Thermal state of the lithosphere in Eastern Paraguay and in Andean Domain (South American Platform)

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Abstract

Crustal thermal models that incorporate thermo-barometric data have been developed for estimating depth to 1300 °C isotherm in two xenoliths provinces: Southeast Paraguay and Andean domain, in South American Platform. Uncertainties in model results has been minimized by imposing reasonable bounds on some of the key model parameters. Considering only the best fit results it is possible to infer average values for geothermal parameters at the surface. This imply heat flow of 86 mWm⁻², radiogenic heat production of 1.8 µWm⁻³. Besides at Moho depth: heat flow of 21 mWm⁻², radiogenic heat production of 4.5x10⁻³ µWm⁻³, temperature of from Southeast Paraguay. For the Andean Domain, we have the following values for the geothermal parameters: heat flow, 72 mWm⁻², radiogenic heat production, 1.0 µWm⁻³ in surface and heat flow of 33 mWm⁻², radiogenic heat production of 2.0x10⁻³ µWm⁻³ and temperature of 785°C in Moho depth. The heat flux estimated for the southeastern Paraguay is higher than that for the Andean domain. This result is in agreement with differences in geological ages between these sites, since the age value for Paraguayan region is approximately 20% lower than the Andean one.

1. Introduction

Mantle derived magmatism and mantle xenoliths of Cretaceous to Early Cenozoic age are the primary sources of information on the thermal and compositional state of the uppermost mantle and lower crust (Kukkonen et al., 1999; Russell and Kopylova, 1999; Russell et al., 2001; Harder and Russell, 2006; Aulbach et al., 2004; Christophe Michaut, et al., 2007; Howarth et al., 2014; Dymshits et al., 2020), because xenoliths preserve their physical and chemical characteristics while being transported by magmatic processes.

Thus, the method of estimating the thermal field using the thermo-barometric equilibrium condition of xenoliths has become an important means of estimating the thermal regime of the lithosphere for estimating the thermal regime of the lithosphere.

The method was used by Christophe Michaut, et al., 2007; Rudnick, and Nyblade (1999), in a global study with the purpose of investigating the thermal regime in Archaean terrains. Russell et al., (2001) evaluated radiogenic heat production and basal heat flow in the Slave Craton region of Canada on the basis of thermo-barometrical xenoliths data. A similar method also was used by Dymshits et al., (2020) in estimating the thermal state, thickness and composition of the Siberian Craton. These result simply that the information extracted via equilibrium conditions from samples of xenoliths of man-made origin constitutes an efficient way to infer geothermal parameters in the lithosphere, especially in the upper mantle and lower crust.

In this context, the region of eastern Paraguay, within the Andean domain, offers an opportunity to infer geothermal parameters at Moho depth. It is based on the temperature and pressure balance information of upper mantle xenolith samples from data compiled in published work over the past decades (Comin-Chiaramonti et al., 1991, 2001, 2007, 2010; Demarchi et al., 1988; Petrini et al., 1994; Lucassen et al., 2005).

In other words, the objective of this work is to use temperature and pressure information from the mineralogical equilibrium for estimating the thermal state of the lithosphere (lower crust and upper mantle) of Southeast Paraguay. The results maybe as representative of South America Platform and the Andean domain.

2. Geologic Context

Xenoliths and alkaline sodic lavas of Cretaceous to Paleogene period occur in southeastern Paraguay (≈26°S /
3. Materials and Methods

This magmatism locally includes mantle xenoliths (spinel facies) in Paraguay (Misiones and Asunción, Figure (1)) and in Andes (Las Conchas, Figure 1), these mantle xenoliths vary in size from a few centimeters to 45 cm and provide the unique opportunity for a direct sampling of the subcontinental mantle (Lucassen et al., 2005).

Southeastern and central Paraguay, (Figure 1), have the most recent magmatic events in the study area. These events are characterized by alkaline-potassic and alkaline-carbonatite magmatism that occurred from the Lower Cretaceous to the Paleogene (Comin-Chiaramonti et al., 2001, 2007, 2010; Velázquez et al., 2006).

In the Andean domain rock types vary between mafic and ultramafic, with ankaramitites predominating in Finca del Rodeo, and basanites in Las Conchas and Cadillal (Lucassen et al., 2005).

