CURIE POINT DEPTH IN THE COLOMBIAN TERRITORY

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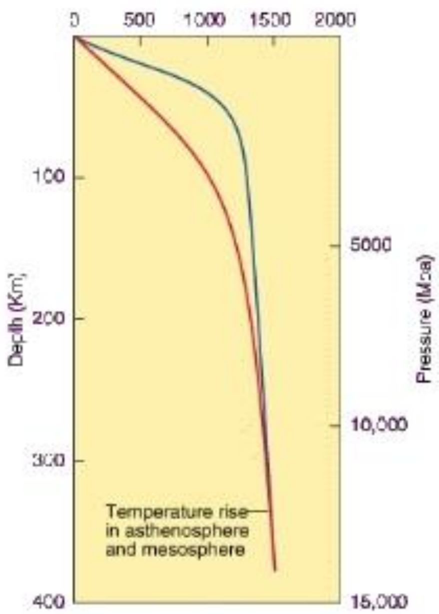
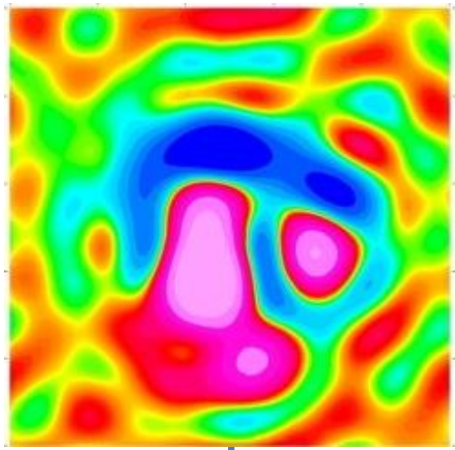
Introduction

Spatial variation of the temperature as approach to the study of the thermal field structure



Direct measurements

Curie Point (CP) is defined as the temperature at which any material loses its capability to acquire permanent magnetism

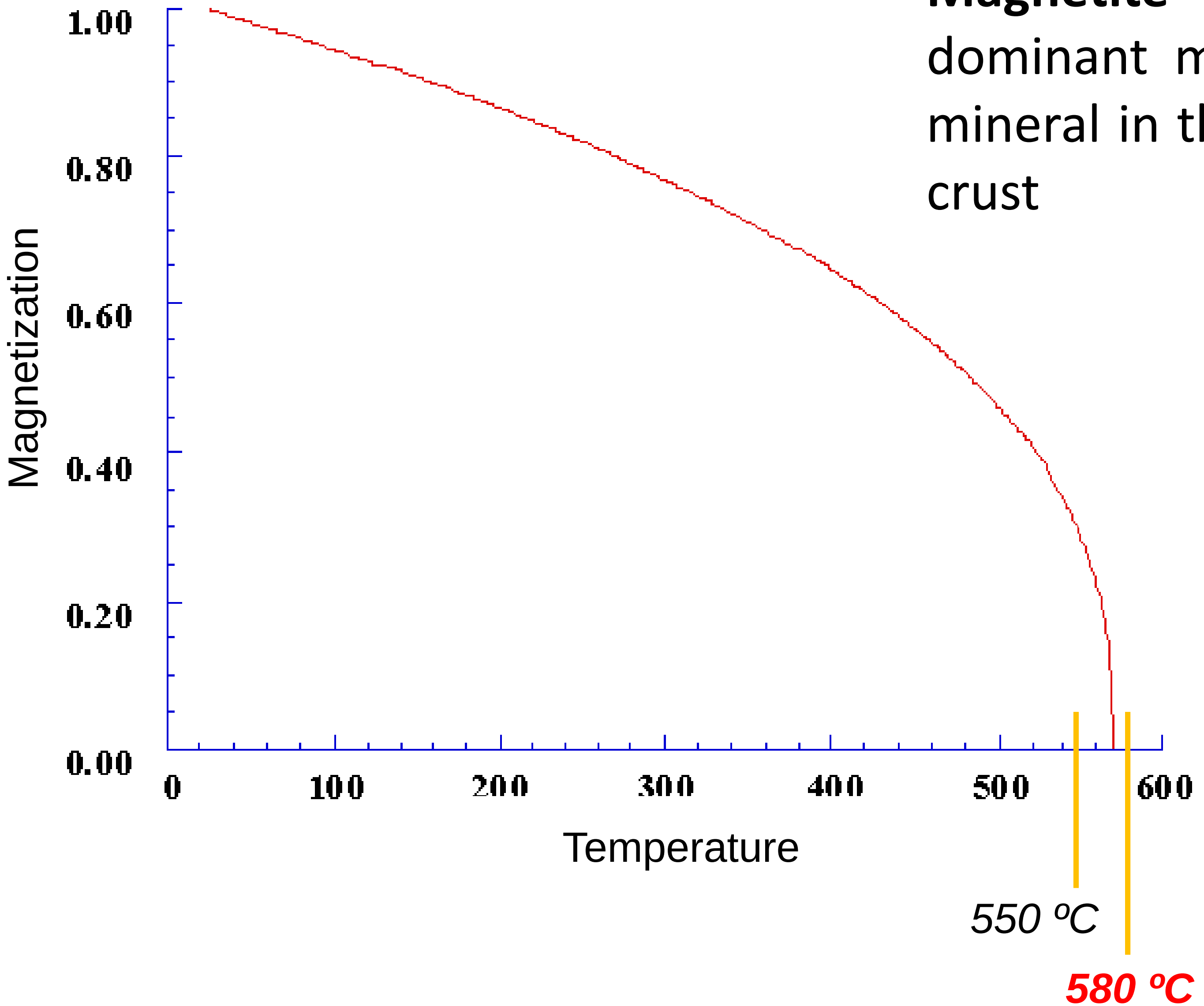


Inversion of magnetic data

Ferromagnetic minerals become paramagnetic by increasing the temperature: **Curie Point Depth (CPD)**

