Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Heat Flow Evaluation at Eastern Llanos Sedimentary Basin, Colombia

Claudia ALFARO[1], Ingrid ALVARADO, Antonio MANRIQUE

Servicio Geológico Colombiano. Dg. 53 No. 34-53 Bogotá, Colombia

[1] calfaro@sgc.gov.co

Keywords: Geothermal gradients, heat flow, thermal conductivity, Eastern Llanos Basin, geothermal map

ABSTRACT

The Eastern Llanos Basin is located in the Eastern region of Colombia. Geomorphologic boundaries are the Colombian-Venezuela border to the north, Macarena high and Vaupes Arch to the south, Guaicaramo Fault system to the west, and Guyana Shield to the east. This basin with an extension of 196.000 km^2 is considered the most productive hydrocarbon basin in continental Colombia. From a preliminary regional map, built from bottom hole temperature (BHT) and average surface temperature data, the Eastern Llanos Basin was identified as the Colombian basin with the highest geothermal gradient magnitudes, except for the Andes (Central Cordillera) where higher anomalies are expected but where very little information is available. The Eastern Llanos basin was chosen as a priority area to improve the data density of the geothermal gradient map and to estimate the heat flow. This work presents the geothermal gradient map of this basin, estimated through the BHT of 870 wells. The results confirm the geothermal gradient trend to increase towards the east and southeast of the basin, as observed in the regional map. The range of variation goes from 8 to 59 °C/km with an average value of about 28.8 °C/km. Thermal conductivity measurements were made directly on well core samples from different geological formations, to obtain representative values. From this, effective average conductivities were estimated in the basin, between 1.12 and 1.57 W/mK, with a mean value of 1.32 W/mK. Low values are probably related to high porosities. From the geothermal gradients and the effective average conductivities, heat flow values were estimated in 84 wells by following the methodology of Carvalho & Vacquier (1977). The variation in heat flow between 20 and 81 mW/m^2, with a mean value of 37 mW/m^2, also shows a trend to increase towards the east and south of the basin. Values higher than 56 mW/m^2 could be considered slight anomalies when compared with the average heat flow for Precambrian shields (42 mW/m^2; σ =10).

1. INTRODUCTION

General Aspects of the Easter Llanos Sedimentary Basin

The Easter Llanos sedimentary basin is classified as a Cenozoic Foreland basin. "This is the most prolific hydrocarbon basin in continental Colombia. The northern limit of this basin is the Colombian-Venezuelan border; to the south the basin extends as far as Macarena high, the Vaupés Arc and the Precambrian metamorphic rocks that outcrop to the south of the Guaviare river; the eastern limit is marked by the outcrops of Precambrian plutonic rocks of the Guyana Shield and to the west the basin is limited by the frontal thrust system of the Easter Cordillera (Figure 1). The evolution of the basin started in the Paleozoic with a rifting phase. Siliciclastic sediments were deposited over the crystalline Precambrian basement. From Triassic to Late Cretaceous the basin was the eastern shoulder of a major rift system. From the Maastrichtian to Paleocene, this basin became a foreland. From Miocene to recent times the basin has been a repository of thick molasse deposits. Cretaceous source rocks range from immature to marginal mature within the region to the east of the frontal thrust. Main reservoirs are siliciclastic units of Late Cretaceous and Paleogene age. Analysis of the individual components of the migration systems within the basin is complicated by thinning of the stratigraphic section, and development of more sand-prone facies towards Guyana Shield" (Barrero et al., 2007).

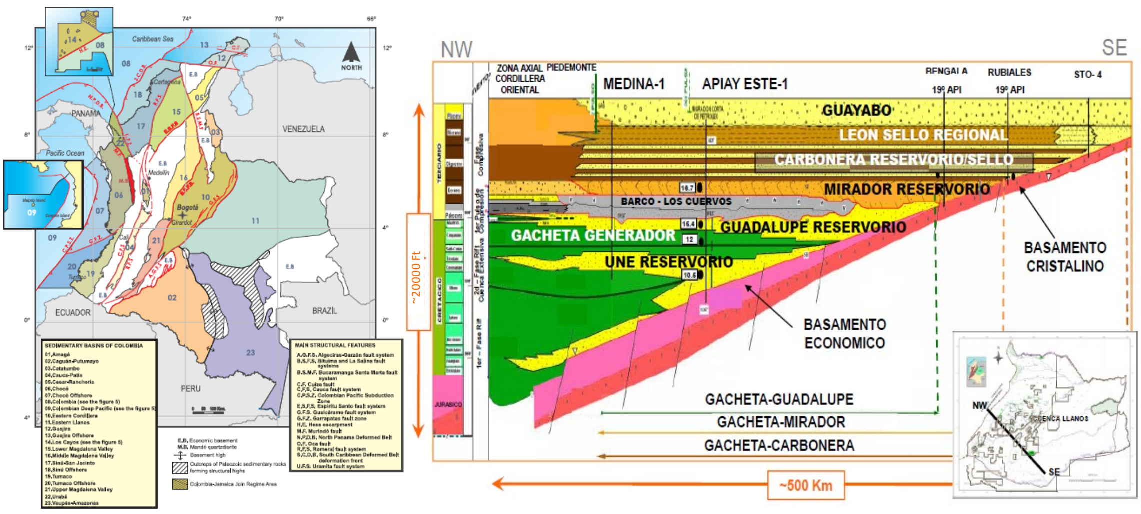

Figure 1. Location and stratigraphic model and oil-bearing systems of the Easter Llanos Basin. Left: Easter Llanos Basin (number 11). Taken from Barrero et al., 2007. Right: The sedimentary sequence is coined against the crystalline basement. This fact and the different regional discordances result in lithological units with an uneven distribution in the basin and a reduction of thickness towards the east. The main petroleum systems of the basin include the sandstones of the Une, Guadalupe, Mirador and Carbonera formations, as reservoirs, Gachetá formation as main source rock and León formation, as regional seal. Taken from Halliburton (2007) In Vargas, 2008.