Tables (1) and (2) present the pressure and temperature information, as well as the types of dominant minerals present in xenoliths samples in the Southeast Paraguay and Andean Domain, compiled from various works (Comin-Chiaramonti et al., 2010; Demarchi et al., 1988; Petrini et al., 1994 and Lucassen et al., 2005).

The last column of Table (1) and Table (2) provide sample description. In Table (1) the samples are Alkaline, either potassic or carbonatite. In Table (2) the samples are mafic or ultramafic. Details on the geothermometers and geobarometers used to estimate the pressure and temperature of equilibrium can be consulted in the references from which the information was compiled.

Table 1 - Pressure and Temperature (P-T) data on mantle xenoliths in Southeast Paraguay.

<table>
<thead>
<tr>
<th>P (kb)</th>
<th>T(ºC)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>841</td>
<td>Alkaline (potassic or carbonatite)</td>
</tr>
<tr>
<td>16</td>
<td>881</td>
<td>Alkaline (potassic or carbonatite)</td>
</tr>
<tr>
<td>17</td>
<td>963</td>
<td>Alkaline (potassic or carbonatite)</td>
</tr>
<tr>
<td>19</td>
<td>971</td>
<td>Alkaline (potassic or carbonatite)</td>
</tr>
<tr>
<td>19</td>
<td>975</td>
<td>Alkaline (potassic or carbonatite)</td>
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<tr>
<td>18</td>
<td>978</td>
<td>Alkaline (potassic or carbonatite)</td>
</tr>
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<td>979</td>
<td>Alkaline (potassic or carbonatite)</td>
</tr>
<tr>
<td>18</td>
<td>983</td>
<td>Alkaline (potassic or carbonatite)</td>
</tr>
<tr>
<td>18</td>
<td>988</td>
<td>Alkaline (potassic or carbonatite)</td>
</tr>
<tr>
<td>20</td>
<td>990</td>
<td>Alkaline (potassic or carbonatite)</td>
</tr>
<tr>
<td>19</td>
<td>995</td>
<td>Alkaline (potassic or carbonatite)</td>
</tr>
<tr>
<td>20</td>
<td>1000</td>
<td>Alkaline (potassic or carbonatite)</td>
</tr>
<tr>
<td>18</td>
<td>1000</td>
<td>Alkaline (potassic or carbonatite)</td>
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<td>Alkaline (potassic or carbonatite)</td>
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<td>1005</td>
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<td>20</td>
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<td>Alkaline (potassic or carbonatite)</td>
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<td>20</td>
<td>1028</td>
<td>Alkaline (potassic or carbonatite)</td>
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<td>21</td>
<td>1033</td>
<td>Alkaline (potassic or carbonatite)</td>
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<tr>
<td>21</td>
<td>1067</td>
<td>Alkaline (potassic or carbonatite)</td>
</tr>
<tr>
<td>20</td>
<td>1104</td>
<td>Alkaline (potassic or carbonatite)</td>
</tr>
<tr>
<td>21</td>
<td>1128</td>
<td>Alkaline (potassic or carbonatite)</td>
</tr>
</tbody>
</table>
In this figure, layer (1) represents the crust with it stop on the Earth’s surface, where \( Z_0 \) is considered zero, and the base on the top of mantle at the \( Z_M \) position. In this layer the radiogenic heat production \( A_0 \) and the thermal conductivity \( \lambda_0 \) are constant. \( T_0 \) represents the temperature and \( q_0 \) the heat flow, both evaluated at the surface.

The layer (2) represents the lithospheric mantle. The top of this region is indirectly as the position of \( Z_M \) and its base at the position \( Z_A \). The Moho's depth is \( Z_M \), this way it also represents the crustal thickness. The radiogenic heat production \( A_M \) in layer (2) is assumed to be constant, but thermal conductivity \( \lambda(T) \) is a function of temperature, while \( B \) is the coefficient of variation of thermal conductivity with temperature. \( T_M \) and \( q_M \) are respectively the temperature and the heat flow at Moho's depth.

The position of \( Z_A \) physically represents the thickness of the thermal lithosphere, which is the domain of the lithosphere by definition, where the current main mode of heat transfer is by conduction. In this position the temperature \( T_A \) has a value of approximately 1300°C and \( q_A \) represents heat flow from the asthenosphere.

