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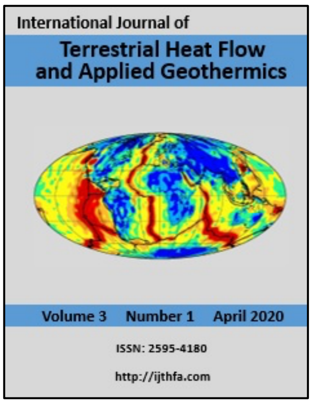

Geothermal Gradients and Heat Flow in Norte Basin of Uruguay

Ethel Morales [1, 2], Agostina Pedro [1], Ricardo De León [2]

[1] Instituto de Ciencias Geológicas, Facultad de Ciencias UdelaR, Montevideo, Uruguay
[2] PEDECIBA - Geociencias. Ministerio de Educación y Cultura, Montevideo, Uruguay

Email address

ethel@fcien.edu.uy (E Morales)
Corresponding author

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Abstract

Progress obtained in a partial update of geothermal gradient and terrestrial heat flow values for the Norte Basin (Uruguay) are presented. It is based on results of temperature measurements carried out in deep water wells. Most of these wells have intersected the southern part of the Guarani Aquifer System, at depths varying from 200 to 1500m. In most of the Norte Basin it is a confined aquifer capped by the flood basalts of Cretaceous age. The results indicate that temperature gradients fall in the range of 15 to 45ºC/km and the thermal conductivity of basalts have a mean value of 2.2W/m/K. Analysis of temperature distributions indicate that heat transfer takes place not only by conduction but also by upflow of groundwater with velocities in the range of 10^{-9} to 10^{-8} m/s. The representative mean heat flow values fall in the range of 30 to 85mW/m^2. Maps of spatial distributions of geothermal gradients and heat flow values have been considered as indicative of the possible existence of an anomalous geothermal zone in the central-northwestern part of the Norte Basin. There are indications that this anomalous geothermal zone extends also to the eastern parts of adjacent regions in Argentina. Theoretical values derived on the basis of spherical harmonic expansion, employed in estimating geothermal gradients and heat flow points to a zone of relatively low heat flow in the other regions of the Norte Basin.

1. Introduction

Knowledge of subsurface temperatures are used extensively in heat flow studies and also in geothermal exploration and development. The temperature and pressure logs are usually carried out during drilling of wells. The biggest challenge in analyzing these logs is to determine reservoir conditions of temperature and pressure intersected by the wells. It allows assessment of the in-situ potential of permeable zones. When data from several wells are available, maps can be drawn to illustrate the spatial variations of formation temperature and pressure distribution in the geothermal reservoir.

The territory of Uruguay situated in the South American continent offers interesting opportunities for studies of contrasting geothermal regimes of Paleozoic cratonic basins and Mesozoic Atlantic continental margin basins. The history of geothermal studies includes measurements of temperatures of pumped waters in wells of the Norte Basin (Heinzen et al., 2003), investigations of potential uses of thermal waters of Guaraní Aquifer System by PSAG (2008), investigations of geothermal energy by Cernuschi (2014) as well as geothermal potential of Uruguay by Morales and Perez (2014). In the present work we examine characteristics of the Norte Basin in the northwestern region of Uruguay with purpose of understanding deep geothermal structure of the crust and in evaluating the potential for geothermal energy development.

2. Geological framework

The geological features of Uruguay consist of Precambrian basement and sedimentary basins of phanerozoic age (Figure 1). The main onshore units are Norte Basin, Santa Lucía Basin, and Laguna Merín Basin. The offshore units include Punta del Este Basin, the southernmost part of the Pelotas Basin, and the Oriental del Plata Basin. Given below is a brief summary of the geological characteristics of some of these units.

2.1. Precambrian Basement

The Precambrian basement of Uruguay includes Archean to Proterozoic rocks out cropping mainly in the southern region of the country. At the north, it is restricted to the so-called "crystalline islands" (Cuñapirú-Vichadero and Aceguá). It consists of metamorphic and plutonic intrusive rocks, as well as various hypabyssal dyke swarms. In a general way, the Uruguayan Shield can be divided into three main domains: the Piedra Alta Terrane (PAT) on the western side of the Sarandí del Yí Shear Zone (SYSZ), the Nico Pérez Terrane (NPT) developed between the Sarandí del Yí and the Sierra

Ballena Shear Zones (SBSZ), and the Don Feliciano Belt (DFB) on the eastern side of the Sierra Ballena Shear Zone (Figure 1).