Compositional change from magnetic to non-magnetic rocks: **MOHO discontinuity**

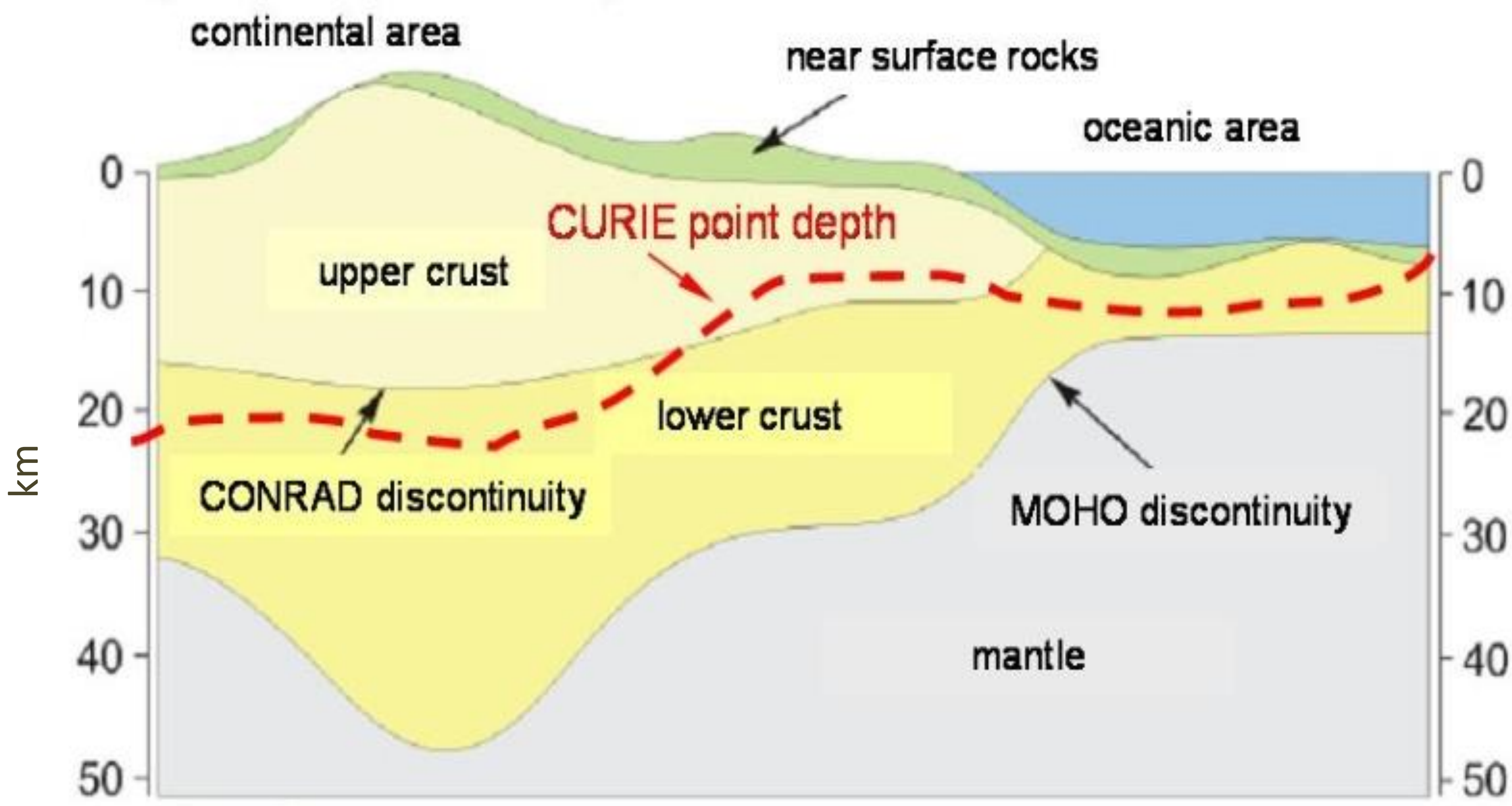
Introduction



Magnetite is the dominant magnetic mineral in the deep crust

Introduction

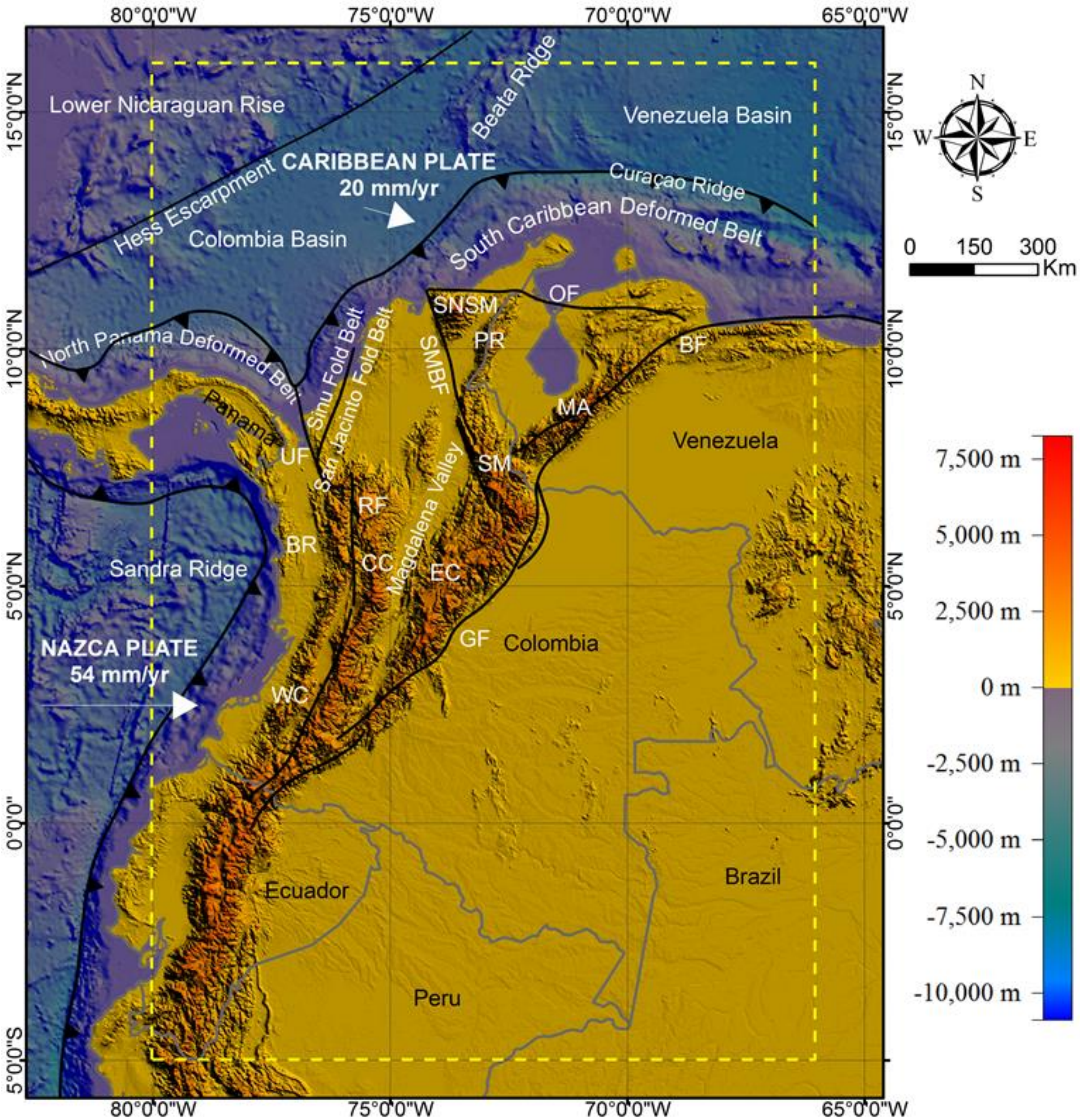
CPD is highly variable: It depends on the geothermal gradient and heat flow of a specific region



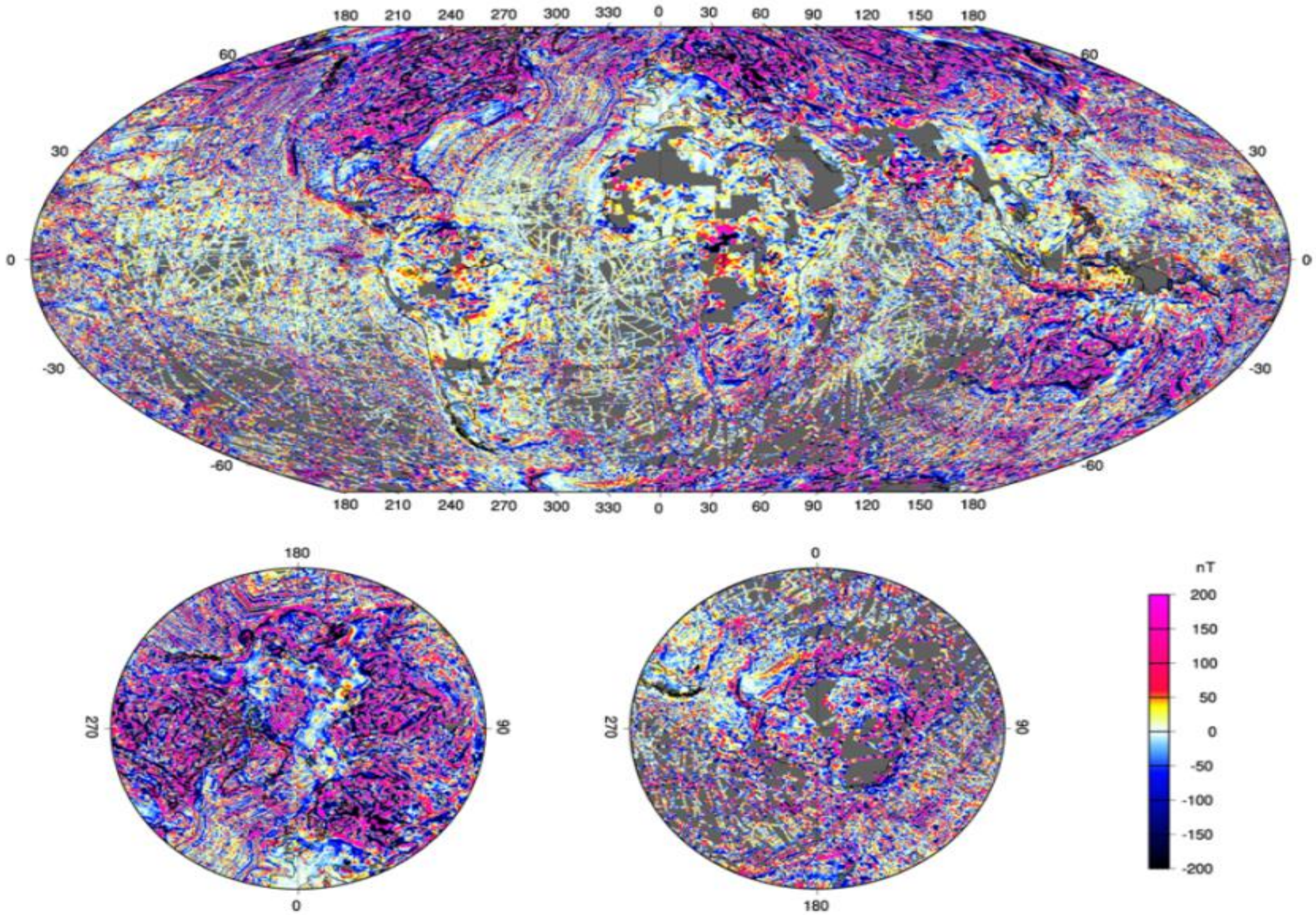
Introduction

REGION	TECTONIC SETTING	HEAT FLOW (mW/m^2)	GEOTHERMAL GRADIENT (°C/km)	Obtained CPD (km)	SOURCE
Baja California, Mexico	Divergent	100	33-38	14-17	Espinosa-Cardeña and Campos-Enriquez (2008)
Jordan	Divergent-Convergent	16-123	11-94	10-35	Al-Zoubi (1992)
Great Valley, USA	Convergent	25-55		36-250	Bouligand et al. (2009)
Azerbaijan	Convergent	33-104	20-43	18-42	Pilchin (1983)
Basin and Range Province, USA	Convergent	35-105	25-45	22	Blackwell (1971)
Eastern USA	Intraplate	35-63	15-25	37	Blackwell (1971)
Armenia	Convergent	38-157	30-100	6-12	Badalyan (2000)
Sinai Peninsula, Egypt	Divergent-Convergent	40-104		15-25	Aboud et al. (2011)
Western Anatolia, Turkey	Convergent	40-140		6-22	Salk et al. (2005)
Western Cascades, USA	Convergent	40-50		41-63	Bouligand et al. (2009)
Bulgaria and south Romania	Convergent	43-90		14-35	Trifonova et al. (2009)
El Barramiya-Red Sea coast, Egypt	Divergent-Convergent	44-84		22-44	Abd El Nabi (2012)
Colorado Plateau, USA	Convergent	60		32	Bouligand et al. (2009)
Ontario, Canada	Intraplate			9-16	Bhattacharyya and Morley (1965)
Yellowstone, USA	Intraplate			4-22	Shuey et al. (1977)
Quseir, Egypt	Divergent			10	Salem et al. (2000)
Kyushu, Japan	Convergent			6.5-15	Okubo et al. (1985)
Indian subcontinent	Convergent			22.9-52.9	Rajaram et al. (2009)
Israel and Palestinian Autonomy	Convergent			40-46	Eppelbaum and Pilchin (2006)
Northern and eastern Turkey	Convergent			20-29	Ibrahim et al. (2005)
Aegean region, Turkey	Convergent			6-10	Ibrahim et al. (2005)
Island of Crete, Greece	Convergent			24-28	Tsokas et al. (1998)
Albania	Convergent			17-25.5	Stampolidis et al. (2005)
Sulu region, China	Convergent			18.5-27	Qingqing et al. (2008)
Portugal	Pasive			20-50	Okubo et al. (2003)
Cuyo Precordillera, Argentina	Convergent			29-40	Ruiz and Introcaso (2004)
Sierras Pampeanas, Argentina	Convergent			20-35	Ruiz and Introcaso (2004)
Venezuela and Eastern Caribbean	Convergent			17-54	Arnaiz-Rodríguez and Orihuela (2013)
Central Nigeria	Pasive			2-8.4	Eletta and Udensi (2012)
Anambra basin, Nigeria	Pasive			16-30	Onwuemesi (1997)
Japanese islands	Convergent			11-30	Tanaka and Ishikawa (2005)

