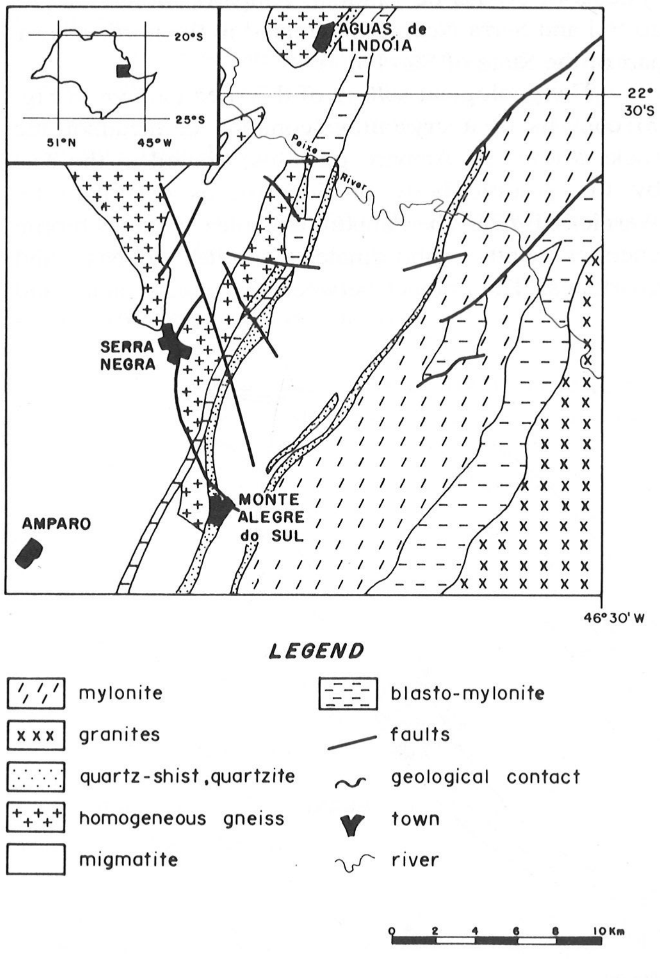


Figure 3. Location of spring systems and the geology of the study area (adapted from Marangoni and Del Rey, 1986).

All existing springs have been considered in the present study, however important data such as chemical composition or mass flow rate are missing for most of the springs.

For Águas de Lindóia, the springs selected for study are São Roque (1), Filomena (2), Beleza (3), Glória (4) and Santa Isabel (5). Locations and geological setting are given on the map of Fig. 6. The spring system of Amparo consists of the springs Nossa Senhora de Amparo (6), Bocaina (7) and Jacob (8) as shown on Fig. 7. Only two isolated springs, Bom Jesus (9) and Saúde (10) are found in Monte Alegre do Sul (see Fig. 7). Fig. 9 shows locations and geological setting of the springs in Serra Negra: Santa Luzia (11), Santo Agostinho (12), São Carlos (13), Nossa Senhora do Rosário (14), Nossa Senhora de Aparecida (15) and Nossa Senhora de Lourdes (16).

Reservoir temperatures were calculated using the quartz (no steam loss), or the chalcedony and the Na-K-Ca (Mg corrected) geothermometers. The equations for these geothermometers may be found in Fournier (1981). The criteria presented by Nathenson (1981) were used for choosing between the quartz and the chalcedony geothermometer. For the cases in which the calculated geotemperature falls below spring temperature, the latter one was used as a lower limit for reservoir temperature, as suggested by Bodmer (1982).

Presented in Table 2 are for each spring the outflow temperature (Ts), its mass flow rate (M) and the geotemperature range (minimum and maximum geotemperature) obtained from applying the geothermometers. The reservoir temperature (Tr) included in Table 2 is the median value of the range or the mean of the median values when data from more than one chemical analysis are available. As may be seen from this table, all spring systems have reservoir temperatures below 50°C. The mean annual air temperature (To) for each locality has been taken from Setzer (1966).