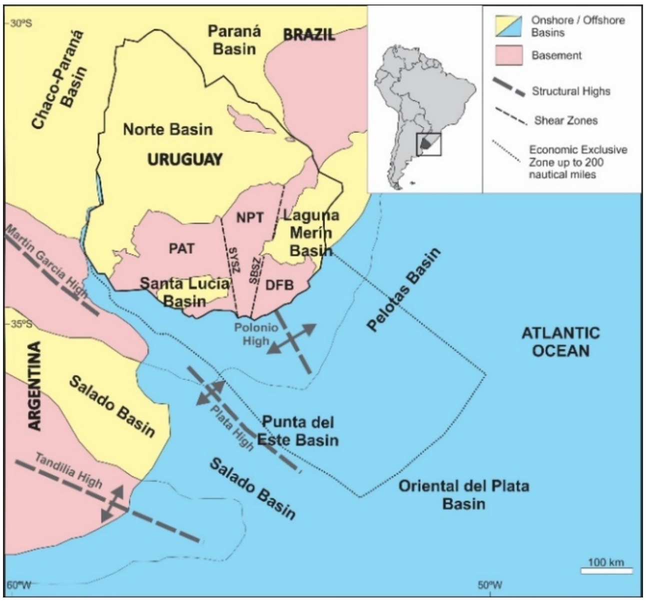

Figure 1 - Main geological elements of Uruguay and surrounding areas (Adapted from Morales et al. 2019).

The Piedra Alta Terrane includes Paleoproterozoic rocks which were not tectonically reworked during the Neoproterozoic (Oyhantçabal et al., 2011). The Nico Pérez Terrane includes Archean and Paleoproterozoic rocks tectonically reworked during the Neoproterozoic. The Dom Feliciano Belt crops out in eastern Uruguay and it was developed between ca. 750 and 550 Ma (Sánchez Bettucci et al., 2001) and represents the Brasiliano/Pan-African orogenic cycle.

2.2. Sedimentary formations

After the assembly of the final shield configuration the territory of Uruguay have been covered by several sedimentary units with ages ranging from Devonian to Quaternary.

The Norte Basin (name given to the Uruguayan portion of the Paraná Basin) comprises Paleozoic to Mesozoic sedimentary rocks and Mesozoic basaltic flows mainly related to the evolution of the Western Gondwana. It is composed of four sequences separated by regional unconformities: Devonian, Late Carboniferous-Permian, Jurassic-Cretaceous and Late Cretaceous (De Santa Ana, 2004).

The Paleozoic sequences represent transgressive-regressive cycles related to second order sea-level changes. The Mesozoic sequences includes sedimentary and volcanic rocks. The deposition in the Mesozoic started with the continental sediments of the Tacuarembó Formation, included in the Jurassic-Cretaceous sequence. The Tacuarembó Formation registers different depositional systems including fluvial and eolian strata deposited in an arid to semi-arid climate (Amarante et al., 2019). This formation is characterized predominantly by very fine to coarse-grained sandstones. It is continuation of the strata holding the Guaraní Aquifer System within the central parts of the Parana basin (Lebac, 2008).

2.3. Flood Basalts

In the northern parts of Uruguay, volcanic materials from the Paraná continental flood basalt province form a major lithological unit extending beyond Uruguay's borders into Argentina and Brazil. Eastern parts of this province has been identified in Namibia on the other side of the Atlantic, consequence of separation between African and South American lithospheric plates. Tacuarembó formation came to be preserved as the Arapey basalts, that erupted 132Ma and covered the sediments. The bulk of this volcanic material is basalt but there are rhyolites as well (Bossi and Schipilov, 1988).

3. Characteristics of Geothermal Data Sets

This data set refers to results of temperature measurements carried out during pumping tests. The coordinates of well locations are provided in Table (1) along with values of temperatures of outflowing waters. In most cases temperatures are in the range of 30 to 50°C. The flow rates are in the range of 100 to 450m^3/h (official data of the National Water Agency of Uruguay - DINAGUA).

Table 1 - Locations of wells, depths of aquifers and temperatures (T) of outflowing waters.