Study Zone

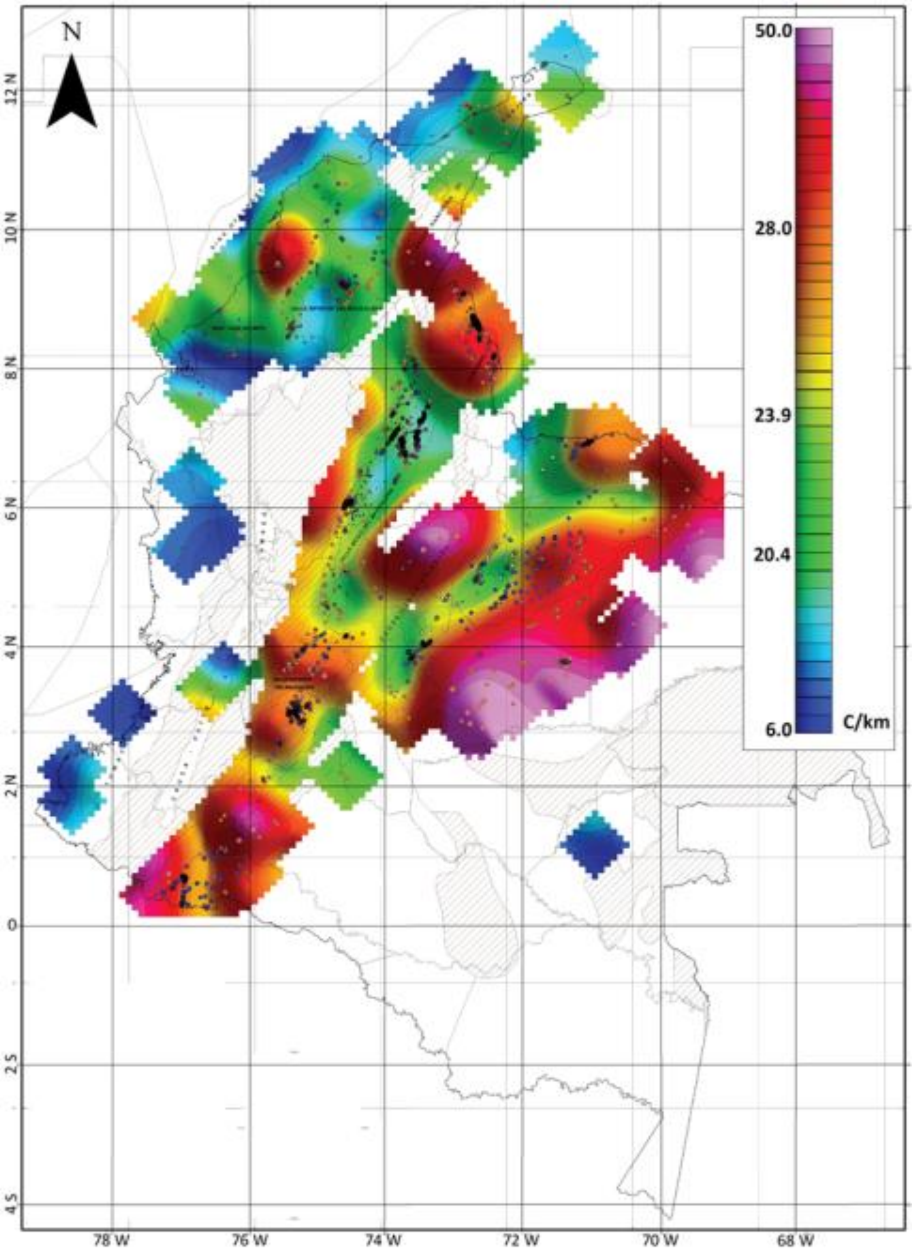

80°0'0"W
75°0'0"W
70°0'0"W
65°0'0"W
15°0'0"N
10°0'0"N
5°0'0"N
0°0'0"
5°0'0"S
Lower Nicaraguan Rise
Beata Ridge
Venezuela Basin
CARIBBEAN PLATE
20 mm/yr
Hess Escarpment
Curaçao Ridge
Colombia Basin
South Caribbean Deformed Belt
North Panama Deformed Belt
Panama
Sinu Fold Belt
San Jacinto Fold Belt
SNSM
OF
PR
SMBF
BF
MA
UF
SM
Venezuela
RF
Magdalena Valley
BR
CC
EC
Sandra Ridge
GF
Colombia
NAZCA PLATE
54 mm/yr
WC
Ecuador
Brazil
Peru
N
S
W
E
0 150 300
Km
7,500 m
5,000 m
2,500 m
0 m
-2,500 m
-5,000 m
-7,500 m
-10,000 m

Data: Magnetic Anomalies



World Digital Magnetic Anomaly Map-WDMAM (Maus et al., 2007) – Global 3-arc-minute resolution grid of the anomaly of the magnetic intensity at 5 km above mean sea level

Data: Geothermal Gradient



Geothermal gradient controlled data taken from the **Geothermal Gradient Map of Colombia** (Vargas et al., 2009)

Methods: CPD estimation

Two important issues to have in mind:

- The CPD is detectable due to the effect of the upper part of the magnetic source, which dominates the signal from the bottom of the source
- Magnetic anomalies caused by the bottom of the magnetic source have longer wavelengths compared to the signals from the top of the source

Blakely (1995) introduced the concept of Power Spectrum Density of the magnetic anomalies $\boldsymbol{\phi_{\Delta T}}$, as:

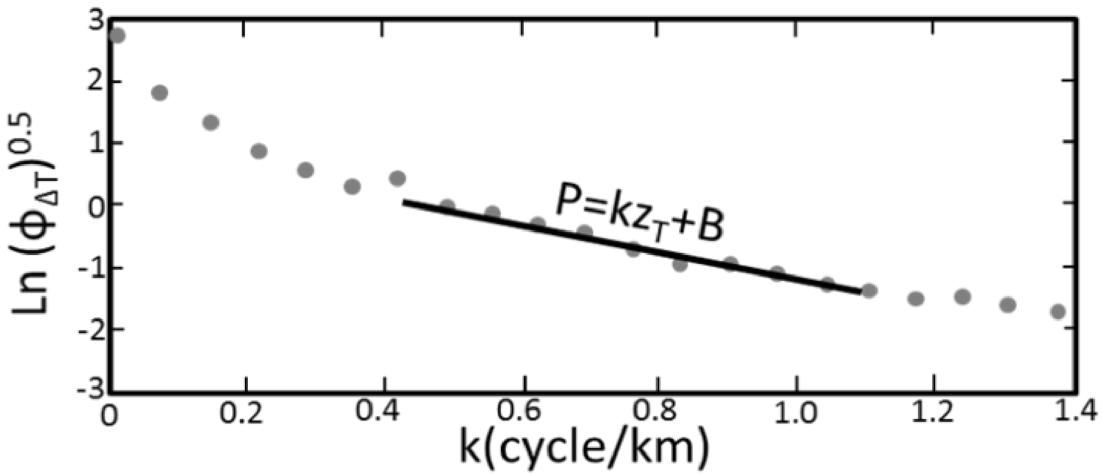
$$\boldsymbol{\phi_{\Delta T}}(k_x, k_y) = \boldsymbol{\phi_M}(k_x, k_y).\boldsymbol{F}(k_x, k_y)$$

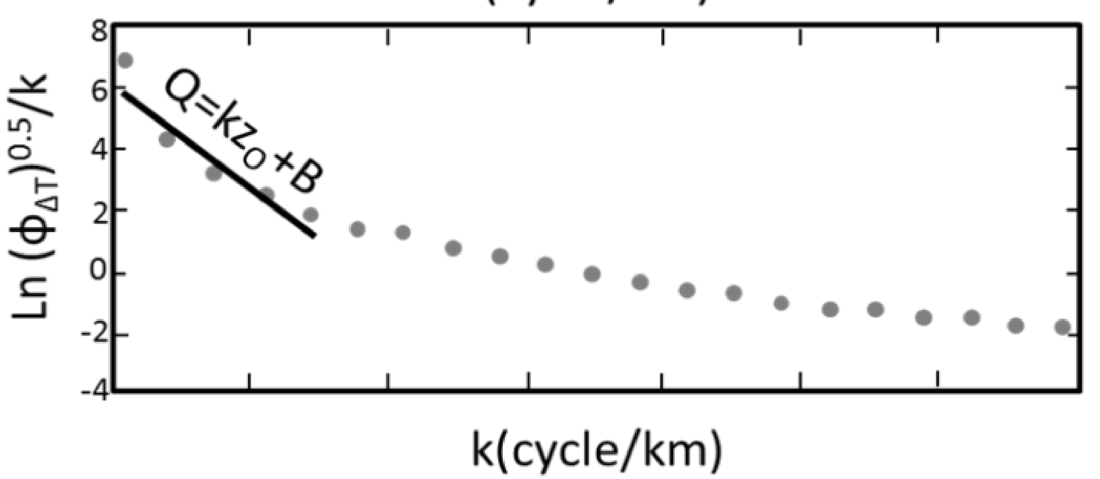
$$\boldsymbol{F}(k_x, k_y) = 4\pi^2 C^2 |\theta_m|^2 \left|\theta_f\right|^2 e^{-2|k|Z_T}.\left(1 - e^{-|k|(Z_C - Z_T)}\right)^2$$

$\boldsymbol{\phi_M}$ power spectral density of magnetization; $\boldsymbol{k_x}$ and $\boldsymbol{k_y}$ are the wave numbers along the coordinates $\boldsymbol{x}$ and $\boldsymbol{y}$; $\boldsymbol{C}$ is proportionality constant; $\boldsymbol{\theta_m}$ and $\boldsymbol{\theta_f}$ are factors of the direction of magnetization and the direction of the geomagnetic field respectively

Methods: CPD estimation

The depth to the top and the centroid of the magnetic source can be estimated by fitting a straight line through the upper and lower parts of the wave number and the radially averaged spectrum (Okubo et al., 1985)





Finally, the **depth to the bottom of the magnetic layer** (or CPD) can be obtained from the expression (Okubo et al., 1985):

