Actualización y revisión de la base de datos de flujo de calor en México: Etapa 1 (2015)

O.M. Espinoza-Ojeda[1], R.N. Harris[2], R.M. Prol-Ledesma[3], E.R. Iglesias[4] y A. Figueroa-Soto[5]
[1]Cátedras CONACyT - Instituto de Investigaciones en Ciencias de la Tierra (INICIT), Universidad Michoacana de San Nicolás de Hidalgo (UMSNH), Morelia, Michoacán, México. Correo: omespinozaoj@conacyt.mx. [2]College of Earth, Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, Oregon, USA. [3]Instituto de Geofísica, UNAM, México, D.F., México. [4]Instituto de Investigaciones Eléctricas, Cuernavaca, Morelos, México. [5]Investigador Postdoctoral - INICIT, UMSNH, Morelia, Michoacán, México.

RESUMEN

El estado térmico de la corteza en México es pobremente conocido comparado con la situación en Estados Unidos y Canadá. Este estudio tiene el objetivo principal de mejorar la comprensión del régimen térmico de México a través de una nueva compilación de datos medidos y estimados sobre flujo de calor. Las mediciones de flujo de calor en México están relativamente dispersas; por lo tanto, no hay suficientes datos para caracterizar exactamente las provincias de flujo de calor y desarrollar un mapa geotérmico consistente. La etapa 1 de este proyecto corresponde a una actualización del número de mediciones de la base de datos de flujo de calor superficial de México usando una variedad de fuentes de datos de más de 100 sitios (mediciones de temperaturas transitorias de pozos y perfiles térmicos). La base de datos térmica actualizada considera las zonas continentales y marinas de México. Los nuevos valores de flujo de calor están principalmente localizados a lo largo de la península de Baja California, la parte central del norte de México y el Cinturón Volcánico. De los nuevos datos, se obtiene que los valores más altos y más bajos de flujo de calor son 1263 mW/m^2 y 4 mW/m^2, respectivamente, y ambos se localizan en el Cinturón Volcánico Transmexicano.

Palabras clave: Flujo de calor superficial, provincias de flujo de calor, mapa geotérmico.

Update and review of the heat flow database for México: Stage 1 (2015)

Abstract

The thermal state of crust in México is poorly known compared to the US and Canada. This study has the predominant objective of better understanding the thermal regime of México through new estimated and compiled heat flow information. Heat flow measurements in México are relatively sparse; therefore, there are not enough data to accurately characterize heat flow provinces and develop a consistent geothermal map. Stage 1 of this project corresponds to update the number of measurements of the surface heat flow database of México by using a variety of data sources from 108 sites (measurements from transient borehole temperatures and thermal profiles). The updated thermal database considers México's continental and offshore zones. The new heat flow values are mainly located along the Baja California Peninsula and the Trans Mexican Volcanic Belt. From the new data, we obtain that the highest and the lowest heat flow values are 1263 mW/m^2 and 4 mW/m^2, respectively, both located in the Trans Mexican Volcanic Belt area.

Keywords: Superficial heat flow, heat flow provinces, geothermal map.

1. Introduction

Geothermal resources are receiving renewed attention because they constitute a viable and renewable energy option. This attention can be attributed in large part to technological advances and the large growth of development worldwide (*Balat et al*., 2007; *Chamorro et al*., 2012; *Zarrouck and Moon*, 2014; *Bertani*, 2015; *DiPippo*, 2015; *Lund et al*., 2015). The exploration and exploitation of geothermal resources, especially for Enhanced Geothermal System (EGS) requires a better understanding of the lithospheric thermal regime. Although many high-enthalpy geothermal resources in México have already been discovered and exploited (e.g. *Gutiérrez-Negrín*, 2015; *Gutiérrez-Negrín et al*., 2015), medium and low enthalpy resources are far more abundant (e.g. *Iglesias et al*., 2011, 2015). These resources may constitute an important resource for direct use energy. Their exploitation depends on a good knowledge of the geothermal potential in México. This knowledge is hampered by a lack of high quality heat flow measurements.

The lack of heat flow measurements in México have led to indirect methods for estimating the thermal regime. Previous geothermal studies provide evidence about the location of low, medium and high enthalpy geothermal systems suitable for exploitation/utilization (e.g. *Ziagos et al*., 1985; *Prol-Ledesma and Juarez*, 1986; *Arango-Galván et al*., 2015; *Gutiérrez-Negrín et al*., 2015; *Iglesias et al*., 2015). The first heat flow values in México were reported by *Von Herzen* (1963) for the ocean crust and *Smith* (1974) for the continent. Since that time, the number of measurements has increased greatly but data location mostly correspond to oil and gas exploration sites and geothermal areas and their periphery.