Well Name	Coord. Lon/Lat	Altitude (m)	Depths (m)		T (ºC)
			Basalt	Total	
OSE- Int. de Salto	-57.962 -31.377	42.3	1070	1368	47
Posada del Siglo XIX	-57.909 / -31.439	25.9	1004	1209	46.5
Kanarek	-57.905 / -31.458	20	940	1280	45.5
Daymán	-57.909 / -31.458	18.2	955	2204	45.5
San Nicanor	-57.802 / -31.545	63.3	838	1104	43.6
Hotel Horacio Quiroga	-57.917 / -31.277	40.9	968	1295	44
Belén	-57.698 -30.831	69	460	2336	39.5
Arapey	-57.518 / -30.949	48.5	543	1494	38
Guaviyú	-57.887 / -31.842	28.4	665	1109	36.7
Almirón	-57.269 / -32.358	62.4	505	923	31
Colonia Viñar	-57.616 / -30.467	80	556	681	35.1
Arapey 2	-57.523 / -30.947	49	530	900	34.7
Paso Ullestie	-57.822 -32.584	32.5	360	973	26
Salsipuedes	-56.456 -32.474	99	210	210	23.2
Pelado	-56.730 -30.556	189	234	1996	-
Artigas 2	-56.457 -30.431	107	0	1857	-
Gaspar	-57.664 -30.629	76	513	2297	-
Yacaré	-56.970 -30.295	80	421	2387	-
Guichón	-57.268 -32.358	63	545	925	-
Altos del Arapey	-57.518 / -30.942	25	539	956	-
Itacumbú	-57.478 -30.541	108	421	2099	-

Vertical distributions of temperatures measured in these are illustrated in Figure (2). Here the full circles indicate values of temperatures of flowing water at the well mouth. For large flow rates the effects of lateral heat losses during upflows are negligible and temperatures of water at the well mouth may be considered as indicative of in-situ aquifer conditions. This approach for determining aquifer temperatures has been designated as the AQT method (Santos et al., 1986). Meteorological records indicate a mean annual temperature of 22°C for the northwest region of Uruguay (data from meteorological station at Salto city, from 1961 to 2017, provided by the Uruguayan Institute of Meteorology - INUMET-). The dashed lines in Figure 2 are interpolations between the mean annual surface temperatures and calculated aquifer temperatures, for gradient values of 15 and 45ºC/km.

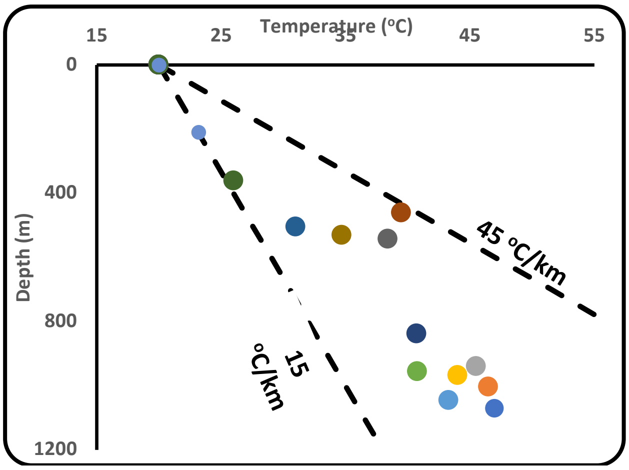

Figure 2 - Vertical distribution of temperatures in the upper parts of the South Guarani Aquifer in the Norte Basin of Uruguay.

4. Upflow of Groundwater in the Norte Basin

One of the surprising features in the distribution of temperatures in the Norte Basin is the large range in temperature gradients. Variations in the range of 15 to 45ºC/km are incompatible with the rather quiescent tectonic characteristics of the region and in fact points to the presence of heat transfer processes other than solid state conduction. In fact, the remarkable relation between temperatures of flowing waters and respective depths of aquifers, illustrated in Figure (3), points to the presence of a specific heat transfer process.

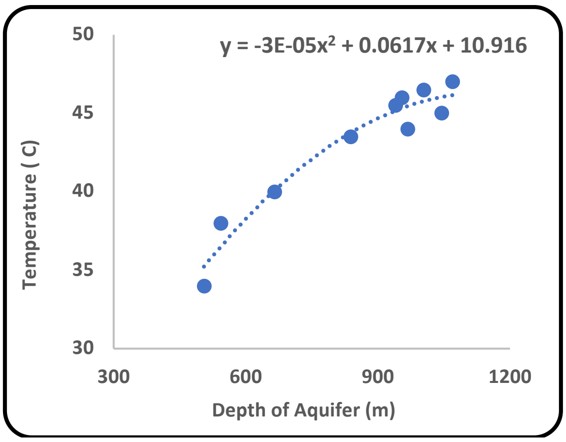

Figure 3 - Non-linear relation between aquifer depths and temperatures of flowing waters.