Geothermal Gradients and Heat flow.

The Colombian Geological Survey (SGC for its abbreviation in Spanish) has developed preliminary versions of geothermal gradients and heat flow maps, based on information of about 1660 deep wells from the oil industry and 104 hot springs, as a first approach to the methodology for the regional study of this phenomena in the Colombian territory (Ingeominas, 2000; Alfaro, 2000). In the same frame a new version of the geothermal gradients map was carried out by INGEOMINAS – ANH (2008), on the basis of a higher number of wells (4400), whose location and geothermal gradients are presented in Figure 2. As in the first version, the calculations of the gradients in wells were based on apparent geothermal gradients (downhole temperature and surface temperatures). The highest geothermal gradients in sedimentary basins were estimated to be in the range 60–65 °C/km. The map does not include Nereidas-1, a 1356 m deep geothermal well drilled in the western flank of Nevado del Ruiz (GESA, 1997), whose apparent geothermal gradient is about 140°C/km. As can be seen in the Figure, the large extension with anomalous gradients is the Easter Llanos basin.

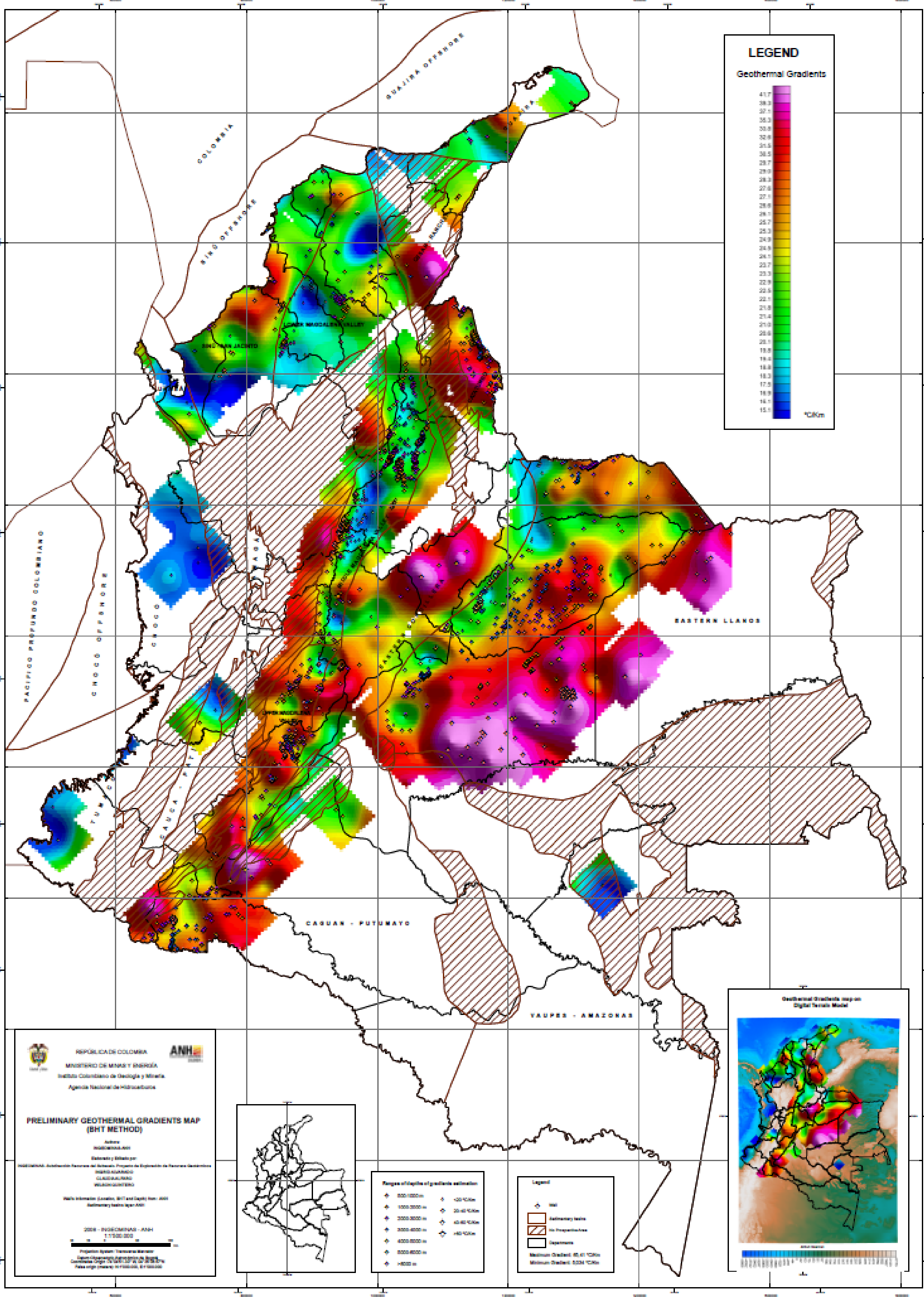

Figure 2. Geothermal Gradients in sedimentary basins of Colombia (INGEOMINAS- ANH, 2008).

Heat flow in the Eastern Llanos Sedimentary Basin.