For the reservoir depth estimation, curves were plotted using equations (3a) and (4a). A mean rock thermal conductivity of 3.0 $Wm^{-1}\,{}^{o}C^{-1}$ was considered adequate for the crystalline rock environment of these spring systems. For the cylindrical model depths of 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0 and 5.0 km were used (Fig. 4). For the plane model, only square ($L^* = 1$) planes of 0.5 x 0.5, 1.0 x 1.0, 1.5 x 1.5, 2.0 x 2.0, 2.5 x 2.5, 3.0 x 3.0, 4.0 x 4.0 and 5.0 x 5.0 km^2 were considered (Fig. 5). The values of τ and M for each spring were plotted on these graphs and the values of H estimated. These are included in Table 2 and the subscript "c" or "p" that follows the estimated value specifies the conduit geometry, cylindrical and plane, respectively. The number before each spring name, or letter before each spring group, refers to the points plotted in Fig. 4 and Fig. 5.

The heat flow values calculated using equation

Table 1. Geochemical data of springs.

Locality	Spring	SiO_2*	Na	Ca	K	Mg	Ref.
Águas de Lindóia	1 São Roque	21.00	0.90	13.40	2.60	4.20	(1)
		21.65	1.83	11.44	2.11	1.83	(4)
		5.00	1.80	11.40	2.10	2.90	(3)
	2 Filomena	21.00	1.20	12.10	2.70	5.60	(1)
		6.50	0.60	6.00	2.60		(2)
	3 Beleza	19.80	0.70	13.10	2.60	6.40	(1)
	4 Glória	24.00	2.00	9.40	2.50	3.20	(1)
	5 Santa Isabel	5.50	1.60	3.00	1.50	7.00	(3)
Amparo	6 N.S. Amparo	33.00	7.10	9.00	2.00	4.50	(1)
		30.81	4.98	2.70	0.99	0.37	(4)
	7 Bocaina	52.00	14.00	6.50	1.50	2.60	(1)
		48.87	8.47	2.19	0.16	0.56	(4)
		6.80	15.50	10.00	1.52	2.90	(3)
	8 Jacob	38.00	6.20	7.30	2.10	2.90	(1)
		7.00	9.30	6.20	2.30	3.15	(3)
		33.31	12.96	3.00	1.31	0.43	(4)
Monte Alegre do Sul	9 Bom Jesús	39.00	5.40	5.70	2.90	1.80	(1)
		38.91	7.60	4.73	0.83	0.50	(4)
		6.00	4.90	5.40	2.60	1.74	(3)
	10 Saúde	5.00	2.50	1.60	2.40	1.20	(3)
Serra Negra	11 Santa Luzia	24.00	4.10	3.80	0.70	0.90	(1)
	12 Santo Agostinho	32.00	5.30	4.80	1.00	2.30	(1)
	13 São Carlos	40.00	5.00	11.00	1.70	3.10	(1)
		32.73	2.76	4.47	5.15	1.82	(4)
	14 N.S. Rosário	26.30	1.45	3.72	2.15	1.14	(4)
		7.50	14.10	1.20	1.00	3.90	(3)
	15 N.S. Aparecida	4.30	5.30	1.20	1.39	1.60	(3)
	16 N.S. Lourdes	40.00	5.60	4.50	1.70	2.70	(1)

References: (1) – CETESB (1978); (2) – Gonsalves (1932); (3) – Szikszay and Teissedre (1978); (4) – Teixeira (1946)
* – all concentrations in mg/l

(5) are also given in Table 2 along with the heat flow density values obtained by Del Rey (1986) with the conventional method.

DISCUSSION

Águas de Lindóia. The value of heat flow density by the conventional method for this area is 51 ± 8 mW/m^2 and the geothermal gradient is 18 $^{o}C/km$ (Del Rey, 1986).

Application of the plane model results in heat flow values of 54 mW/m^2 for springs (4) and (5) respectively, in good agreement with the conventional value. However, the same procedure does not provide good estimates for other springs, 14 mW/m^2 for spring (1) (cylindrical model) and 19 mW/m^2 for spring (2) (cylindrical model), respectively. As can be seen on Fig. 4 and Fig. 5 (point 3), the data of spring (3) do not fall within the range of model curves considered, so that no reservoir depth could be estimated.

On the other hand, because of the close proximity of occurrence of springs (1), (2), (3) and (4), these may be considered as manifestations of the same source. In this case it is necessary to plot the mean reservoir temperature of this group (32 ^{o}C) against the total mass flow output (15,010 g/s) to determine the depth of circulation and heat flow. This is shown as point "a" in Fig. 5. For this group of springs, the CGHL method yields a heat flow of 26 mW/m^2 (plane model), a value too low when compared with the results of the conventional method..