The equation displayed in this figure refers to second order polynomial fit to the data set. The curvature in the vertical distribution of temperatures in this figure may be considered as indication of hydrological processes operating in the local aquifer system. In this context we note that it is common practice in geothermal studies to look for non-linear features in temperature logs of boreholes as the first step in identifying thermal effects of advection. Nevertheless, this approach is not always practical, as the availability of suitable temperature log data is severely limited.

In the present work we adopt a modification of this procedure that allows determination of groundwater flows in Norte Basin where AQT data are available. It is based on the approach proposed by Stallman (1963) for analysis of vertical temperature variations in wells and is capable of addressing effects of simultaneous heat transfer by conduction and advection. It has been employed widely in the geothermal literature (see for example Bredehoeft and Papadopulos, 1965; Cartwright, 1970; Mansure and Reiter, 1979). The theoretic framework of this method is based on a solution to the differential equation for simultaneous heat transfer by conduction and convection. For the boundary conditions that the temperature (T) is T0 at the surface (at z = 0) while it is TL at the aquifer depth (z = L) the relation between temperature and depth may be expressed as:

$$\frac{T-T_0}{T_a-T_0} = \frac{[\exp(\beta z/L)-1]}{[\exp(\beta)-1]} \qquad (1a)$$

where β is the Peclet number given by:

$$\beta = \frac{\rho\, C_P\, v\, L}{\lambda} \qquad (1b)$$

The parameter beta defines the ratio of convection to conduction heat transfer. Under these conditions the relation between dimensionless temperature (left side of equation 1a) and depth (z) provides information on the direction and velocity of groundwater flow. An example of this procedure is illustrated in Figure (4) for the Norte Basin where observational data on well temperatures (black circles) are compared against theoretical values (dotted and dashed curves) corresponding to different values of flow velocities. The curve fitting procedure indicates that the flow is upward and have velocities in the range of 10^{-9} to 10^{-8}m/s. The upflow of groundwater in the Norte Basin has also been referred by Manzano and Guimaraens (2009).

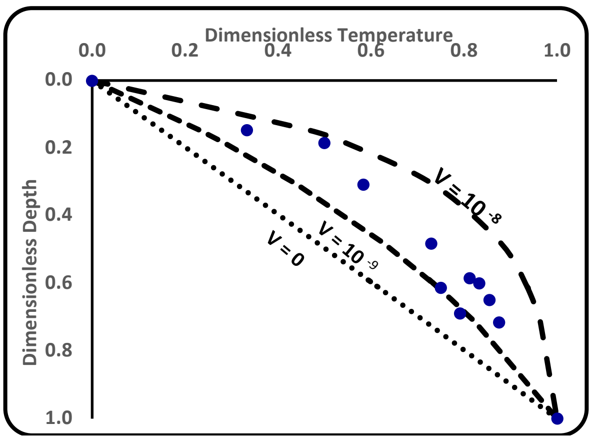

Figure 4 - Relation between dimensionless values of temperatures and aquifer depths in the Norte basin.

5. Temperature Gradients and Heat Flow

The data sets on temperatures and depths assembled in Table (1) has been useful in determining geothermal gradients for 14 localities in Norte Basin. The gradient (Γ) values are calculated using the relation:

$$\Gamma = (T_a - T_0)/z_w \qquad (2)$$

Where T_a is the temperature of pumped water at the well mouth, T_0 mean annual surface temperature and z_w the aquifer depth. It is assumed that temperature of the pumped water is nearly equal to the in-situ temperature of the aquifer. Santos et al. (1986) demonstrated that effects of lateral heat flosses of up flowing waters in wells of Paraná Basin are negligible when flow rates are in excess of 100m^3/hour. In the case of wells with lower flow rates one may make use of the relation between out flow temperature (Tw) and in-situ aquifer temperature (Ta), proposed by Bolditzar (1958):

$$\frac{T_W - T_0}{T_a - T_0} = M' \, R \left[1 - exp\left(-\frac{1}{M\,R}\right)\right] \qquad (3)$$

In equation (3) M' = MC/λH dimensionless mass flow rate (M is the mass flow rate during pumping tests, c the specific heat of water, λ the thermal conductivity of rock units traversed by the well and H the depth to the top of the aquifer). R is a parameter defined by Birch (1947) as:

$$R = \frac{1}{4\,\pi} \int_{r^2/4\,\alpha\,t}^{\infty} Z^{-1} \exp(-z) \; I_0\,(z) dz \qquad (4)$$