$$Z_C = 2Z_O - Z_T$$

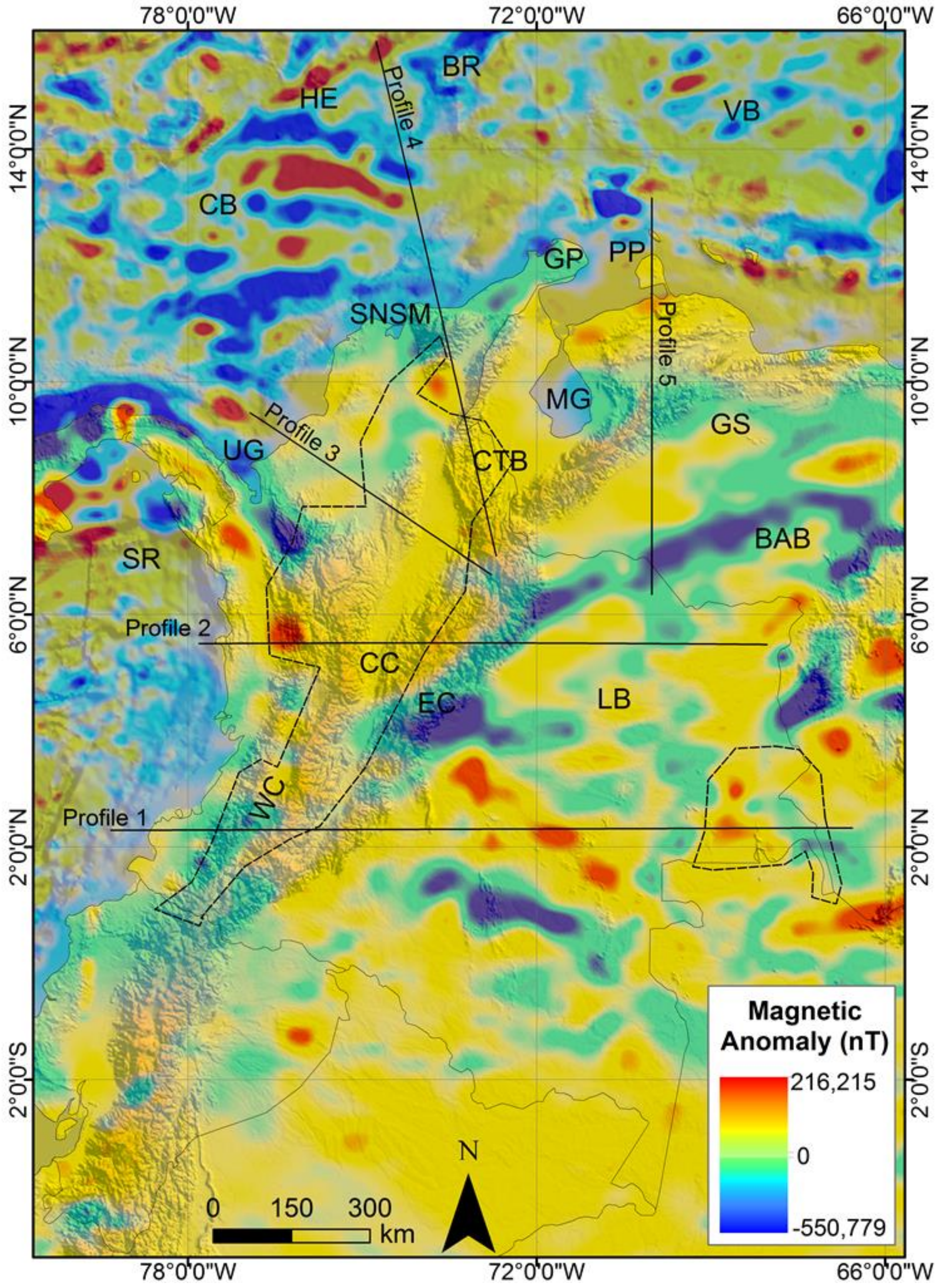
Methods: CPD estimation

The study zone was divided into a number of square windows such that could ensure the dimension criterion of **4 to 6 times the depth of the target**, as suggested by Okubo et al. (1985)

Since the database of magnetic anomalies has a resolution of 5.6 km, **we evaluated different sized windows** seeking to establish the best response to the above procedure: 302 km x 302 km, 325 km x 325 km, 372 km x 372 km, 406 km x 406 km, and 441 km x 441 km

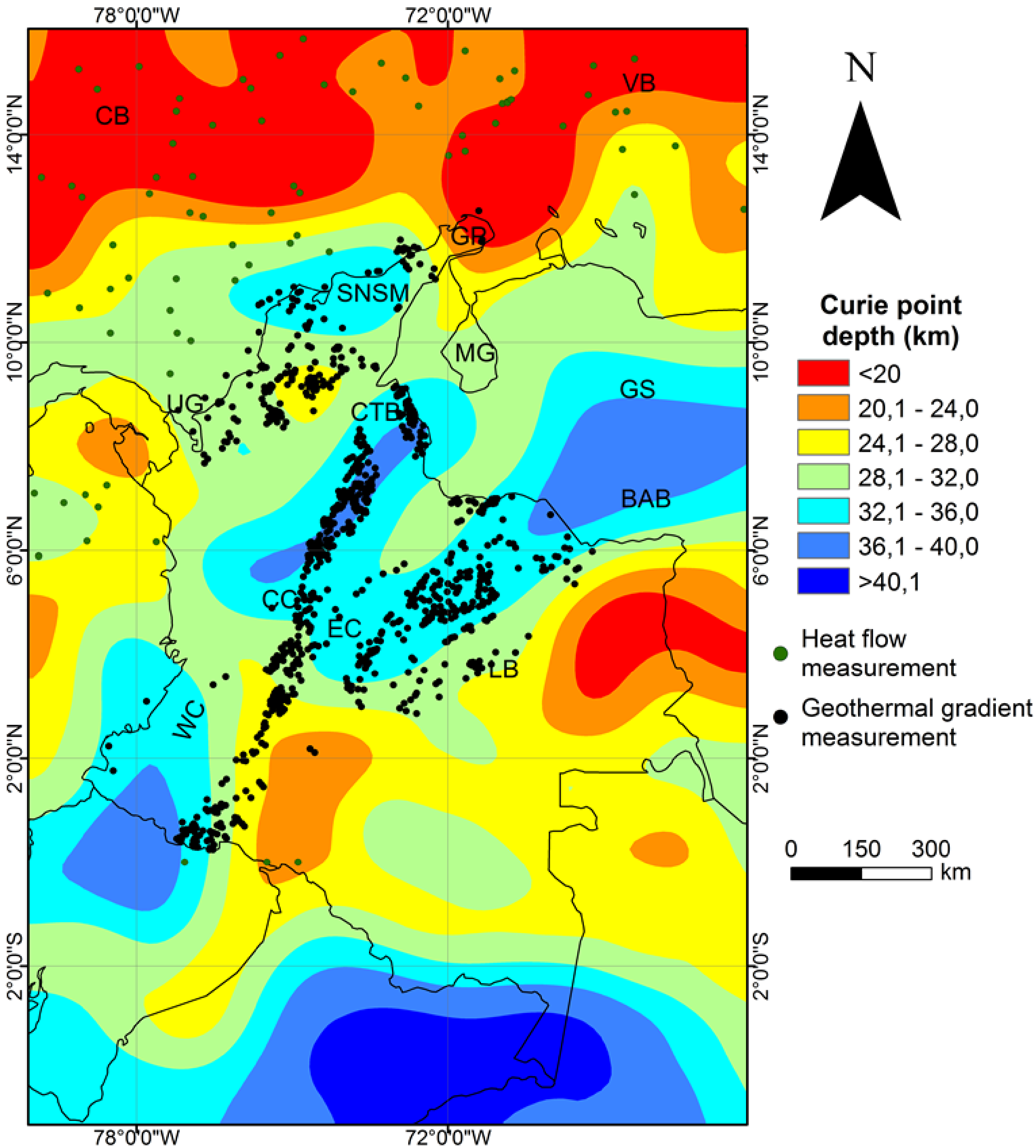
Analysis of the power spectrum in each window allowed us to calculate the depth to the bottom of the magnetic source, that is, the CPD. This procedure was repeated by **moving the window with steps of 5.6 km** in the entire area for the set of the available data

Results: Magnetic Anomalies



- Offshore area: **NE-SW anomalies** related to Hess escarpment, Beata Ridge and Venezuela Basin. **E-W anomalies** in Colombia basin and South Panama
- Onshore area: **NW-SE**, **NE-SW and E-W positive and negative anomalies** in Eastern Cordillera, and Eastern Llanos, Vaupés-Amazonas, Caguán-Putumayo, and Barinas-Apure basins

Results: Curie Point Depth (CPD)

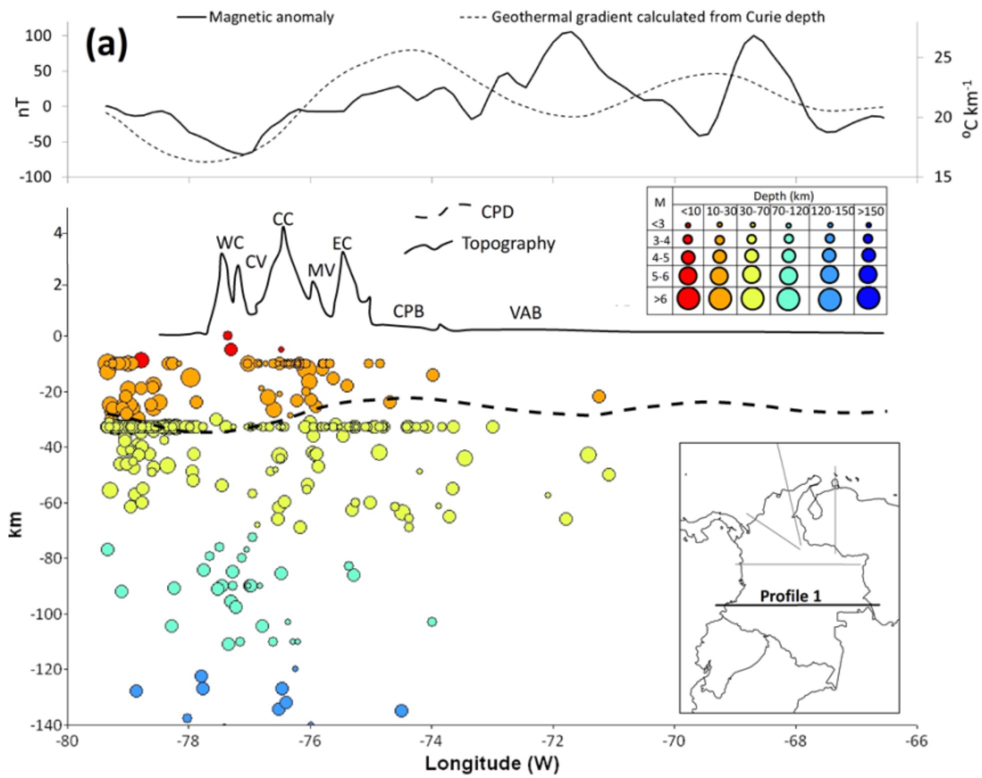


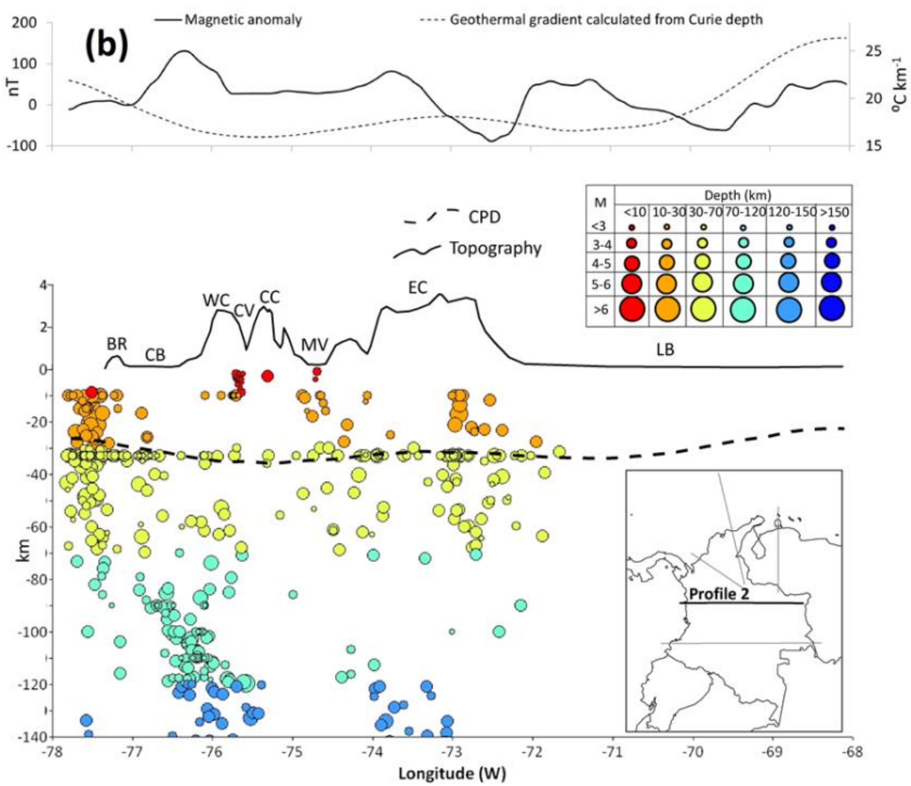
The lowest values (<20 km) in the Caribbean plate, corresponding to the Venezuela and Colombia basins. Inland, an E-W elongated trend east of Eastern Llanos basin