If we consider the geothermal gradient of 18 $^{o}C/km$, a temperature of 32 ^{o}C would be expected at a depth of 0.7 km. Hence the reservoir depth for the spring group (1 + 2 + 3 + 4) seems to be overestimated (1.5 km). If the geochemical reservoir temperatures are considered reasonable, the mass flow rate is responsible for overestimated depth. Dislocation of point "a" on Fig. 5 to shallower depths means reducing the mass flow rate. For a depth of 0.7 km, equation (5) yields a heat flow of 56 mW/m^2, in good agreement with the conventional value. A possible explanation of the poor estimate for this group of springs would be that only a fraction of the total mass flow output originates in the reservoir, the rest being due to addition of shallower meteoric water. This signifies that mixing of waters of different origins affects the heat flow estimated with the CGHL method.

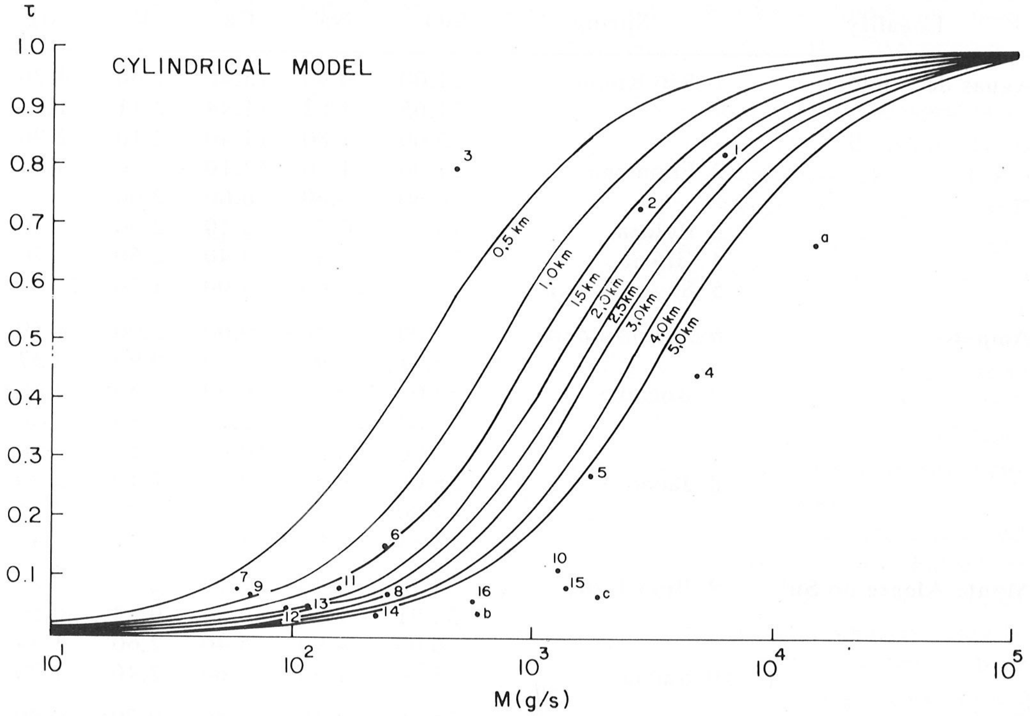


Figure 4. Dimensionless spring temperature (τ) versus spring mass flow (M) for the cylindrical model. The curves correspond to reservoir depths of 0.5, 1.5, 2.0, 2.5, 3.0, 4.0 and 5.0 km. Numbers and letters refer to the springs and spring groups identified on Table 2.