4. Model Description

According, with Dymshits et al., 2020, Greenfeld et al., 2013, Harder and Russell, 2006, Artemieva and Mooney, 2001, Jaupart and Mareschal, 1999; and Russell and Kopylova (1999) among others in the lithosphere the main mode of heat transfer is conduction. Therefore, based on this physical concept, it is possible to develop models to estimate its thermal field based on the following geothermal parameters: heat flux, radiogenic heat production, thermal conductivity and temperature.

The model used in this work, shown in Figure (2), consists of two, and is similar to that proposed by Russell and Kopylova (1999); Harder and Russell, (2006); and Greenfeld et al., (2013).

![Figure 2 - Schematic representation of model for conductive heat transfer in the crust and mantle lithosphere.](image)

**Table 2 - Pressure and Temperature (P-T) data on mantle xenoliths in the Andean Domain**

<table>
<thead>
<tr>
<th>P (kb)</th>
<th>T(°C)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>936</td>
<td>Mafic and Ultramafic</td>
</tr>
<tr>
<td>18</td>
<td>995</td>
<td>Mafic and Ultramafic</td>
</tr>
<tr>
<td>20</td>
<td>1053</td>
<td>Mafic and Ultramafic</td>
</tr>
<tr>
<td>20</td>
<td>1028</td>
<td>Mafic and Ultramafic</td>
</tr>
<tr>
<td>20</td>
<td>1020</td>
<td>Mafic and Ultramafic</td>
</tr>
<tr>
<td>20</td>
<td>1070</td>
<td>Mafic and Ultramafic</td>
</tr>
<tr>
<td>21</td>
<td>1052</td>
<td>Mafic and Ultramafic</td>
</tr>
<tr>
<td>21</td>
<td>1087</td>
<td>Mafic and Ultramafic</td>
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<td>21</td>
<td>1067</td>
<td>Mafic and Ultramafic</td>
</tr>
<tr>
<td>21</td>
<td>1159</td>
<td>Mafic and Ultramafic</td>
</tr>
<tr>
<td>21</td>
<td>1119</td>
<td>Mafic and Ultramafic</td>
</tr>
<tr>
<td>22</td>
<td>1147</td>
<td>Mafic and Ultramafic</td>
</tr>
<tr>
<td>22</td>
<td>1109</td>
<td>Mafic and Ultramafic</td>
</tr>
<tr>
<td>22</td>
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</tr>
<tr>
<td>22</td>
<td>1160</td>
<td>Mafic and Ultramafic</td>
</tr>
<tr>
<td>23</td>
<td>1148</td>
<td>Mafic and Ultramafic</td>
</tr>
<tr>
<td>23</td>
<td>1126</td>
<td>Mafic and Ultramafic</td>
</tr>
</tbody>
</table>

**Figure 2 - Schematic representation of model for conductive heat transfer in the crust and mantle lithosphere.**

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Equation (2e), shows the solution for the temperature distribution for layer (2).

\[
T_d(Z) = \frac{q_M}{\lambda_0}(Z - Z_M) - \frac{A_M}{2\lambda_0} (Z - Z_M)^2 - \frac{B}{2} [T_d(Z) - T_M]^2 + T_M
\]

The solution of equation (1) was obtained by applying conventional methods for solving differential equations, already the equation (2) was solved by applying Kirchhoff Transform to remove nonlinearity and consequently transform the nonlinear problem into a linear one. (For details see Özisik, 1980). This technique was used by Dipple and Kopylova (2000) and Russel et al., (2001) to determine the production and flow of heat in the region of Slave Craton. Canada. Alexandrino and Hamza (2008) used this technique to estimate the thermal field of the Brazilian geological province of San Francisco.