The intermediate values (20-32 km) in the Colombian and Venezuelan Caribbean. N-S oriented trends in the Pacific region. Also Eastern Llanos, Caguán-Putumayo and Vaupés-Amazonas basins

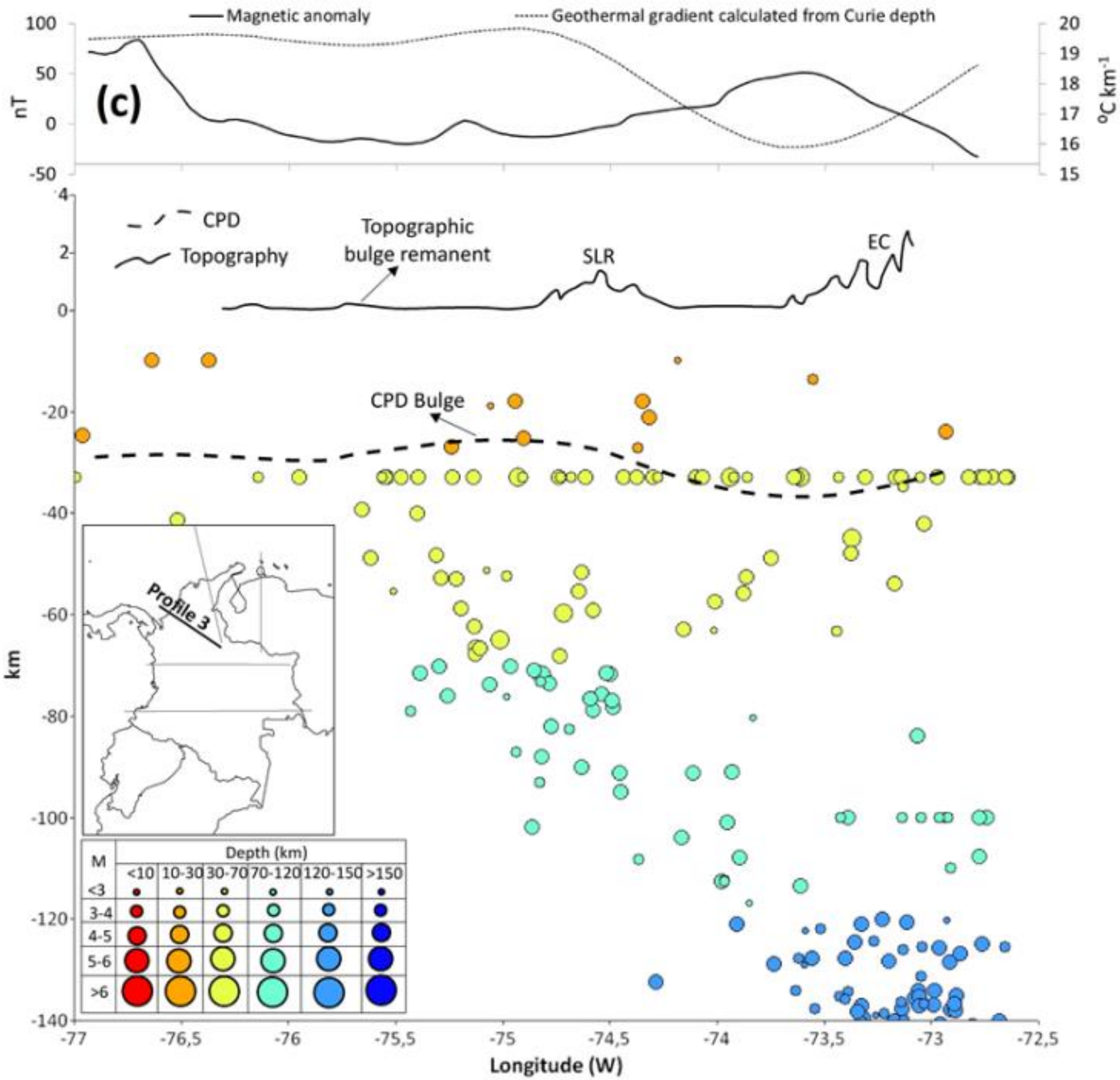
The highest values (>32 km) associated with two NE-SW oriented trends in central and eastern sectors of the study zone. Also in Pacific region, Santa Marta massif and Vaupés-Amazonas basin