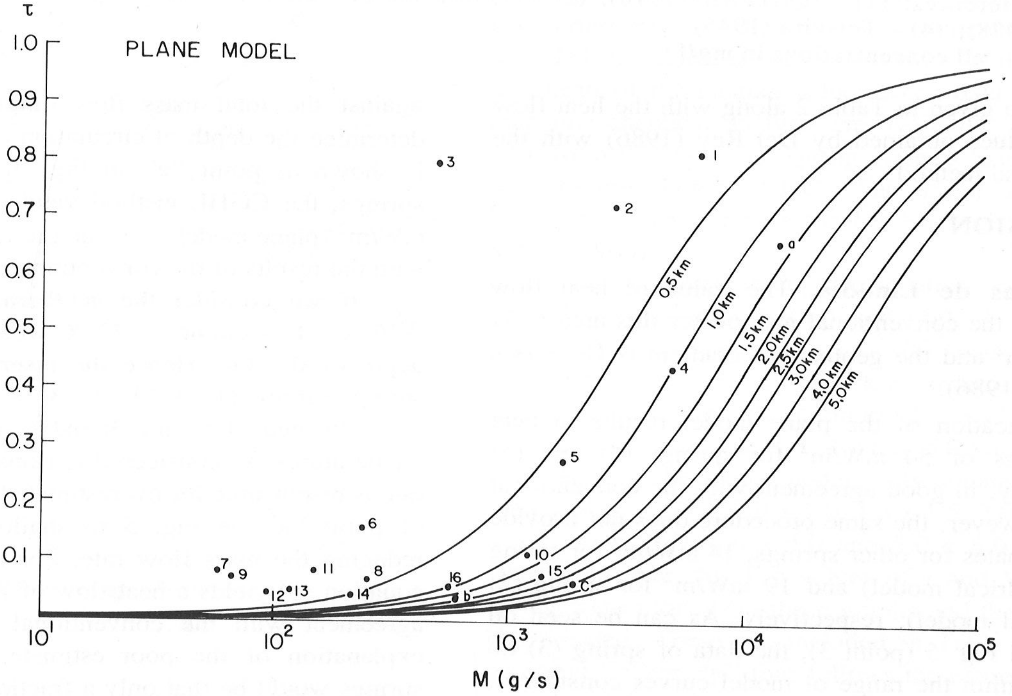


Figure 5. Dimensionless spring temperature (τ) versus spring mass flow (M) for the plane model. The curves correspond to reservoir depths of 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0 and 5.0 km. Numbers and letters refer to the spring and groups identified on Table 2.

Table 2. Data related to the use of the CGHL method including the obtained heat flow density estimates and conventional heat flow density values.

Locality	Spring	Ts (°C)	M (g/s)	Geotemp Range (°C)	Tr (°C)	H (km)	q (mWm^{-2})	qc (mWm^{-2})
Águas de Lindóia To = 19°C	1 São Roque	28(1)	6670 (5)	28-33 28-34 28	30	2.3c	14	51 ± 8
	2 Filomena	27(1)	2840 (7)	27-33 27-32	30	1.7c	19	
	3 Beleza	27(1)	500 (1)	27-31	29	-	-	
	4 Glória	27(1)	5000 (6)	34-39	37	1.0p	54	
	5 Santa Isabel	22(3)	1790 (3)	22-38	30	0.6p	55	
	a 1+2+3+4	27	15010		32	1.5p	26	
Amparo To = 19°C	6 N.S. Amparo	23(8)	250 (1)	39-52 39-49	45	1.5c	52	58 ± 10
	7 Bocaina	21(9)	60 (9)	44-74 21-71 27-37	46	0.7c	116	
	8 Jacob	21(9)	260 (10)	43-59 28-52 53	48	3.0c	29	
Monte Alegre do Sul To = 18°C	9 Bom Jesús	20(9)	70 (10)	55-60 29-60 24-52	47	1.0c	87	88 ± 12
	10 Saúde	21(3)	1300 (11)	21-67	44	1.1p	71	
Serra Negra To = 19°C	11 Santa Luzia	20(1)	160 (1)	23-39	31	1.7c	21	71 ± 13
	12 S. Agostinho	20(1)	100 (1)	30-51	41	2.0c	33	
	13 São Carlos	21(1)	120 (1)	29-61 71-83	61	2.3c	55	
	14 N.S.Rosário	20(3)	220 (3)	42-43 30-64	45	0.6p	130	
	15 N.S.Aparecida	21(3)	1420 (3)	21-64	43	1.8p	40	
	16 N.S.Lourdes	21(1)	590 (1)	45-61	53	1.0p	102	
	b 11+12+13+14	20	600		45	1.5p	52	
	c 15+16	21	2010		48	3.0p	29	

References: (5) Falcão (1978); (6) Data from MSc Thesis under progress (Del Rey, A.C.); (7) Mean value of references (1), (2), (3) and (5); (8) Mean value of references (1) and (4); (9) Mean value of references (1), (3) and (4); (10) Mean value of references (1) and (3); (11) Mean value of references (5) and (3); (12) Conventional values from Del Rey (1986).
c – cylindrical model; p – plane model; q – heat flow (GHCL method); qc – heat flow (conventional method).