In equation (4) *r* is the radius of the well, α the thermal diffusivity of the rock column, *t* the time elapsed since pumping started and I_0 the modified Bessel of the first kind of order zero. Results of numerical simulations reveal that for large values of time elapsed, that is wells which have been in use for long times, the value of R approached 2/π. Further, it is rather insensitive to small changes in time elapsed. Thus, for large times the dimensionless temperature (left hand side of equation 3) approaches unity, which means that temperature of pumped water approached the in-situ aquifer temperature. This method of determining geothermal gradients using equation (2) has been classified as the aquifer temperature (AQT) method (Hamza et al., 2005).

The approach employed for determining thermal conductivity values is relatively more complex, mainly because of the technical and operational difficulties in obtaining representative core samples for laboratory measurements. In such cases it is usual practice to supplement experimental data with results derived for similar sections of lithologic sequences identified in nearby wells or results obtained for representative samples from outcrops (see for example Pimentel and Hamza, 2012; Vieira and Hamza, 2019). The solution adopted in the present compilation has been to employ proxy values based on experimental data on representative samples collected from nearby boreholes and outcrops of lithotypes identified in local geologic surveys. In the present case proxy values for thermal conductivity of Arapey basalts that overly the sedimentary strata of Tacuarembó formation fall in the range of 1.9 to 2.2W/m/K (Hamza et al., 2005).

In all cases, heat flow values were calculated as the product of representative values of geothermal gradient and thermal conductivity. The respective errors in heat flow (q) values were calculated using the relations for propagation of errors:

$$q = \lambda \cdot G \; \pm \; \sigma_q \qquad (5a)$$

$$\sigma_q = \sqrt{(\frac{\partial q}{\partial \Gamma})^2 \sigma_\Gamma{}^2 + (\frac{\partial q}{\partial \lambda})^2 \sigma_\lambda{}^2} = \sqrt{\lambda^2 \sigma_\Gamma{}^2 + \Gamma^2 \sigma_\lambda{}^2} \qquad (5b)$$

In equations (5a) and (5b) *G* represents the geothermal gradient and *λ* the thermal conductivity. The list of temperature gradients and heat flow values along with estimated values of uncertainty are presented in Table (3). Heat flow in excess of global mean of 65mW/m^2 (Vieira and Hamza, 2019) has been encountered only in two localities.

Table 3 - Estimates of geothermal gradients (Γ) and heat flow (q) for the Norte Basin of Uruguay. σ indicates estimated uncertainty.

Well Name	Depth	Γ (°C/km)		q (mW/m²)	
	(m)	Mean	σ	Mean	σ
Belén	460	42.4	4.2	93	19
Arapey	543	33.9	3.4	75	18
Arapey 2	530	27.7	2.8	61	14
Kanarek	940	27.1	2.7	60	15
Posada Siglo XIX	1004	26.4	2.6	58	14
OSE - Salto	1070	25.2	2.5	56	12
Guaviyú	665	25.1	2.5	55	13
Horacio Quiroga	968	24.8	2.5	55	14
San Nicanor	838	24.7	2.5	54	14
Remeros Salto	1045	22.3	2.2	49	16
Daymán	955	21.8	2.2	48	15
Almirón	505	21.8	2.2	48	15
Ullestie	360	16.7	1.7	37	12
Salsipuedes	210	15.2	1.5	34	14

6. Geothermal Maps

The data sets on temperature gradients, heat flow compiled in the present work and theoretical values derived on the basis of spherical harmonic expansion has been employed in deriving geothermal maps of the Norte Basin (figures 5 and 6).

The map of geothermal gradients presented in Figure (5) reveals a region of relatively high values (>30ºC/km) in the central parts of the northwestern region of Norte Basin. The southern and eastern parts of the Norte Basin seem to be characterized by geothermal gradients of less than 25ºC/km. It is quite likely an extension of relatively low heat flow values proposed for the adjacent Precambrian regions in the southern parts (Vieira and Hamza, 2019).

This zone of high gradient values has been interpreted as indicative of a regional geothermal anomaly in the central-northwestern part of the Norte Basin. The reason for such lateral changes in gradient values is not clear. However, it seems to be an extension of areas of relatively higher gradients in adjacent areas of Argentina, reported by Pesce (2001). Results of deep drilling and crustal geophysical surveys are necessary for understanding the processes responsible this geothermal anomaly.