5. Methodology to estimate the geothermal parameters.

In order to use the model proposed in this work is necessary to know some initial conditions. This information is given in Table (3) where \(T_0\) is the average annual surface temperature of the study area. Thermal conductivity \(\lambda_0\) and density \(\rho\) have similar values to those used by Russell and Kopylova (1999), Harder and Russell (2006), and Greenfield et al., (2013). According to Rivadeneyra-Vera et al., (2019) the thickness of the crust in the region varies between 35 to 40 km. Therefore, we assume the average value of 37 km as the characteristic of the crustal thickness of the region.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Lithospheric Layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>(T_0 (\degree C))</td>
<td>Crust</td>
</tr>
<tr>
<td>(Z_M (km))</td>
<td>10</td>
</tr>
<tr>
<td>(\lambda_0 (W \cdot m^{-1} \cdot \degree C^{-1}))</td>
<td>37</td>
</tr>
<tr>
<td>(\rho (kg \cdot m^{-3}))</td>
<td>2.5</td>
</tr>
<tr>
<td>(\rho (kg \cdot m^{-3}))</td>
<td>2700</td>
</tr>
</tbody>
</table>

In the following sections we describe the sequential process to estimate the geothermal parameters of interest.

5.1- Geothermal parameters at Moho depth

To estimate the geothermal parameters at the depth of Moho such as temperature \(T_M\), heat flow \(q_M\) and radiogenic heat production \(A_M\). For the coefficient of variation of thermal conductivity with temperature B at the depth of Moho we use the pressure and temperature balance data described in tables (1), (2), (3), the physical parameters described in table (4) and equation (4) to form a system of equations.

This system of equations formed from temperature and pressure balance data allowed us to estimate \(T_M, q_M, A_M\) and B at Moho depth using appropriate numerical methods. In this work we used the RNLIN routine available in IMSL. The RNLIN routine uses a modified Levenberg-Marquardt method.

5.2 - Radiogenic heat production in the surface \(q_0\).

To estimate heat production at the surface we use equation (1d), thus obtaining equation (3).

\[
\frac{dT}{dZ}(Z) = \frac{A_0}{\lambda_0} Z + \left[ \frac{T_M - T_0}{Z_M} \right] + \frac{A_0}{2\lambda_0} Z_M
\]

We multiply equation (3) by \(\lambda_0\) and then evaluate it at position \(Z=Z_M\). Following this procedure, we arrive at equation (4b) and thus can estimate \(A_0\).

\[
\lambda_0 \frac{dT}{dZ} (Z=Z_M) = \frac{A_0}{\lambda_0} Z + \frac{A_0}{2\lambda_0} Z_M
\]

5.3 - Geothermal heat flow at the surface \(q_0\).

To estimate the value of the heat flux at the surface, we first need to multiply eq. (3) by \(\lambda_0\), and then evaluate it at the position. \(Z=Z_0=0\), to obtain the value of the heat flow at the surface.

\[
q_0 = \frac{A_0}{Z_M} \left( T_M - T_0 \right) + \frac{A_0 Z_M}{2}
\]

6. Results and Discussion

Tables (4) and (5) present the results of geothermal parameter estimates. The values of the coefficient of variation of thermal conductivity with temperature and radiogenic heat production in all provinces are compatible with those expected for these parameters (Jaupart and Mareschal, 1999; Kukkonen and Peltonen, 1999; Russell et al., 2001; Artemieva and Mooney, 2001; Dymshits et al., 2020).

<p>| Table 3 - Physical parameters used in the model. | Table 4 - Synthesis of model results for geothermal parameters for Southeastern Paraguay. |</p>
<table>
<thead>
<tr>
<th>Parameters</th>
<th>Lithospheric Layers</th>
<th>Estimated value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(T_0 (\degree C))</td>
<td>Crust</td>
<td>Upper</td>
</tr>
<tr>
<td>(Z_M (km))</td>
<td>764</td>
<td>845</td>
</tr>
<tr>
<td>(q_0 (mWm^{-2}))</td>
<td>79</td>
<td>90</td>
</tr>
<tr>
<td>(A_0 (mWm^{-2}))</td>
<td>17</td>
<td>28</td>
</tr>
<tr>
<td>(A_M (mWm^{-2}))</td>
<td>1.5</td>
<td>2.0</td>
</tr>
<tr>
<td>(A_M (mWm^{-2}))</td>
<td>3.5E-03</td>
<td>1.9E-02</td>
</tr>
<tr>
<td>(B (W \cdot m^{-1} \cdot \degree C^{-1}))</td>
<td>1.5E-04</td>
<td>1.4E-04</td>
</tr>
<tr>
<td>(Z_M (km))</td>
<td>146</td>
<td>99</td>
</tr>
</tbody>
</table>

In Southeast Paraguay (see Table - 4) the measured heat flow varies from 79 to 90 mWm\(^{-2}\), and the estimated radiogenic heat value is 1.8 µWm\(^{-3}\) at the surface. At Moho
depth the temperature and the heat flow have average values of 805°C and 21 mWm⁻² respectively and 117 km is the value of the thermal thickness of that region.