The clustering of points 5 and "a" on the curves for the plane model finds justification from the fact that this spring system seems to be associated with faults (Fig. 6). These faults and their associated fractures could form an extensive network responsible for circulation and heat loss at depth of the ascending water.

Amparo. Del Rey (1986) provides for this area a conventional heat flow value of 58 ± 10 mW/m^2, in reasonably good agreement with the value of 52 mW/m^2 for spring (6) by the CGHL method for a cylindrical model. On the other hand, use of a cylindrical model leads to a very high value (116 mW/m^2) for spring (7) and to a very low value (29 mW/m^2) for spring (8).

For a mean rock thermal conductivity of 3.0 Wm^{-1} C^{-1}, the conventional heat flow implies a geothermal gradient of 19 °C/km. The reservoir temperature (45 °C) of spring (6) would be expected at a depth of 1.4 km. So, the estimated depth of 1.5 km for this spring seems to be reasonable. For spring (7), depth is underestimated, that is, point 7 on Fig. 4 is "too far left". The reservoir temperature of 46 °C would be expected to occur at 1.5 km depth. Moving point 7 to the right (deeper) can bring estimated depth to the expected value. This is equivalent to augmenting the mass flow of this spring. It is interesting to note from Table 2, that this spring has a very low mass flow compared to the other two of this system. Lateral mass flow loss near the surface would explain the overestimated heat flow in this case.

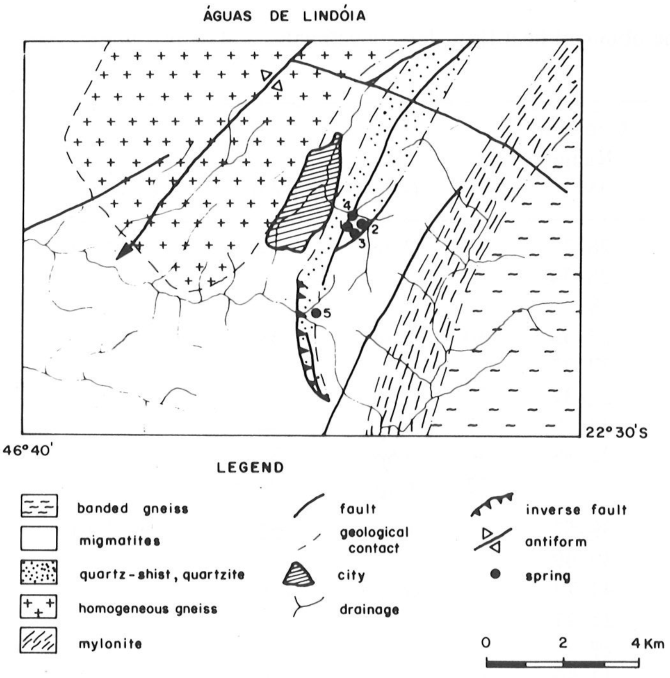


Figure 6. Map showing the geologic and structural setting of the Águas de Lindóia spring systems. Spring numbers refer to Tables 1 and 2 (Geology compiled from IPT, 1985).

An opposite situation is encountered for spring (8). The underestimated heat flow results from an overestimated reservoir depth. This can be interpreted as due to addition of cold waters at shallow depths, resulting in mass flow excess for the graphical estimate of reservoir depth.

Fig. 8 is a sketch of this system of springs showing the influence of mass flow gain or loss on the estimated heat flow.

Monte Alegre do Sul. The heat flow value for this area, obtained using the conventional method is 88 ± 12 mW/m^2 (Del Rey, 1986). Applying the CGHL method to each spring, values of 87 mW/m^2 (cylindrical model) and 71 mW/m^2 (plane model) are obtained for springs (9) and (10) respectively. The first value is in good agreement with the conventional heat flow and the second is slightly below the range given by one mean standard deviation of this conventional value. The estimated reservoir depth is of the same order for both springs (1.0 km and 1.1 km).

Spring (10) has a higher mass flow compared to spring (9). Reducing the mass flow of spring (10), the heat flow estimates can be brought closer to the conventional value. This would mean that part of the mass flow of this spring is due to addition of shallower waters.