Results: CPD and other geophysical observations

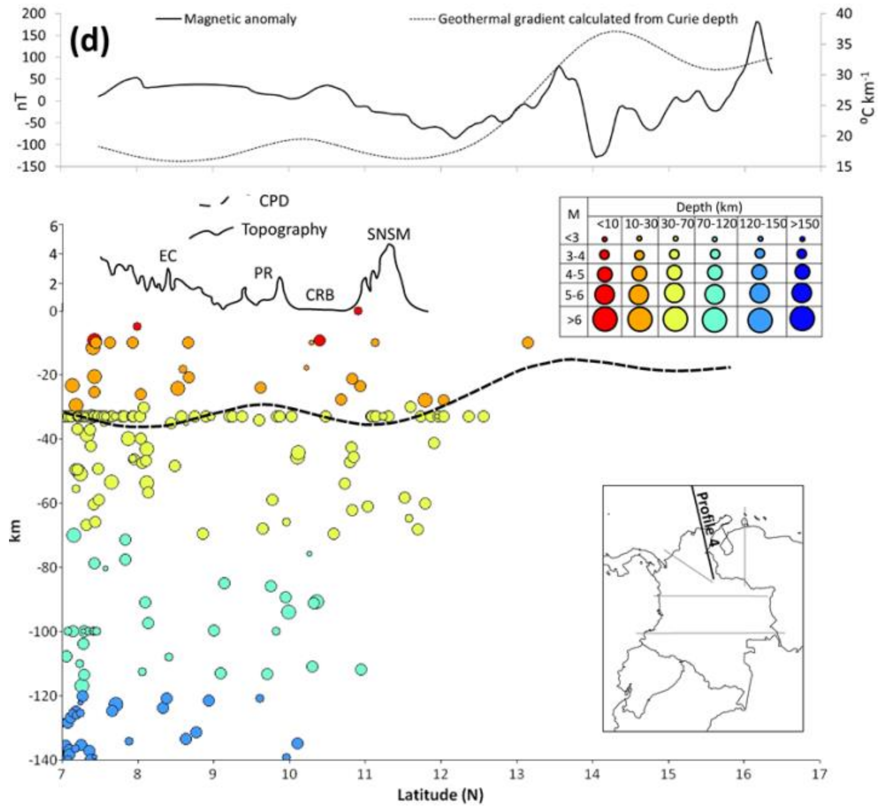


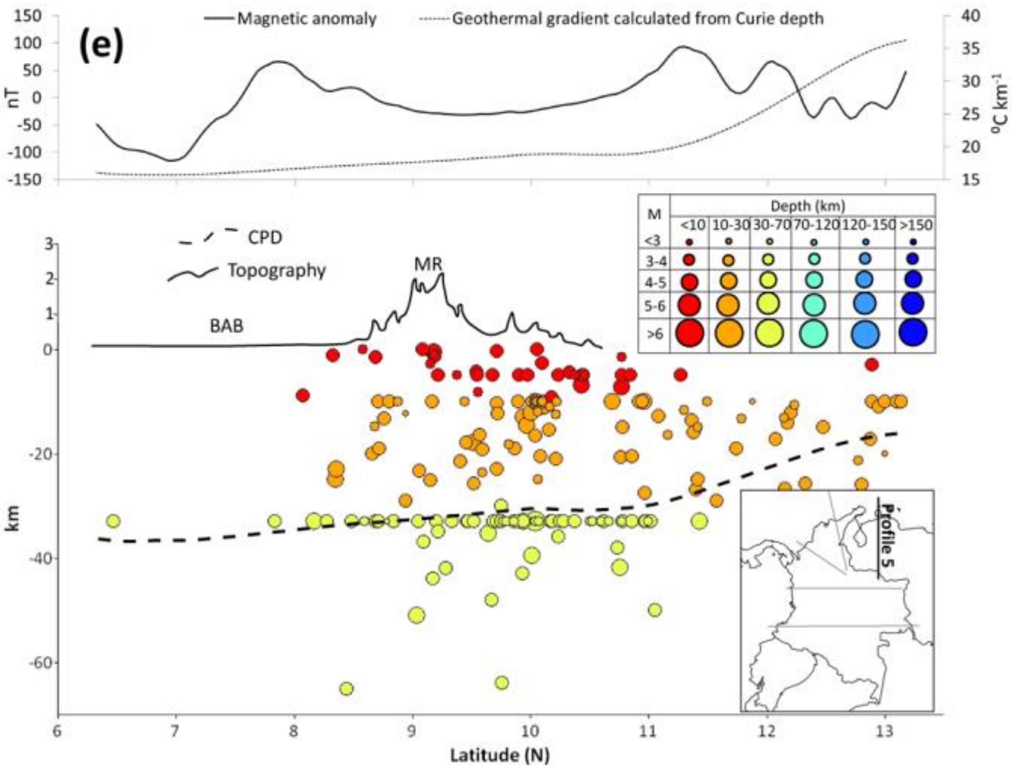


Results: CPD and other geophysical observations

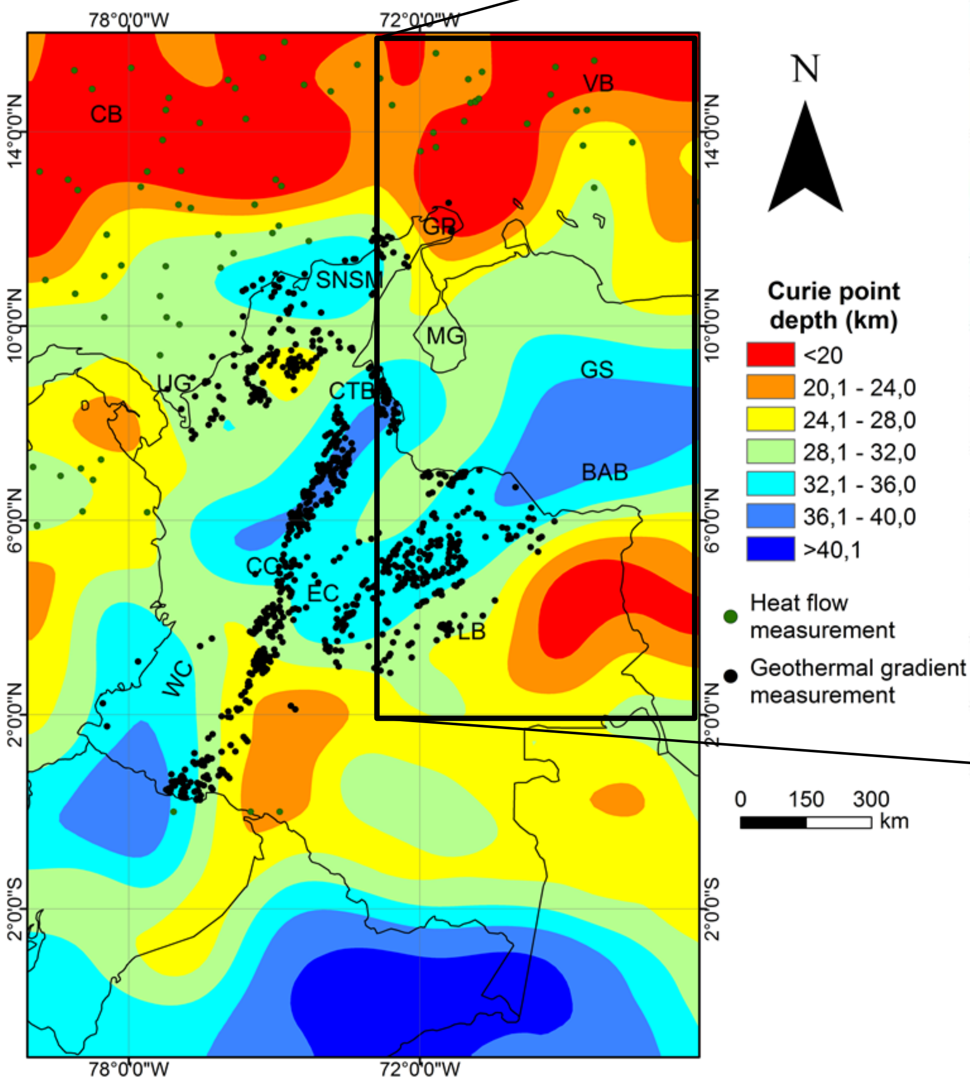


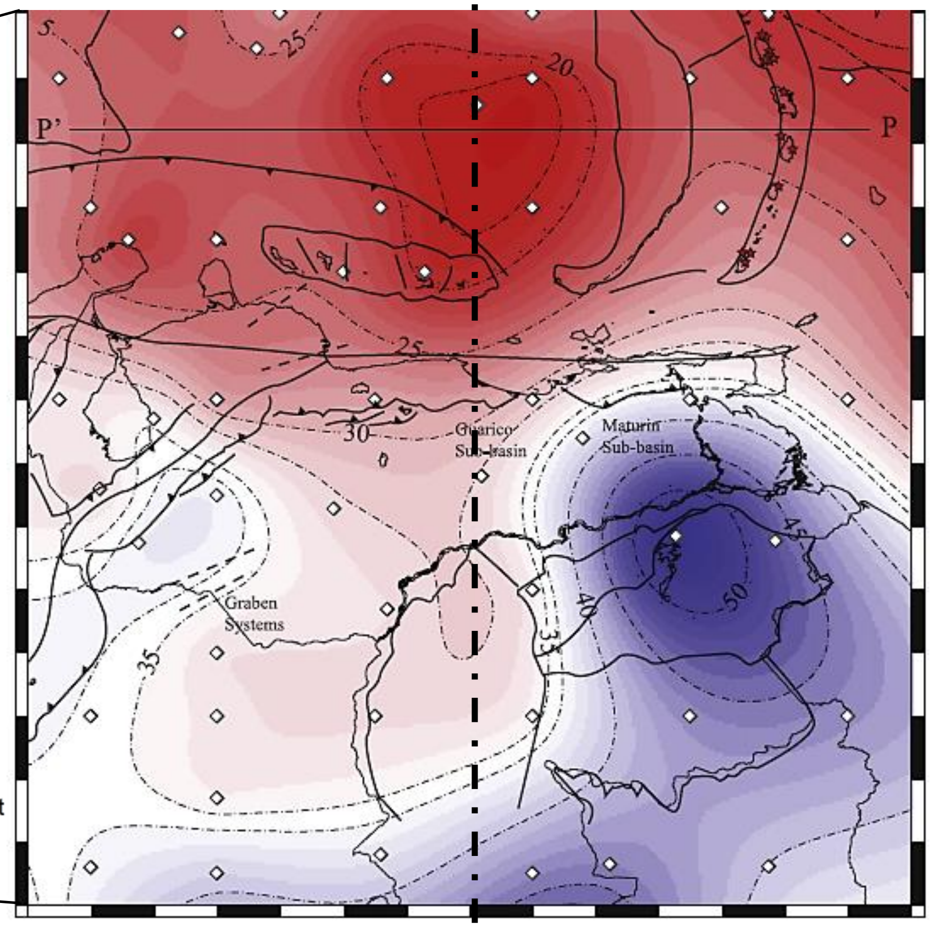
Results: CPD and other geophysical observations





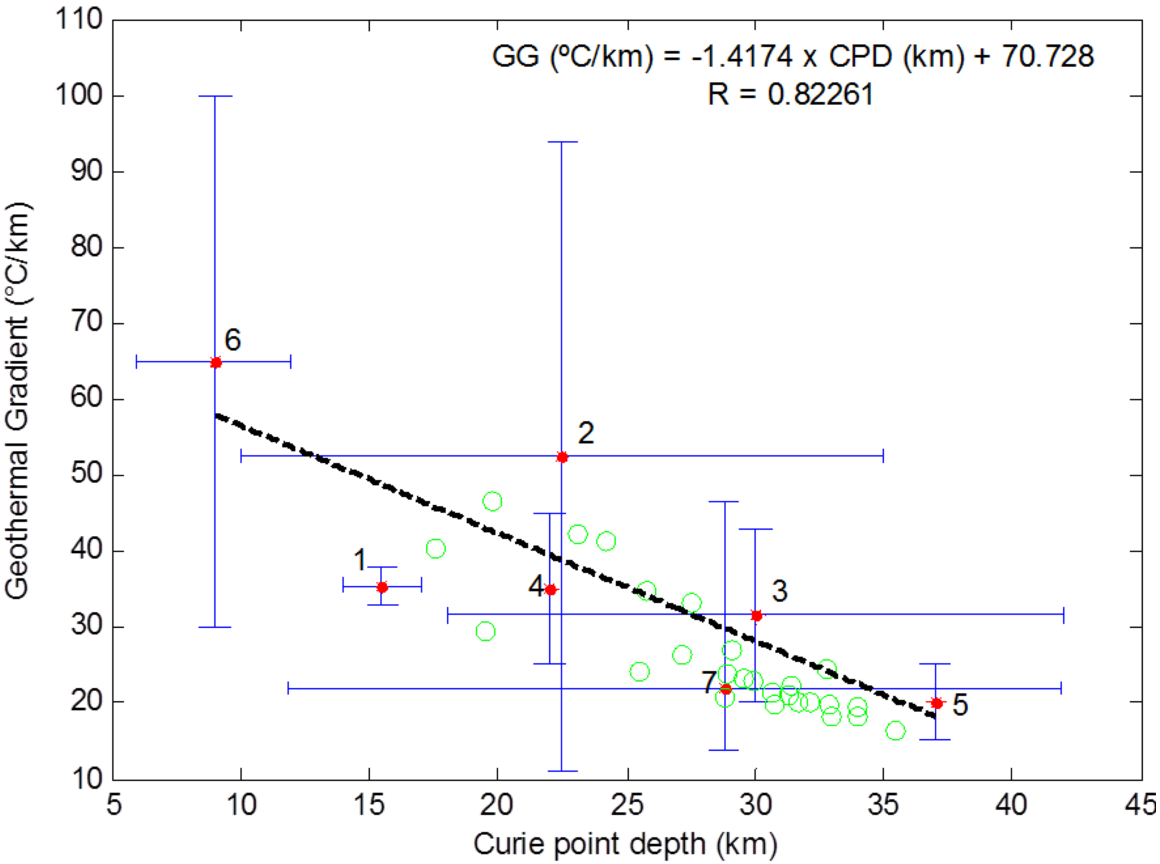
Discussion: Comparison with other models