Previous studies on heat flow were performed by Bachu et al. in 1995 and Moretti et al. in 2009. Bachu et al., (1995) estimated the geothermal gradient in 318 oil wells, between 20 and 50°C/km with a general trend of higher values towards the east of the basin, close to the Precambrian Guyana Shield. Reduction of geothermal gradients with depth was also observed. The spatial variations were attributed to reduction of thermal conductivity with depth, cooling by advection in the center-west of the basin (due to Cretaceous aquifers in Une, Mirador and Guadalupe Formations) and reduction of the heat flow of the basement rocks towards the west. The heat flow estimation done by these authors (Bachu et al., 1995) was based on 17 wells with lithologic logs by following the cumulative thermal resistivity and assuming thermal conductivity values measured in sub-Andean basins of Peru and Bolivia with similar lithology (Henry & Pollack, 1998; Bachu et al., 1995). The heat flow at the top of the Paleozoic was estimated between 29 and 63 mW/m^2 (Figure 3) with a trend similar to the one observed for geothermal gradients; that is increase of the heat flow towards the east and south of the basin.

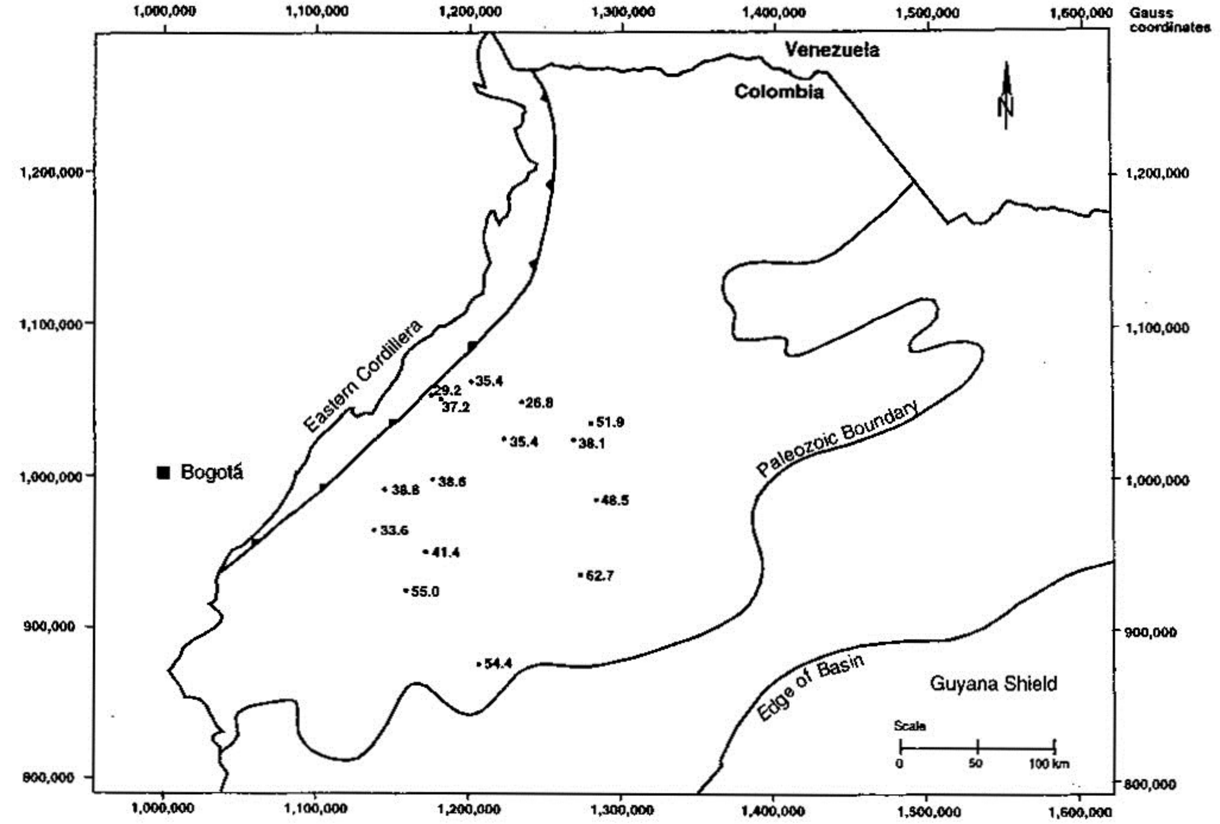

Figure 3. Heat flow (mW/m^2) at the top of the Paleozoic in Easter Llanos Basin. Taken from Bachu et al., 1985.

Later, Morelli et al., (2009) used bottom hole temperature (BHT) information from 40 wells to calculate geothermal gradients between 18.2 °C/km by the foothill, west border of the basin, and 29.2 °C/km towards the east. The heat flow estimation was done automatically by using the software Petromode, from lithological composition, porosity and temperature, in each geological formation. The heat flow was estimated around 40 mW/m^2 in the center of the foothill and 55 mW/m^2 towards the east and south of the basins.

2. METHODOLOGY

On the basis of the observed extension of the geothermal gradient anomaly (Figure 2) in the basin with the oldest basement rocks and the higher tectonic stability in the Colombian territory, the Easter Llanos basin was chosen to recalculate the geothermal gradient from a greater number of wells and to estimate the terrestrial heat flow.

Apparent geothermal gradients and heat flow were calculated assuming the following: (1) the current thermal regime of the Eastern Llanos Basin is steady-state (constant heat flow); (2) the dominant heat transmission mechanism is conduction (the influence of the aquifers was not taken into account); (3) the radiogenic source contained in the sedimentary sequence is insignificant (as it was established by Bachu et al., 1995); (4) the dominant direction of the geothermal gradient is vertical; (5) the topography and erosion process do not have influence on the geothermal gradient nor on the heat flow calculations; (6) the formation temperature can be calculated from the correction of the bottom hole temperature by applying the AAPG experimental formula obtained in wells from Louisiana and Texas Occidental (AAPG, 1976. In Deming, 1989); (7) the geometric mixing model (Brigaud et al. (1990) is valid for calculating the mean thermal conductivity (rock's matrix and saturation fluids); (8) the measurements of thermal conductivity in storage conditions (saturated with air) is representative of the rock's matrix thermal conductivity; (9) the *in situ* fluid of saturation is water; (10) although the thermal conductivity is an anisotropic property, the measurements on the surface of the core samples performed parallel to the dominant direction of the heat flow is representative of the thermal conductivity of the rocks; and (11) the average values of porosity and thermal conductivity assigned to each lithologic level are representative of the whole level.