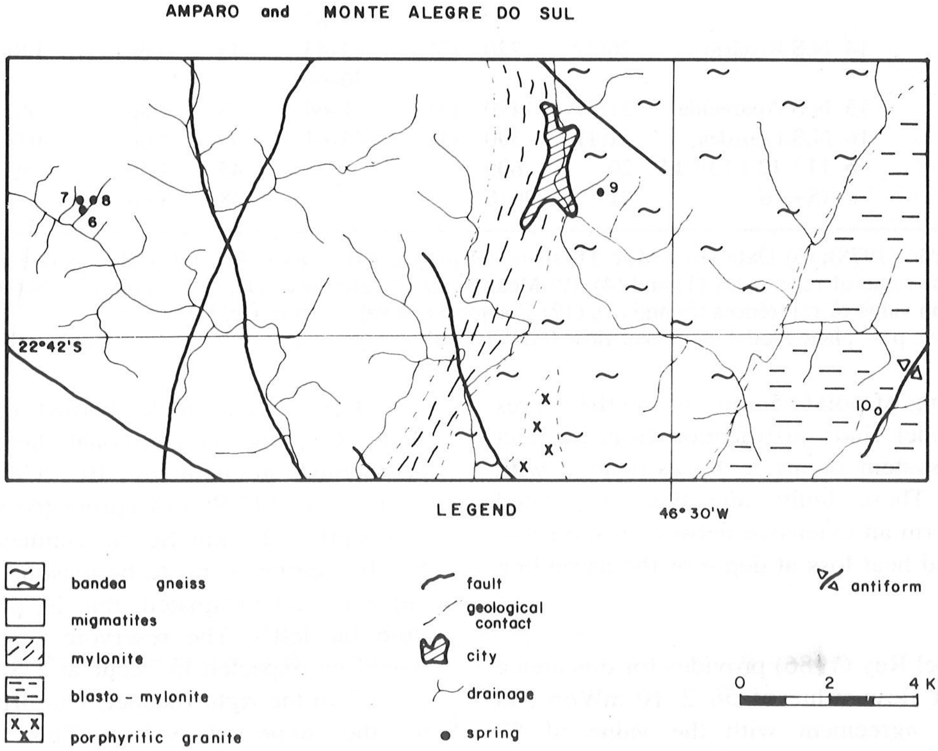


Figure 7. Map showing the geologic and structural setting of the Amparo and Monte Alegre do Sul spring systems. Spring numbers refer to Tables 1 and 2 (Gelogy compiled from GEOSOL, 1985).

In general, these isolated springs seem to provide better heat flow estimated than the preceding systems in which closely located springs do not result in good estimates.

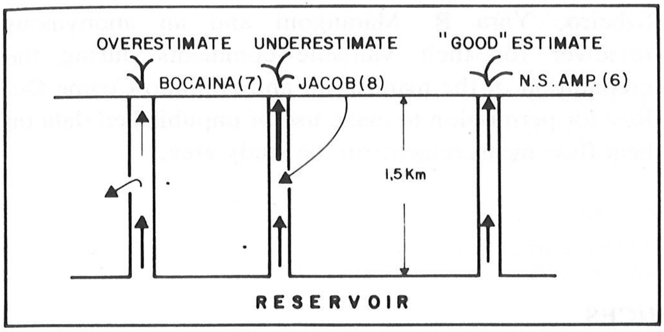


Figure 8. Sketch showing the influence of mass flow gain and loss on the estimated heat flow density for the Amparo spring systems.

Serra Negra. The value of 71 ± 13 mW/m^2 is given by Del Rey (1986) for heat flow in this area. In this locality reservoir temperatures are found to vary more than in the preceding cases. Use of the CGHL method to individual springs provides values outside one mean standard deviation of the conventional value (see Table 2).