The map of heat flow values illustrated in Figure (6) reveals a pattern similar to that of geothermal gradients. Thus, relatively high values of heat flow (>60mW/m^2) are found to occur in the central-northwestern segments of the Norte Basin. The southern and eastern parts seem to be characterized by heat flow values of less than 50mW/m^2. It is possible that these higher values are related to a deep-seated geothermal zone in the central-northwestern part of the Norte Basin. There are indications that this anomalous geothermal zone extends also to the eastern parts of adjacent regions in Argentina (Pesce, 2001). The other parts of the Norte Basin have low to normal heat flow.

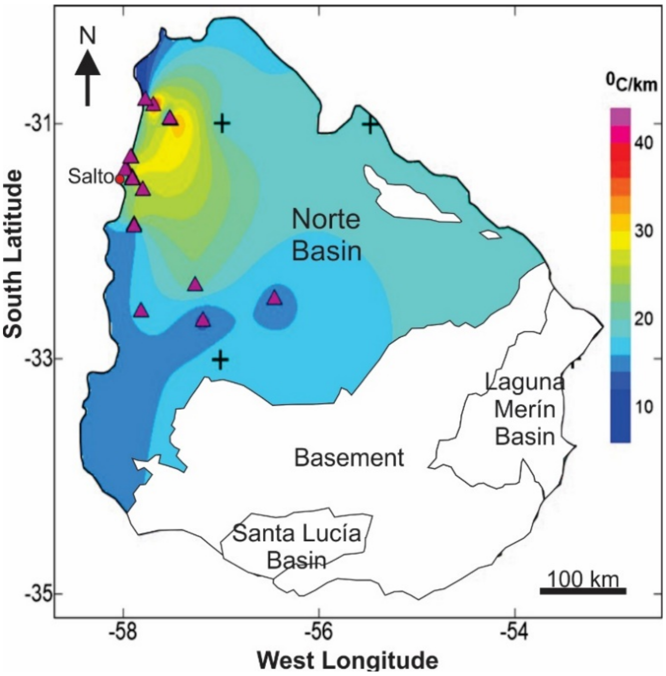

Figure 5 - Geothermal gradient map of the Norte Basin of Uruguay. The triangles indicate locations of geothermal gradient determinations. Red circle: Salto city.

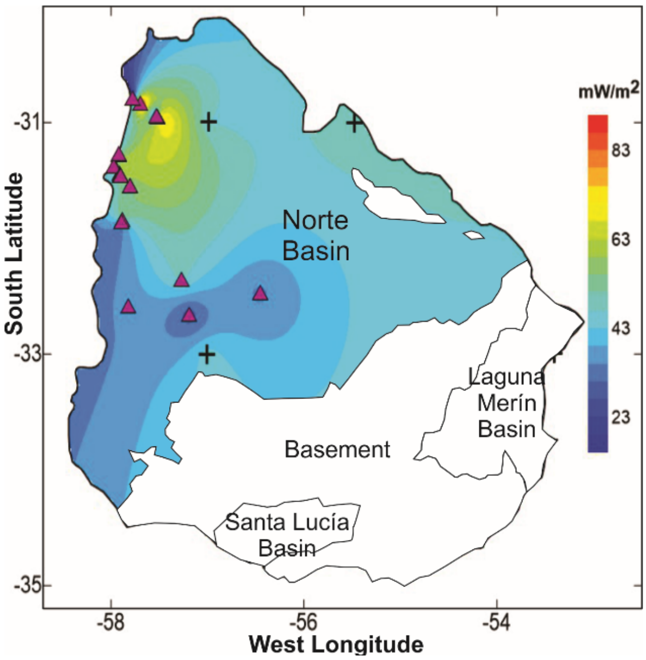

Figure 6 - Heat flow map of the Norte Basin of Uruguay. The triangles indicate locations of heat flow determinations.

7. Conclusions

This work presents compilations of geothermal and heat flow data acquired for 14 sites in the Norte Basin of Uruguay. There are indications heat transport by upflow of groundwater occurs in this basin, with upflow velocities falling in the range of 10^{-9} to 10^{-8} m/s. The results obtained point to the existence of a region of relatively high values of geothermal gradients and heat flow in the central-northwestern part of the basin. It is possible that this anomaly is related to a deep-seated geothermal zone in the central-northwestern parts of the Norte Basin. There are indications that this anomalous geothermal zone extends also to the eastern parts of adjacent regions in Argentina. The other parts of the Norte Basin have low to normal heat flow.

8. Acknowledgments

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