2.1 Geothermal Gradient

Apparent geothermal gradients were determined for 870 wells by the equation:

$$\frac{\partial T}{\partial z} = \frac{T_{BHT} - T_S}{Z_{BHT}} \tag{1}$$

where $\boldsymbol{T_{BHT}}$ is the corrected bottom hole temperature[1], $\boldsymbol{T_s}$ the surface average temperature[2] and $\boldsymbol{Z_{BHT}}$ the depth of downhole temperature measurement.

2.2 Heat flow estimation by Bottom Hole Temperature (BHT) Method

The heat flow was calculated based on information from 84 deep wells by following BHT method (Carvalho & Vacquier, 1977; Hamza 2008), which can be considered an adaptation of the Bullard's or Cumulative Thermal Resistance method, applicable for single downhole temperatures measurements. The equation for heat flow calculation is as follows:

$$q = \frac{(T_{BHT} - T_S)}{(Z_{BHT} - Z_S)} * \frac{(Z_{BHT} - Z_S)}{\sum_{i=1}^{n} R_i h_i} \tag{2}$$

where $\boldsymbol{q}$ is the vertical heat flow, $\boldsymbol{T_{BHT}}$ is the formation temperature obtained by correction of the bottom hole temperature, $\boldsymbol{T_s}$ is the surface temperature, $\boldsymbol{Z_{BHZ}}$ is the depth of BHT measurement, $\boldsymbol{Z_s}$ is zero (surface), $\boldsymbol{R_i}$, the thermal resistivity of the layer $\boldsymbol{i}$, $\boldsymbol{h_i}$ the thickness of the layer $\boldsymbol{i}$ and $\boldsymbol{n}$, the number of layers. The first term of the right side of equation (2) is the apparent geothermal gradient and the second term is the effective thermal conductivity (inverse of the cumulative thermal resistance).

2.3 Sources of information

The variables used for the estimation of geothermal gradient and heat flow are: well location and depth; estimated surface temperature; measured BHT temperature, depth to the top of the geological formations; and thickness, depth, porosity and thermal conductivity of each textural level of the intercepted geological formations. Location, temperature and depth were obtained mainly from the LogDB and Finder databases provided by the Exploration and Production Information System (EPIS) from the Hydrocarbons National Agency (ANH for its acronym in Spanish). The depth to the top of the geological formations (Guayabo, León, Carbonera, Mirador, Barco - Los Cuervos, Guadalupe, Gachetá, Une and Paleozoic basement) was taken from well logs, also provided by EPIS and from the interpretation of the stratigraphic model of the basin (Fajardo et al., 2000).

Thermal conductivity, as well as volumetric heat capacity (and thermal diffusivity), were estimated by using a portable heat transfer analyzer (ISOMET 2104). The measurement is based on the analysis of the variation of the temperature of the material over time, in response to a heat flow caused by an electrical resistor, in direct contact with the measured material. Surface probes were calibrated by the manufacturer using the determination of the thermal resistance in steady-state through the protected hot plate, according to the norm ISO 8302 technique. Calibration of the instruments was verified by certified standards (granite and marble, with nominal thermal conductivity of 2.68 and 3.87 W/mK) and a secondary standard (glass with thermal conductivity of 1.00 W/mK). Measurements of thermal conductivity were done on around 570 flat surfaces of core samples, dried in storage conditions (20°C), from 47 out of 84 wells, used for the heat flow calculations. Average thermal conductivity values were defined, for each lithology of the geological formations in the stratigraphical sequences found in the wells. The values in the table were assumed as thermal conductivities of the rock's matrix.

The lithological classification and thickness of each level were done qualitatively, mainly based on gamma ray logs. Sandstones were defined below 55 API Units, siltstones between 55 and 95 API Units and claystones, above 95 API Units. Porosity values were taken from petrophysical logs of about 32 wells (ANH-Halliburton-Landmark, 2006), interpreted from density and sonic logs. As in the case of the thermal conductivity, average porosity values were defined, for each lithology for the geological formations in the stratigraphical sequences.

2.4 Calculations

<u>Bulk thermal conductivity</u>

The bulk thermal conductivity of rocks, as a function of the thermal conductivities of the rock´s matrix and fluid saturation, porosity, and temperature, was calculated using the geometric mixing model (Brigaud et al., 1990):

$$\lambda_{1,\,\mathrm{in\,situ}} = \lambda_{mr,t}^{(1-\phi)} * \lambda_{H2O,t}^{\phi} \tag{3}$$

---

[1] $\Delta T = az + bz^2 + cz^3 + dz^4$, where ΔT is the temperature increase in centigrade degrees added to the bottom hole temperature to estimate the formation temperature. $a=1.878x10^3$; $b=8.46x10^{-7}$; $c=-5.091x10^{-11}$ and $d=-1.681x10^{-14}$ (AAPG, 1976 in Deming, 1989).