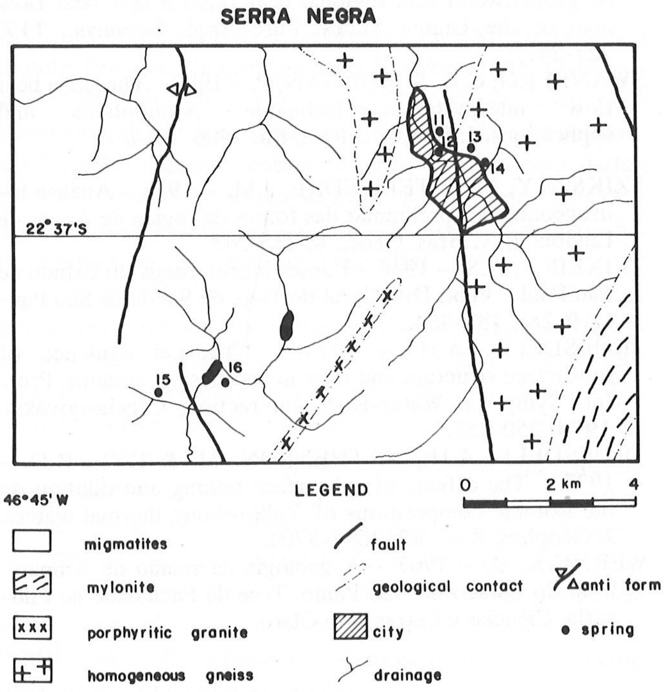


Figure 9. Map showing the geologic and structural setting of the Serra Negra spring system (Geology compiled from GEOSOL, 1985).

Considering springs (11), (12), (13) and (14) as a group and using the total mass flow and mean reservoir temperature (point "b" on Fig. 5) a heat flow estimate of 52 mW/m^2 (plane model) is obtained. For springs (15) and (16), the same procedure results in 29 mW/m^2 (plane model). Here the reservoir depth seems overestimated. The total mass flow output of springs (15) and (16) is much higher than for the group of springs (11), (12), (13) and (14). A reduction of mass flow resulting in a reservoir depth of 1.5 km, of the same order as the northern spring group, would yield an estimate of 58 mW/m^2 in better accordance with the conventional value.

The presence of faults in the proximity of both spring groups suggests that the plane model may be more adequate for the estimation of reservoir depths.

CONCLUSIONS

The preliminary results shown in this paper are not conclusive. Not enough data are available at the present moment for a statistical analysis of the results obtained by this method.

This paper has looked into a few of the problems that can occur during the application of the CGHL method, which does not yet constitute an independent means of estimating heat flow.

On the other hand, this method is intrinsically more reliable and complete than the geochemical method, because it uses more information than the former one, such as spring temperature and mass flow rate, without loosing its simplicity.

The validity of reservoir temperatures predicted by chemical geothermometers, for low temperature spring systems can also be questioned, but this has not been discussed here. An attempt to evaluate more realistic reservoir temperatures is made by combining the use of several geothermometers. As Nathenson (1981) has pointed, when the use of different geothermometers leads to convergent values it is possible that the geotemperatures reflect reservoir temperatures.

Better results seem to be obtained with the data of isolated springs (spring (5) in Águas de Lindóia and springs (9) and (10) in Monte Alegre do Sul). When springs occur grouped close together, the estimated heat flow for either the individual spring or the grouped springs is usually not in good agreement with the conventional values. It is possible that spring groups might have a more complex system of interrelated conduits that cannot be described in a simplified way by a cylindrical or plane model. Another possibility is that the model does not take into consideration mixing of meteoric and thermal waters. The fact that diverse springs occur close together suggests that the permeability of the area is high, which allow easy access of superficial waters to the system.

The method shows itself sensitive to mass flow gain or loss near to the surface. We suggest, using mixing models to estimate the reservoir fraction of the mass flow and to use this instead of the total mass flow for the graphical estimation of reservoir depth. In the case of lateral mass loss, the method will usually overestimate heat flow. Very high heat flow estimates should then be discarded, especially if the geological and geotectonic context of the region indicates that low to normal heat flow values are to be expected.

ACKNOWLEDGEMENTS

I thank Valiya M. Hamza, Fernando Brenha Ribeiro, Yara R. Marangoni and an anonymous reviewer for their valuable comments during the preparation of the manuscript and Antonio Cosme Del Rey for permission to make use of unpublished data on heat flow measurements in the study area.

REFERENCES

APHA (American Public Health Association), AWWA (American Water Works Association) & WPCF (Water pollution Control Federation) – 1976 – Standard methods for the examination of water and wastewater. Am. Publ. Health Assoc., Washington, 14th ed., 1193 pp.

BODMER, H.P. – 1982 – Beitraege zur geothermie der schweiz. PhD Thesis, ETH Zuerich, No. 7034, 201 pp.

CETESB (Companhia de Tecnologia de Saneamento Ambiental) – 1978 – Boletins de exames d'água.