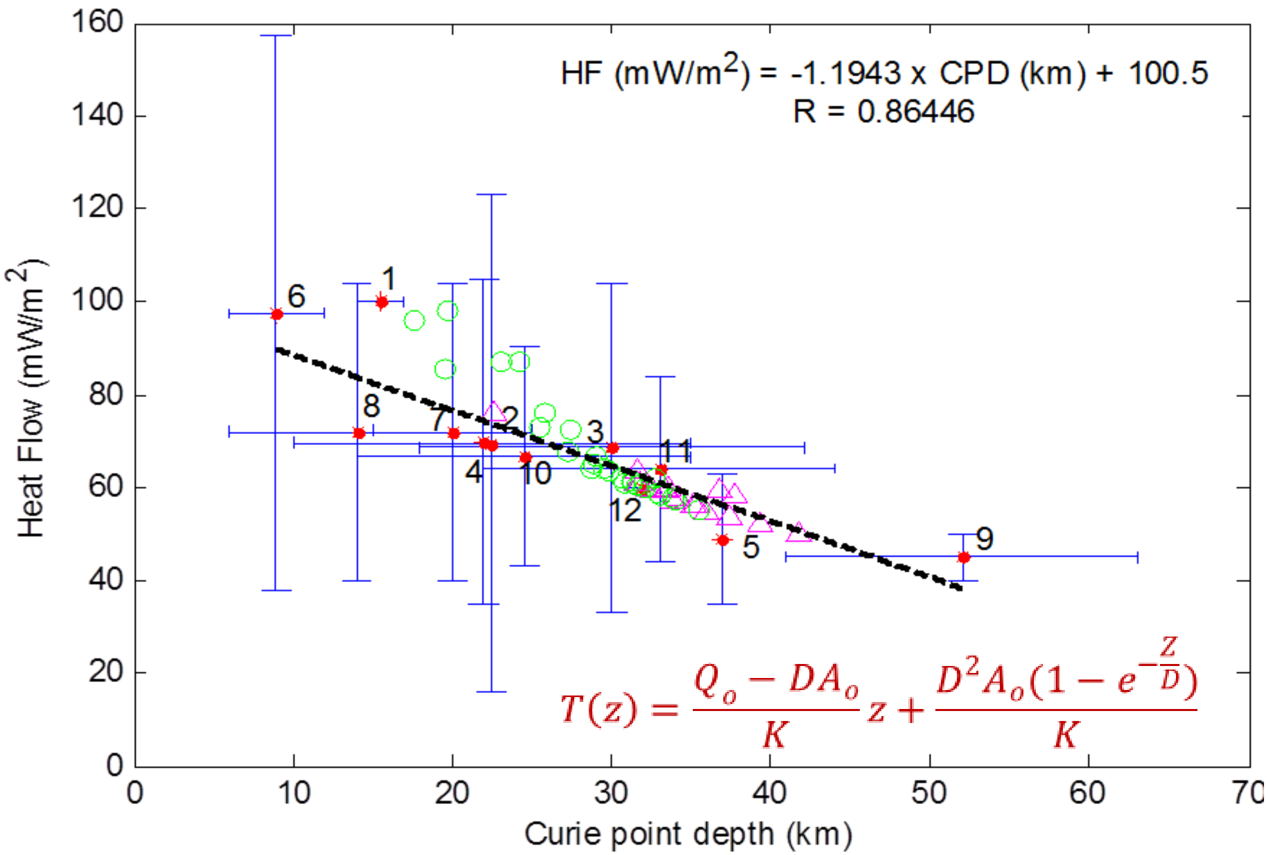
Arnaiz-Rodríguez and Orihuela (2013)

Discussion: Relationship between CPD, GG and HF



The trend confirms the hypothesis of high geothermal gradients in areas related to shallow CPD

Discussion: Relationship between CPD, GG and HF



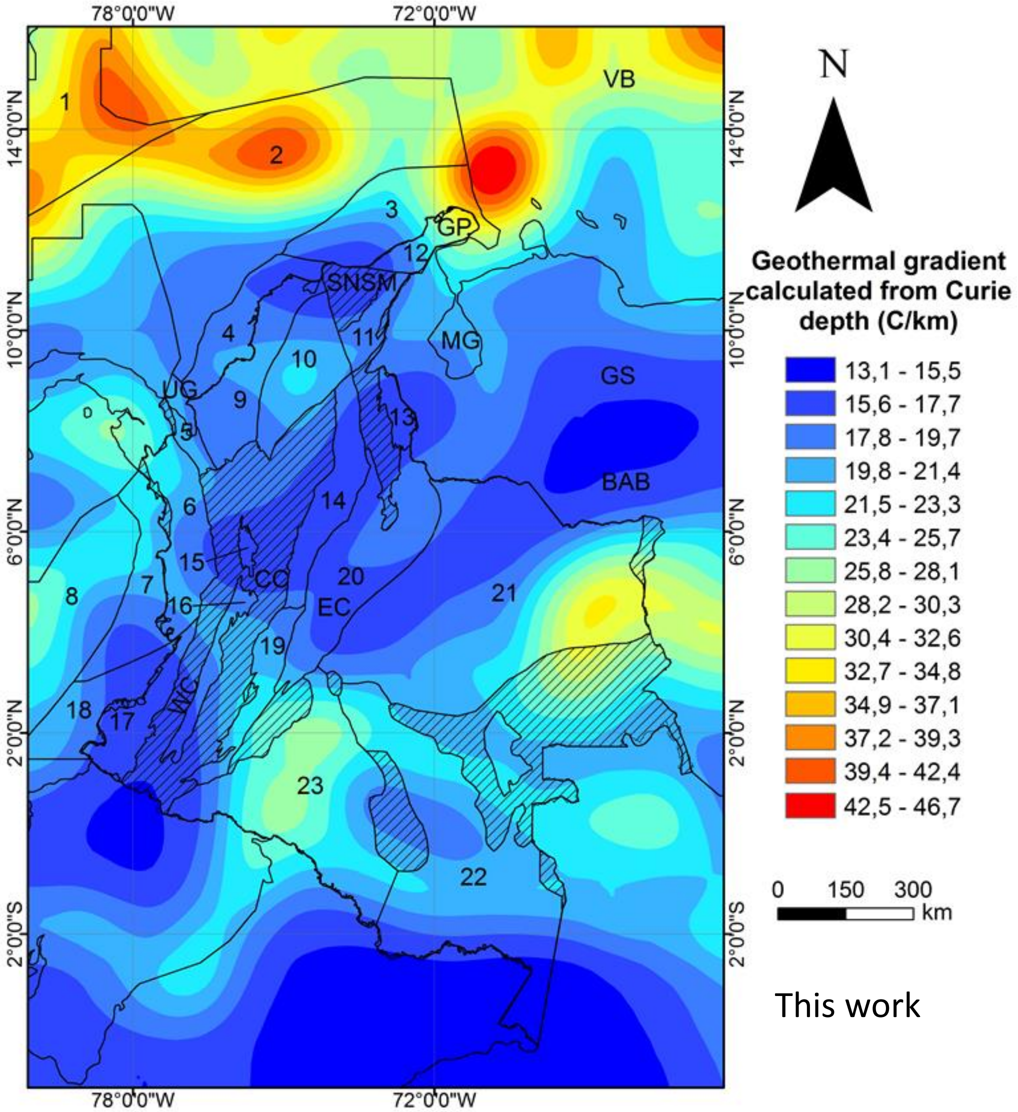
$K = 2.5\ Wm^{-3}K^{-1}$

$A_o = 2\mu Wm^{-3}$

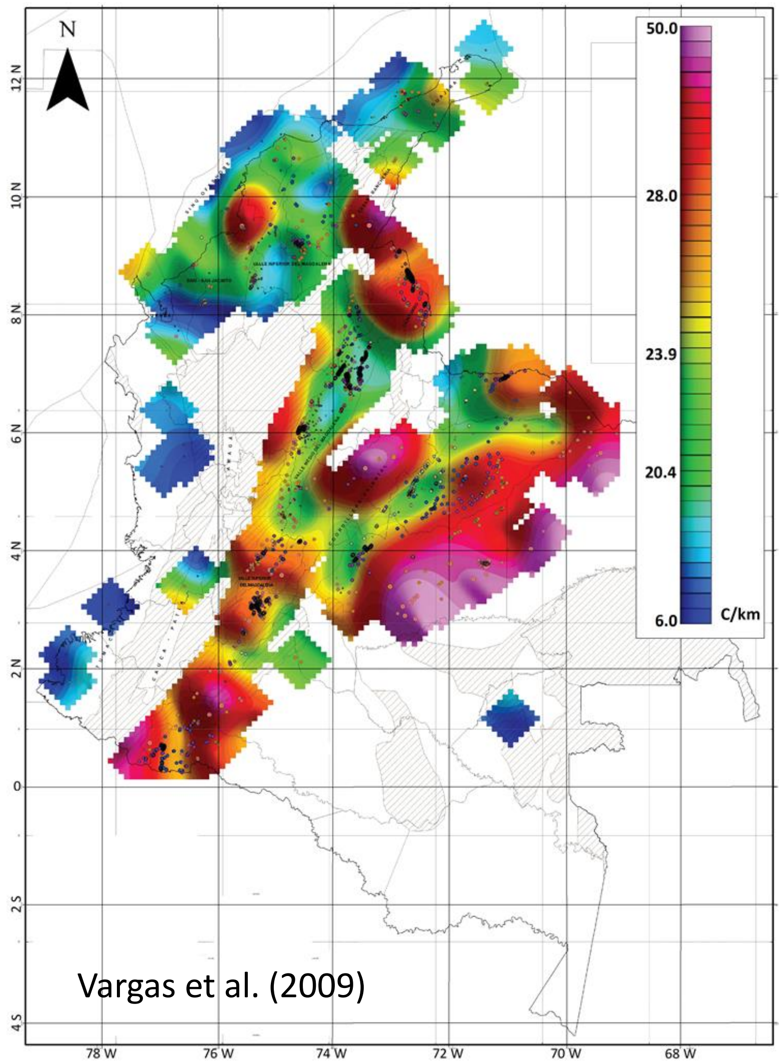
$D = 10$ km

The trend confirms the hypothesis of high heat flow in areas related to shallow CPD

Discussion: Relationship between CPD, GG and HF



This work

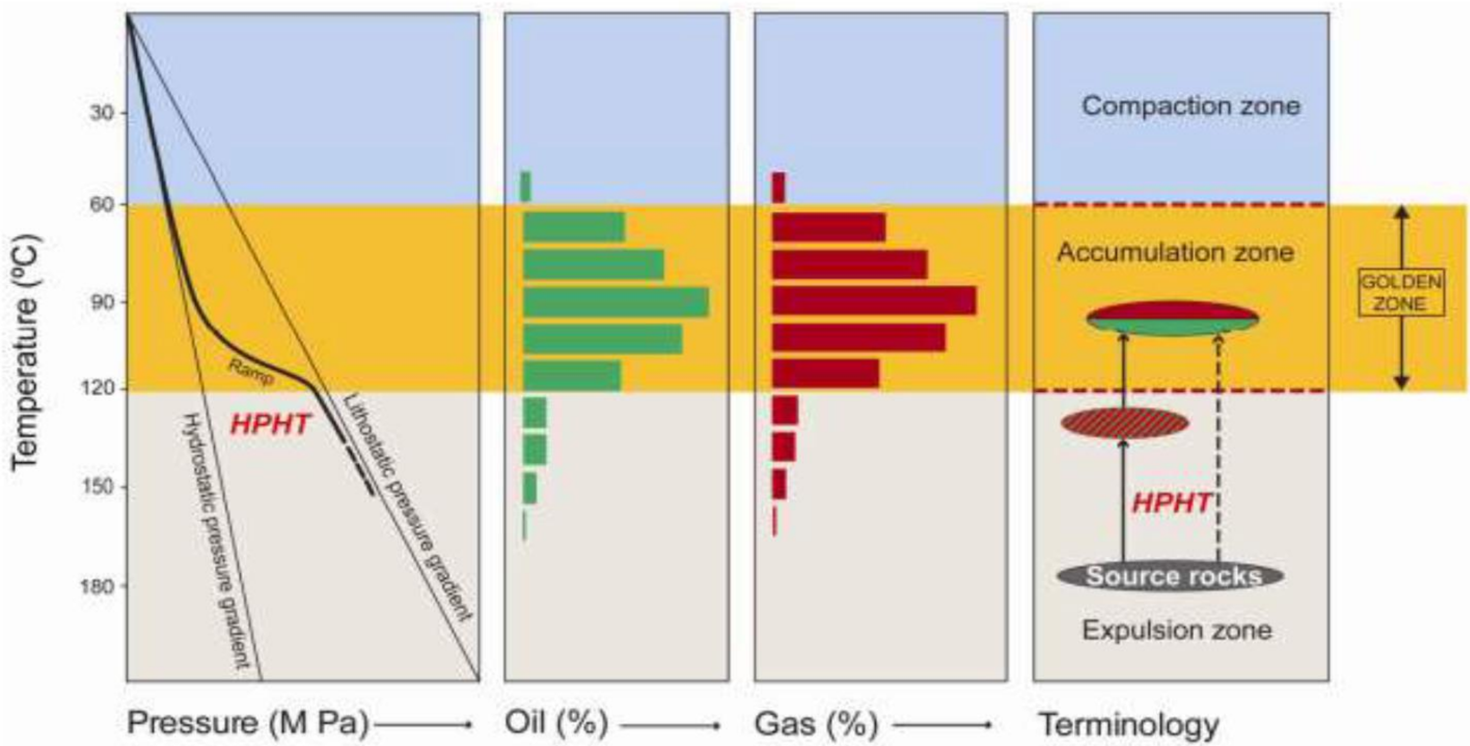


Vargas et al. (2009)