[2] $Ts = 28.2 - (0.005*h)$, where h is elevation of the surface in meters (IDEAM, 2008).

where $\lambda_{i,\ in\ situ}$ is the bulk thermal conductivity of lithological level ***i*** at in situ conditions (at formation temperature), $\lambda_{mr,\ t}$ the thermal conductivity of the rock's matrix at formation temperature ***t***, φ the porosity and $\lambda_{H2O,t}$ the thermal conductivity of the water at formation temperature ***t***.

The thermal conductivity of the rock's matrix was corrected to in situ temperature conditions with the following equation (Chapman et al., 1984):

$$\lambda_{\text{mr, t}} = \lambda_{\text{mr, 20°C}} \frac{293}{273+t} \quad (4)$$

where $\lambda_{mr,t}$ is the thermal conductivity of the rock´s matrix of layer **i** at the formation temperature, $\lambda_{mr,20°C}$ the thermal conductivity of the same rock's matrix at 20°C (measuring temperature), **293** is 20°C in Kelvin, **273** the conversion factor to absolute temperature and **t** the formation temperature in degrees Centigrade.

Also the thermal conductivity of the water, assumed as saturation fluid, was corrected to the conditions of the stratigraphical level using the following equations (Deming & Chapman, 1988; Bachu et al., 1995):

$$\lambda_{\text{H2O,t}} = 0.5648 + 1.878 * 10^{-3}\ \text{t} - 7.231 * 10^{-6} t^2 \quad (5)$$

for $0 \leq t \leq 137°C$ and,

$$\lambda_{\text{H2O,t}} = 0.6020 + 1.309 * 10^{-3}\ \text{t} - 5.14 * 10^{-6} t^2 \quad (6)$$

for $0 \leq t \leq 300°C$.

Cumulative thermal resistance

The cumulative thermal resistance was calculated for the whole lithologic column using the following equation

$$R_c = \sum_{i=1}^{n} \Delta Z_i / \lambda_i \quad (7)$$

where Rc is the cumulative thermal resistance, ΔZi the thickness of layer i defined by top and bottom depths of the lithologic level, and λi the bulk thermal conductivity of layer ***i*** corrected to in situ conditions.

Heat flow

Based on the product of Z_{BHT}, the depth of downhole temperature measurement and Rc, the cumulative thermal resistance, the effective thermal conductivity was calculated. Finally, the heat flow was calculated by the product between effective thermal conductivity and apparent geothermal gradient.

3. RESULTS

3.1 Geothermal gradients

The estimation of apparent geothermal gradients was based on downhole temperatures between 42°C and 179°C and depths between 515 m and 6273 m, as illustrated in the Figure 4. The highest temperature of 179°C was measured at 5319 m (Cumaral 1AX well).

The apparent vertical geothermal gradients range between 8°C/km and 59°C/km with a mean value of 28.82°C/km. Negative anomalies determined from the mean and standard deviation values below 16°C/km, were found in 13 wells located towards the western border of the basin, with depths above 3000 m. Positive anomalies, with gradients above 42.15°C/km, were calculated in 42 wells with depths lower than 1550 m, located mainly towards the east and southeast, as it is shown in Figure 5.

The spatial distribution of the geothermal gradients, with a remarkable increase towards east and south, confirm the observations of previous studies (Bachu et al. 1995; INGEOMINAS, 2000; and Moretti et al, 2009). The geothermal gradients for depths lower that 500 m were rejected as a result of very high and doubtful values, probably due to the effect of climate changes up to 300 m, as proposed by Stein (1995) or due to the influence of topography and erosion, which normally affect depths up to 500 m (Jeffreys, 1937; Lachenbruch, 1968; and Hamza, 2009).

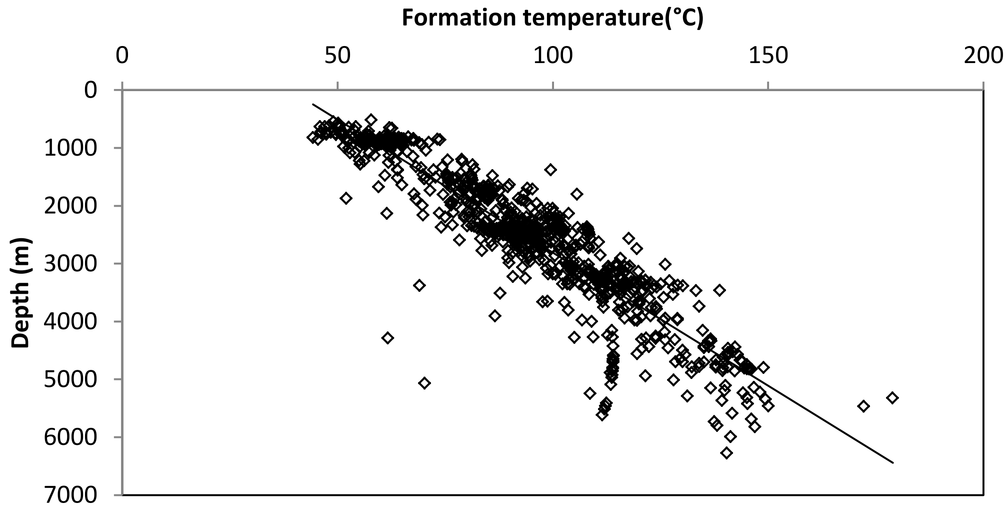

Figure 4. Variation of the bottom hole temperature with depth in wells of Eastern Llanos Basin.