DAEMON, R.F. & QUADROS, L.P. – 1970 – Bioestratigrafia do neopaleozóico da Bacia do Paraná. In: Congr. Bras. Geol., 24, Brasilia, 1970, Anais ... Brasilia, Soc. Bras. Geol.: 355-42.

DEL REY, A.C. – 1986 – Heat flow in the northeastern part of the State of São Paulo. Revista Brasileira de Geofísica (submitted).

FALCÃO, H. – 1978 – Perfil analítico de águas minerais. Departamento Nacional de Produção Mineral (DNPM), Boletim 49, **2**: 160 pp.

FOURNIER, R.O. – 1981 – Application of water geochemistry to geothermal exploration and reservoir engineering. In: Geothermal Systems: Principles and Case Histories. (L. Rybach and L.P.J. Muffler, eds.), John Wiley & Sons Ltd., 109-144.

GEOSOL (Geologia e Sondagens Ltda) – 1985 – Mapa geológico da Folha Socorro (parcial). In: Instituto de Pesquisas Tecnológicas do Estado de São Paulo. Integração e preparo para editoração das folhas geológicas na escala 1:50.000 levantadas para o Pró-Minério em 1982, São Paulo (IPT, relatório 22462).

GONSALVES, A.D. – 1932 – Águas minerais do Brasil. Bol. Ministério da Agricultura, Diretoria de Estatística e Produção, Rio de Janeiro, 164 pp.

IPT (Instituto de Pesquisas Tecnológicas do Estado de São Paulo) – 1985 – Mapa geológic da Folha Águas de Lindóia (parcial). In: Instituto de Pesquisas Tecnológicas do Estado de São Paulo. Integração e preparo para editoração das folhas geológicas na escala 1:50.000 levantadas para o Pró-Minério em 1982, São Paulo (IPT, relatório 22462).

MARANGONI, Y.R. & DEL REY, A.C. – 1986 – Condutividade térmica de amostras do complexo Amparo. Revista Brasileira de Geofísica, **4**: 61-71.

NATHENSON, M. – 1981 – The relation between geothermometer, reservoir and spring temperatures for low-and intermediate temperature (< 150 °C) hydrothermal systems in southwestern Montana. Geothermal Res. Counc. Bull., **10**(7): 3-7.

NATHENSON, M., URBAN, T.C. & DIMENT, N.H. – 1979 – Approximate solution for the temperature distribution caused by flow up a fault and its application to temperatures measured in a drillhole at Raft River geothermal area, Cassia County, Idaho. Geothermal Res. Coun. Trans., **3**: 477-480.

SETZER, J. – 1966 – Atlas climatológico e ecológico do Estado de São Paulo. Comissão Interestadual da Bacia do Paraná-Uruguai/CESP.

SOREY, M.L. – 1975 – Numerical modeling of liquid geothermal systems. U.S. Geol. Surv. Open-file Report 75-613, 66 pp.

SWANBERG, C.A. & MORGAN, P. – 1978 – The linear relation between temperatures based on the silica content of groundwater and regional heat flow: a new heat flow map of the United States. Pure Appl. Geophys., **117**: 227-241.

SWANBERG, C.A. & MORGAN, P. – 1980 – The silica heat flow interpretation technique: assumptions and applications. J. Geophys. Res., **85**: 7206-7214.

SZIKSZAY, M. & TEISSEDRE, J.M. – 1978 – Análise hidrogeoquímica preliminar das fontes da região de Águas de Lindóia. Rev. Bras. Geoc., **8**: 235-248.

TEIXEIRA, A.S. – 1946 – Fontes hidrotermais do Estado de São Paulo. Publ. Dir. Geral do Dep. de Saúde de São Paulo, **9**(28): 137-354.

TRUESDELL, A.H. – 1976 – Chemical evidence of subsurface structure and flow in geothermal systems. Proc. Int. Symp. on Water-Rock Interaction, Czechoslovakia, **1974**: 250-257.

TRUESDELL, A.H., NATHENSON, M. & RYE, R.O. – 1977 – The effects of subsurface boiling and dilution on the isotopic compositions of Yellowstone thermal waters. J. Geophys. Res., **82**: 3694-3704.

WERNICK, E. – 1967 – A geologia da região de Amparo, leste do Estado de São Paulo. Tese da Faculdade de Filosofia, Ciências e Letras, Rio Claro.

Versão original recebida em Jan./87
Versão final, em Nov./88