For the Andean Domain (Table (5)) the estimated heat flow value at the surface is between 67 to 76 mWm⁻². At Moho depth the parameters vary as follows: temperature between 876 to 694 ºC and heat flow from 29 to 38 mWm⁻². The average thermal thickness estimated for the province is 86 km, and the estimated surface radiogenic heat production value was 1.8 µWm⁻³.

Table 5 - Synthesis of model results for geothermal parameters of the Andean Domain.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lower</th>
<th>Upper</th>
<th>Best</th>
<th>±</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_M (°C)</td>
<td>694</td>
<td>876</td>
<td>785</td>
<td>91</td>
</tr>
<tr>
<td>q_M (mWm⁻²)</td>
<td>67</td>
<td>76</td>
<td>72</td>
<td>5</td>
</tr>
<tr>
<td>q_M (mWm⁻²)</td>
<td>29</td>
<td>38</td>
<td>33</td>
<td>5</td>
</tr>
<tr>
<td>A₀ (µWm⁻³)</td>
<td>1.1</td>
<td>0.9</td>
<td>1.0</td>
<td>0.1</td>
</tr>
<tr>
<td>A_M (µWm⁻³)</td>
<td>1.0E-03</td>
<td>3.0E-03</td>
<td>2.0E-03</td>
<td>1.0E-03</td>
</tr>
<tr>
<td>B (W m⁻³°C⁻²)</td>
<td>1.0E-04</td>
<td>2.0E-04</td>
<td>1.1E-04</td>
<td>5.0E-05</td>
</tr>
<tr>
<td>Z_L (km)</td>
<td>102</td>
<td>72</td>
<td>86</td>
<td>14</td>
</tr>
</tbody>
</table>

Figures (3) to (4) show the results of the temperature distribution. These figures illustrate the maximum and minimum values of the modelled temperature profiles, as well as the observed data.

The parameters B, according to Kukkonen and Jõeleht, 1995; Seipold, 1998; Jaupart and Mareschal, 1999; Artemieva and Mooney et al., 2001, in the lithospheric mantle their typical values are between 1x10⁻⁴ < B < 5x10⁻⁵ Wm⁻¹°C⁻², which causes a variation of ± 15°C in the T_M value and in the flow of heat q_M this variation is around ± 4.0 mWm⁻².

Figure (5) shows that using the strategy of fixing Z_M and A_M refine the values of A_M and B within the range of expected values for these quantities. It was possible to estimate the variables in equation (4) T_M, A_M, q_M, and B in order to obtain the difference between T_OBS and T_MODEL within the range of uncertainties of the geothermobarometer.
The other constraint used to solve equation (4) was to establish a difference between the observed temperature $T_{OBS}$ and $T_{MODEL}$ below or equal to 20°C. This value was chosen due to the uncertainty in the thermo-barometry calibration estimated at ± 20 °C and ± 0.3 GPa for the geothermometer proposed by Brey and Kohler, 1990.

Imposing these restrictions, we obtain a good quality of adjustment, as can be verified by the analysis of Figure (6) where we can observe a strong correlation between the observed data and that predicted by the model.

7. Conclusions

The value of heat flow at the surface is similar to that estimated by Vieira and Hamza (2019), Cardoso et al., (2010), Hamza and Muñoz (1996). This agreement was considered as relevant information for validation of the model.

The values of radiogenic heat production and the parameter for variation of thermal conductivity at Moho depth are within the expected range. Hence, we may consider that the model presents coherent results, which indicate the validity of the model when more accurate data are available.

The heat flux estimated for the southeastern Paraguay (8626 mWm$^{-2}$) is higher than that for the Andean domain (72± mWm$^{-2}$).

This result is in agreement with differences in geological ages between these sites, since the age value for Paraguayan region is approximately 20% lower than that for the Andean one.

8. Acknowledgments

Revision of this manuscript benefited from comments by the editorial board of JTHFA.

References