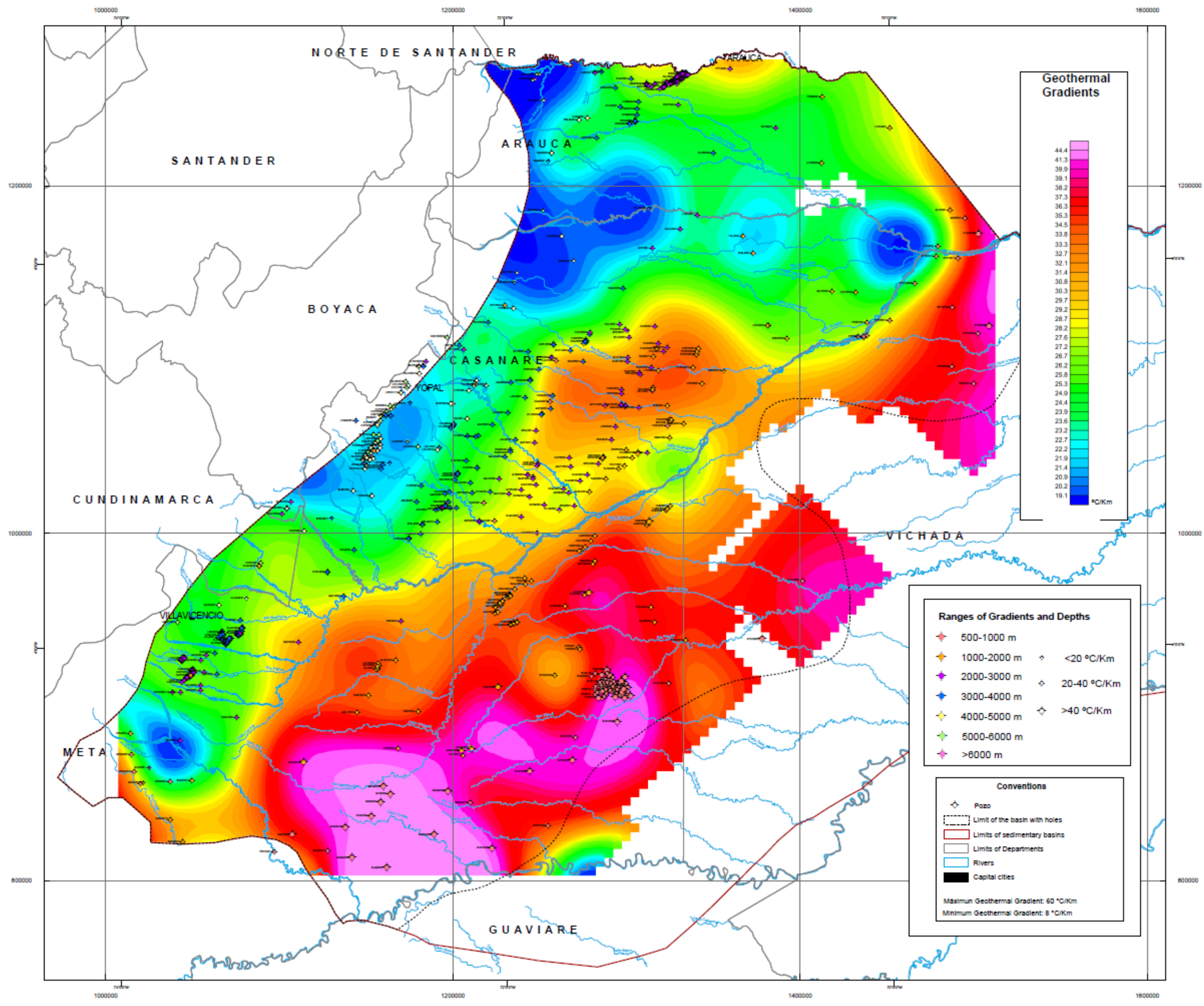

Figure. 5. Map of Geothermal Gradients of Eastern Llanos Basin. A clear trend of the increase of the geothermal gradients towards the east and south of the basin is observed.

3.2 Heat flow

A general trend to increase the thermal conductivity from claystones to sandstones was observed in most of the geological formations as indicated in Table 1. The mean values calculated for the three lithologies without differentiating by geological formation illustrate that trend: sandstones, 3.31 W/mK; siltstones, 2.85 W/mK and claystones, 1.90 W/mK. However, as observed before (Beardsmore & Cull, 2001) a high dispersion was found (variance of 1.17 for a mean value of 3.31 W/mK for sandstones, variance of 0.63 for a mean value of 2.85 W/mK, for siltstones and variance of 0.66 for a mean value of 1.9 W/mK, for claystones. The reference values, most of them equivalent to mean values, shown in the Table 1, were used as rock's matrix thermal conductivities for the heat flow calculation. As core samples for all the lithologies were not available, some of the reference values indicated in the table by an asterisk, were obtained by interpolation in a correlation observed between lithologies and rocks ages.

Table 1. Mean thermal conductivities for geological formations from laboratory measurements. Core samples from Easter Llanos Basin.

	Thermal conductivity (W/mK)		
Geological Formation	Sandstones	Siltstones	Claystones
Guayabo	1,88	1,63 *	1,26
León	1,55	1,88 *	1,37 *
Carbonera	2,03	1,77	1,52
Mirador	2,76	2,73	1,84 *
Los Cuervos	3,02 *	2,73 *	2,16 *
Barco	3,21 *	2,88 *	2,30 *
Guadalupe	4,11	3,12	2,43
Gachetá	3,37	3,06	2,73
Une	3,83	3,62	2,93
Paleozoic	4,88	2,51	1,61

The calculated average effective thermal conductivity (for the lithologic columns) ranges between 1.12 W/mK and 1.56 W/mK. From this and the apparent geothermal gradients, the average heat flow calculated for the Eastern Llanos basin is 36.95 mW/m^2, in a range between 19.9 and 81.5 mW/m^2.