CPD can vary laterally due to the medium composition and because the broad data ranges compiled from the literature incorporate high uncertainties

Discussion: Application to the petroleum geology

Buller et al. (2005) introduced the concept of **Golden Zone**



Taken from Buller et al. (2005)

The overall pattern is independent of the location, type of basin, geological age, sedimentation rate, subsidence rate, geothermal gradient, hydrocarbon volumes and fields sizes

Discussion: Application to the petroleum geology

Basin	Sub-basin/region	Maximum sedimentary thickness (km) *	Mean geothermal gradient (ºC/km)	Golden Zone depth interval (km)	Possible Golden Zone
Amagá-Cauca Patía	Patía sub-basin	4.4	17.2	3.5-7.0	Yes
Chocó-Urabá	Atrato sub-basin	10.0	20.3	3.0-6.0	Yes
Caguán-Putumayo	Putumayo sub-basin	6.8	21.4	2.8-5.6	Yes
Catatumbo	Eastern region	4.6	17.1	3.5-7.0	Yes
Cesar-Ranchería	NE region	5.0	18.6	3.2-6.5	Yes
Eastern Cordillera	Cundinamarca sub-basin	10.5	19.3	3.1-6.2	Yes
Guajira-Los Cayos	offshore Upper Guajira	9.0	29.9	2.0-4.0	Yes
Eastern Llanos	Llanos foothills	7.8	24.4	2.5-4.9	Yes
Lower Magdalena	Plato sub-basin	9.5	19.0	3.2-6.3	Yes
Middle Magdalena	Foothills region	7.5	17.1	3.5-7.0	Yes
Sinú-San Jacinto	Sinú fold belt region	6.0	18.3	3.3-6.0	Yes
Tumaco	Southern Tumaco sub-basin	8.5	17.8	3.4-6.8	Yes
Upper Magdalena	Girardot sub-basin	6.5	20.0	3.0-6.0	Yes
Vaupés-Amazonas	Mitú region	3.0	19.2	3.1-6.3	No

* Taken from Cediel et al. (2011)

General Conclusions

- A CPD map of the northwestern South America and southwestern Caribbean basin has been estimated from magnetic data reported by WDMAM (Maus et al., 2007). CPD estimates by using power spectrum analysis suggest a range of depths varying between 12±3 km y 43±5 km. The major uncertainties of this map are associated with areas where the WDMAM includes interpolated values

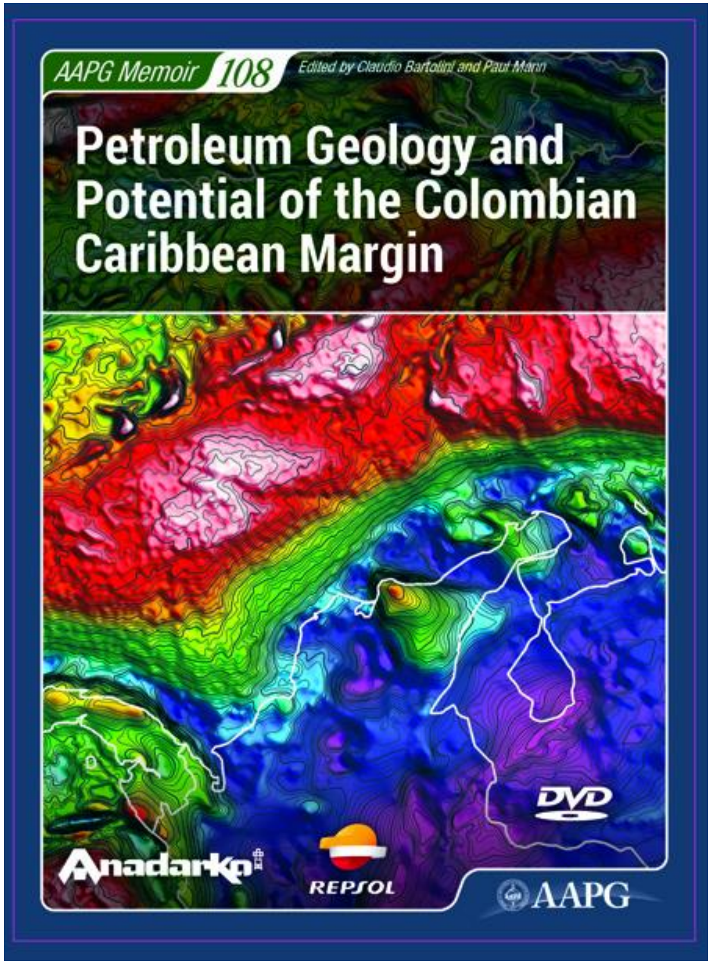
- A comparison of the geothermal gradient map derived from this study and that reported by Vargas et al. (2009) allowed to identify similarities and discrepancies. These discrepancies could be related to the interpolating process of the magnetic anomalies data used in this work

General Conclusions

- Empirical relationships between CPD, geothermal gradient and heat flow that support the thermal behavior of the upper lithosphere in the northwestern South America have been estimated. These relationships allow to calculate geothermal gradient and heat flow values in areas where there is absence of this information

- The estimation of the CPD by spectral analysis method has limitations, which are extensively discussed by Blakely (1995) and Ross et al. (2004)

- Deep magnetic sources have long wavelengths and low amplitudes that make them difficult to distinguish with respect to anomalies caused by surface sources. The size of the analyzed subregion must be large enough to capture these long wavelengths



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Curie Point Depths in Northwestern South America and the Southwestern Caribbean Sea

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ABSTRACT

We have estimated the Curie point depth (CPD) in the northwestern corner of South America and the southwestern Caribbean Sea from spectral analysis of magnetic anomalies extracted from the World Digital Magnetic Anomaly Map. To do this, we performed three different spectral methods and chose the model that best fits the geologic and geophysical characteristics of the study area. Then, we calculated the geothermal gradient from these CPD values to assess the likelihood of the hydrocarbon "Golden zone" being present in some of Colombia's sedimentary basins. Similarly, we tried to establish empirical relationships between CPD, geothermal gradient, and heat flux.

Our results show that the CPD lies between 12.6 km (7.8 mi) and 74 km (45.9 mi). The shallowest depths (<25 km [<15.5 mi]) are in the offshore Venezuela and Colombia basins of the Caribbean Sea, the onshore eastern Llanos and Caguan–Putumayo Basins, and southwestern Venezuela. The greatest depths (>50 km [>31 mi]) occur in parts of the western and central Cordilleras, Santander massif, and middle Magdalena, Catatumbo, Barinas-Apure, and Vaupes-Amazonas Basins. Based on the results, we found a relationship between an unexpected zone of deep CPD values (40–47 km [24.8–29.2 mi]) in the Colombia Basin and the presumable presence of an abnormal thick Caribbean Plateau with a continental inheritance. On the other hand, the contrasting deep and shallow CPD values in the Caribbean support the interpretation of flat subduction of the Caribbean plate beneath South America with a flexural topographic bulge toward the Sinu–San Jacinto and lower Magdalena Basins. Partial erosion of this bulge could have resulted in shallowing of the CPD with a consequent increase in geothermal gradient and heat flux. Also, we found a CPD shallowing beneath Caguan–Putumayo and eastern Llanos Basins.

Finally, based on the calculated geothermal gradient values in Colombia, we consider that the Golden zone of hydrocarbon occurrence most likely exists in the Choco–Uraba, eastern Cordillera, Guajira–Los Cayos, eastern Llanos, and lower Magdalena Basins, while the Golden zone would be absent only in the Vaupes–Amazonas Basin.

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Curie point depth in the SW Caribbean using the radially averaged spectra of magnetic anomalies

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ABSTRACT

We have estimated the Curie Point Depth (CPD) using the average radial power spectrum in a tectonically complex area located in the SW Caribbean basin. Data analyzed came from the World Digital Magnetic Anomaly Map, and three methods have been used to compare results and evaluate uncertainties: Centroid, Spectral Peak, and Forward Modeling. Results show a match along the three methods, suggesting that the CPD values in the area ranging between 6 km and 50 km. The results share the following characteristics: A) High values (>30 km) are in continental regions; B) There is a trend of maximum CPD values along the SW-NE direction, starting from the Central Cordillera in Colombia to the Maracaibo Lake in Venezuela; C) There is a maximum CPD at the Sierra Nevada de Santa Marta (Colombia) as well as between Costa Rica - Nicaragua and Nicaragua - Honduras borders. The lowest CPD values (<20 km) are associated with the coastal regions and offshore. We also tested results by estimating the geothermal gradient and comparing measured observations of the study area. Our results suggest at least five thermal terrains in the SW Caribbean Basin: A) The area that is comprising the Venezuela Basin, the Beata Ridge and the Colombia Basin up to longitude parallel to the Providencia Throat. B) The area that includes zones to the north of the Cocos Ridge and Panam Basin up to the trench. C) The orogenic region of the northern Andes and including areas of the Santa Marta Massif. D) The continental sector that encompasses Nicaragua, northern Costa Rica and eastern of Honduras. E) Corresponds to areas of the northern Venezuela and Colombia, NW of Colombia, the Panamanian territory and the transition zones between the Upper and Lower Nicaragua Rise.

THANK YOU VERY MUCH!!!