Based on mean and standard deviation values, positive heat flow anomalies are identified above 55.9 mW/m^2. The spatial distribution of the heat flow is presented in Figure 6. The color palette of the map is consistent with the global heat flow map[3]. An increase of the heat flow occurs towards the south and southeast of the area following the same trend observed for the geothermal gradients. The highest values are found in the wells SM-8, Rubiales-10, Manacacias-1 and Las Brujas-1, located with depths between 860 m and 1196 m.

[3] http://www.geophysik.rwth-aachen.de/IHFC/heatflow.html

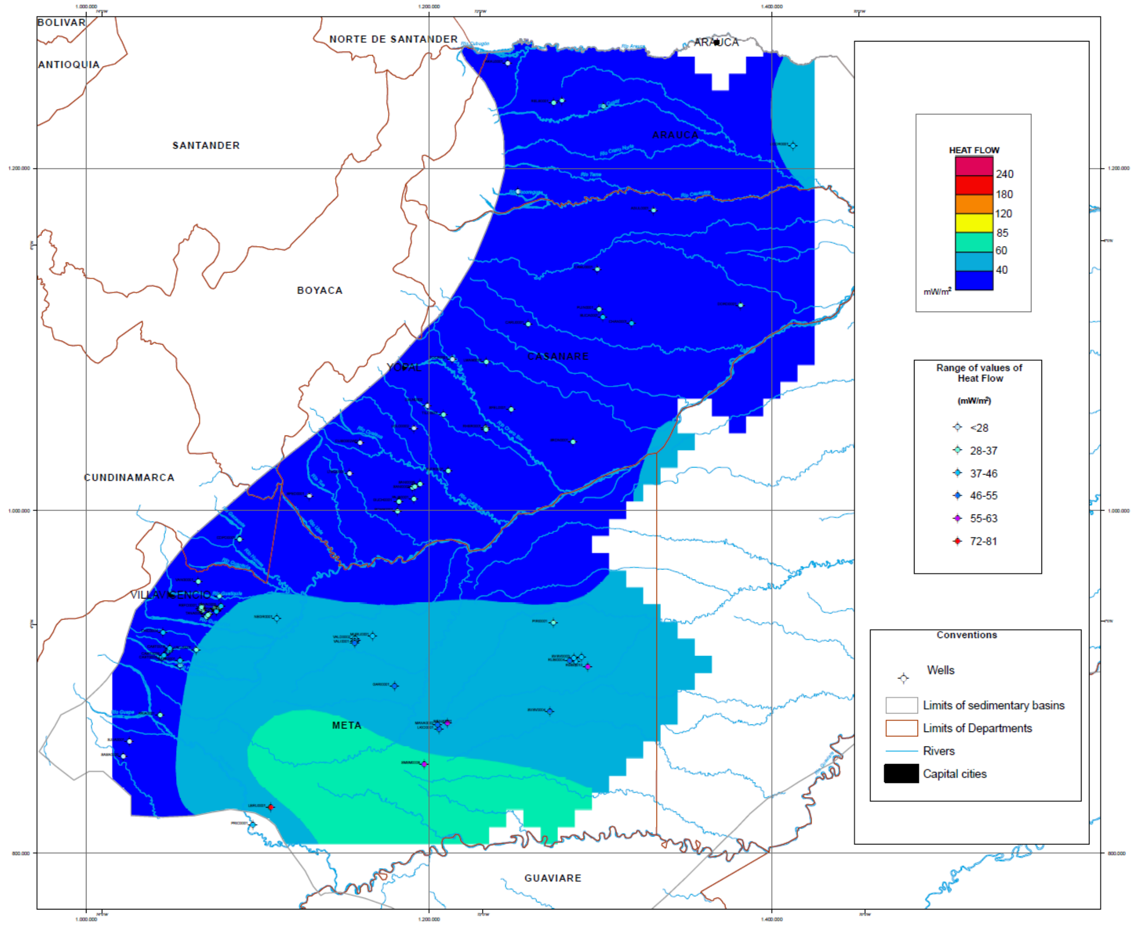

Figure 6. Heat flow map of the Easter Llanos basin. Similar as for the geothermal gradient, there is a trend for the heat flow to increase towards the South (and possibly to the East) of the basin.

4. CONCLUSIONS

The distribution pattern of the apparent geothermal gradients suggests a relation of this variable with the geometry of the basin. It varies between 8°C/km and 59°C/km with a mean value of 27.9°C/km with an increase towards the east and south of the basin. This pattern seems to be followed by the heat flow. More data are required to confirm these observations.

Heat flow in the Eastern Llanos Basin was estimated for 84 wells between 20 and 81 mW/m^2, with a mean value of 37 mW/m^2. By the western border of the basin where the sedimentary sequence is thickest (up to 8 km), the heat flow ranges between 20 and 46 mW/m^2. Towards the south where the sedimentary sequence is thinner (1 to 2 km) the heat flow magnitude is higher: 46 to 81 mW/m^2. The heat flow map illustrates the described trend and the signs of a tendency to increase also towards the east. However the information is too limited to be representative of a basin with a drilled area of about 100.000 km^2.

The heat flow values estimated for Eastern Llanos Basin are normal if they are compared with 65 mW/m^2 (σ_q= 25), the mean average value in the continental crust (Pollack et al.,1993) and with 50-60 mW/m^2, the heat flow calculated for sub-Andean sedimentary basins from Perú and Bolivia (Henry & Pollack, 1988), which are considered by Bachu et al. 1995, as similar in lithology and evolution to the Eastern Llanos Basin. However from the statistical distribution the heat flow values above 56 mW/m^2 could be considered anomalous (mean of 37 mW/m^2 with a standard deviation of 9.6). On the other hand some of the estimated values could also be considered anomalous if they are compared with 42 mW/m^2 (σ =10), the heat flow value established for Precambrian shields (Hamza, 2008).

From direct measurements, the effective thermal conductivity was estimated in the range 1.1 to 1.5 Wm^{-1}K^{-1} in the sedimentary sequence while the basement, located shallower towards the east and south of the study area, it was estimated to be 5.5 Wm^{-1}K^{-1}. The heat flow distribution trend could be a consequence of basement thermal refraction (Beardmore & Cull, 2001), related to the distribution and differences in thermal conductivities. However the heat flow is not always higher in wells where the basement is shallower as it was observed in 4 wells located northeast (Dorotea-1), at the center (Gariby-1) and west of the basin (Castilla 12 and 18), which reach the basement and have a normal heat flow.

The relatively low mean effective thermal conductivity (1.51 W/mK), is likely related to the high porosity, of sandstones mainly, ranging between 4 and 27% with an average of 16% and thick claystones levels.

An increase of the thermal conductivity with the burial age of the geological formations and with the textural change from claystone to sandstone, were observed for this work's set of data.

A preliminary approximation of the heat flow was done for the Eastern Llanos Basin. The implementation of the methodology for more precise and reliable calculations of the terrestrial heat flow demands more information, integration and improvement of processing and specific studies. Some of the identified requirements include the increase of number of wells, improvement of the estimation of formation temperatures, temperature logs (profiles), corrections of the geothermal gradients (by topography, sedimentation and erosion), thermal conductivity measurements by following the procedure of samples drying and water saturation (Brigaud et al, 1990), automation of processing and interpretation of well logs to determine porosity and saturation, modeling of heat flow by advection, studies of thermal refraction of the basement, anisotropy of thermal conductivity and correlation between measurements of thermal conductivities and physical parameters, from well logs, to model e.g. thermal conductivity logs.

5. ACKNOWLEDGMENTS

The authors would like to thank ANH, EPIS and Pacific Rubiales Energy, for the provision of information and for the permission to access to core samples for thermal conductivity measurements. Thanks also to Dr. Valiya Hamza form the National Observatory of Brazil for his assessment in the initial stage of the project, in practical aspects of thermal conductivity measurements in rocks and in the calculations involved in the heat flow estimation. Finally, the authors thank Juan David Hincapié for his contribution to the information review on thermal conductivity of rocks.

REFERENCES

Alfaro, C. (Ed.): Mapa Geotérmico de Colombia. Memoria explicativa. Versión 1.0. Escala 1:1'500.000. INGEOMINAS. Bogotá. (2000). 35 p.

Alfaro, C., Alvarado, I., Quintero, W., Hamza, V., Vargas, C., and Briceño, L.: Mapa preliminar de gradientes geotérmicos de Colombia. Memorias. XII Congreso Colombiano de Geología. Paipa, Boyacá. (2009) 18 p.

Alfaro, C., Alvarado, I., Manrique, Quintero, W: Mapa preliminar de Flujo de Calor Terrestre en la Cuenca de los Llanos Orientales. INGEOMINAS. Informe Técnico. Bogotá. (2010). 95 p.

ANH-HALLIBURTON-LANDMARK. Estudio integrado-Crudos pesados. Registros Petrofísicos. (2006).

Bachu, S.; Ramon, J. C.; Underschultz, J.; Villegas, M.: Geothermal Regime and Thermal History of the Llanos Basin, Colombia. AAPG Bull. 79 (1), (1995), 116-129.

Barrero, D.; Pardo, A.; Vargas, C.; Martinez, J.: Colombian Sedimentary Basins: Nomenclature, Bundaries and petroleum Geology, a New proposal. Edited and compiled by: ANH and B&M Exploration Ltda. Bogotá. (2007). 91 p

Beardsmore, G. & Cull, J.: Crustal heat flow. A guide to measurement and modeling. Cambridge University Press. (2001). 324 p.

Brigaud, F., Chapman D. S., Le Douran S.: Estimating thermal conductivity in sedimentary basins using lithologic data and geophysical well logs: AAPG Bull. 74 (9). (1990). 1459-1477.

Fajardo, A.; Cristancho, J.; Rojas, L.: Definición del modelo estratigráfico en la Cuenca Llanos Orientales y Piedemonte Llanero. Instituto Colombiano del Petróleo. Informe interno. Piedecuesta – Santander, Colombia. (2000). 200 p

IDEAM: Temperatura Media Máxima y Mínima. (2008). Available at http://www.ideam.gov.co/atlas/mclima.htm. (December 2008)

INGEOMINAS – ANH: Mapa preliminar de gradientes geotérmicos (Método BHT). 1:1'500.000. (2008).

Deming, D.: Application of bottom-hole temperature corrections in geothermal studies. Geothermics, Vol. 18. No. 5/6, (1989). pp. 775-786.

Geoenergía Andina (GESA) SA and Desingpower GENZL: Nevado del Ruiz Geothermal Prospect. Nereidas Exploration. (1997).

Hamza, v.: The thermal state of the Earth. Handouts of the short course carried out for INGEOMINAS and ANH. 246 p. Bogotá. (2008)

INGEOMINAS. Mapa geotérmico de Colombia. Escala 1: 1'500.000. V.1.0. (2000)

Moretti, I.; Mora, C.; Zamora, W.; Valencia, M.; Mayorga, M.; Rodríguez, G.: Petroleum System Variations in the Llanos Basin (Colombia). 8 p. (2009). Available at (http://www.simposiobolivariano.org/WEB2/memorias/download.ph). (October 2009)

Vargas, C.: Características Cuenca de los Llanos Orientales y descripción de bloques. Taller para empresas precalificadas proceso licitatorio Proyecto DCO-Zona Oriental. 25 p. (2008). Available at www.anh.gov.co/privados/base_datos.pdf. (October 2009.