The purpose of this study is to update and expand the heat flow database for México to develop a better understanding of México's potential from the perspective of geothermal energy. New heat flow estimates from 108 sites are combined with published continental and marine heat flow measurements to update the geothermal database in México (e.g. *Smith*, 1974; *Smith et al*., 1979; *Von Herzen*, 1963, 1964). We use the updated heat flow map to address the question of whether there is enough heat for economic geothermal exploitation outside of the known Mexican geothermal fields.

2. New heat flow values

All boreholes used in this study exceed 100 m in depth, have at least three temperature-depth measurements and have stratigraphic information. Of the 113 borehole provided by Comisión Federal de Electricidad (CFE) and Petróleos Mexicanos (PEMEX), 108 satisfy these criteria. Temperature-depth data consist of either thermal recovery data logs, also known as transient borehole temperatures logs (TBT), or bottom-hole temperatures (BHT). These sites are dominantly around the Cerro Prieto geothermal system and along the Baja California Peninsula (Fig. 1). A few additional sites also come from the north central and central areas of México.

TBT and BHT are generally measured directly after drilling and before the borehole has returned to thermal equilibrium conditions. During the drilling process, fluids are circulated through the borehole to lubricate and cool the bit. These fluids generally decrease the temperature within the borehole and corrections must be applied to estimate equilibrium temperature, which is known as stabilized formation temperatures (SFT). TBT data consist of temperature, depth, and the elapsed time since circulation stopped known as the shut-in time (Fig. 2). Shut-in times are commonly up to 24 or 36 hours in the geothermal or oil industry (e.g. *Kutasov*, 1999). BHT are similar to TBT but in this case the temperature is measured just one time at the bottom of the borehole (Fig. 2). These temperatures are thought to be closer to equilibrium temperature because are less influenced by the circulating fluids. Of the 108 borehole data reported here, 63 are based on TBT (MEX0001 to MEX0063) and 45 are based on BHT (MEX0064 to MEX0108).

To estimate heat flow in the presence of thermal conductivity variations we use the Bullard method (*Bullard*, 1939),

$$T_i = T_0 + q_0 R_i, \quad (4)$$

where T_i is the temperature, T_0 is the surface temperature intercept, q_0 is the heat flow, and R is thermal resistance that can be expressed as,

$$R_i = \sum_i^n \frac{dz_i}{k_i}, \quad (5)$$

where $k(z)_i$ is the thermal conductivity over the *i*th depth interval, dz_i, and the summation is performed over *n* depth intervals from the surface to the depth of interest *z*. In practice q_0 and T_0 are estimated by plotting *T*(z) against summed thermal resistance.

3. New and compiled heat flow data from México. Location and classification of the heat flow according to their energy scale

We compiled published and unpublished heat flow data in México, from conductive and non-conductive systems, to better define different heat flow values scale in a map. Additionally, published heat flow with their respective standard deviations and site location, are included in this work. The compiled database contains data from 1465 sites, which includes continental and oceanic zones (Gulf of California, the Pacific Ocean, Gulf of México and the Yucatan Basin). Published data sources consulted include the following papers: *Von Herzen* (1963, 1964); *Von Herzen and Maxwell* (1964); *Epp et al*. (1970); *Erickson et al*. (1972); *Henyey and Bischoff* (1973); *Lawver et al*. (1973); *Smith* (1974); *Lee and Henyey* (1975); *Lawver and Williams* (1979); *Smith et al*. (1979); *Williams et al*. (1979); *Reiter and Tovar* (1982); *Lonsdale and Becker* (1985); *Ziagos et al*. (1985); *Prol-Ledesma et al*. (1989); *Khutorskoy et al*. (1990); *Becker and Fisher* (1991); *Sanchez-Zamora et al*. (1991); *Nagihara et al*. (1996); *Flores-Márquez et al*. (1999); *Chavez et al*. (2000); *Fisher et al*. (2001); *García-Estrada et al*. (2001); *Blackwell and Richards* (2004); *Wilhelm et al*. (2005); *Rosales Rodríguez* (2007); *IHFC* (2011); *Lorenzo Pulido et al*. (2011); and *Prol-Ledesma et al*. (2013).

Overall compiled and calculated (new) heat flow values were summarized in histogram plots (Fig. 3): (a) the new 108 heat flow calculations; (b) continental heat flow observations, published and new data; and (c) off-shore heat flow values. Fig. 3 illustrates the ranges of most values. The histogram plots in Fig. 3 present the large variation of values in the new and published heat flow data, that show a statistical non-normal distribution, which is produced by the combination of stable and thermally perturbed conductive systems.

Since continental heat flow observations in Mexico have a non-uniform distribution (see Fig. 3), there large areas with no heat flow sites or large distances between each heat flow sites (except eastern México, along the Gulf of México coast). Thus, the updated heat flow data were divided into two energy flux subsets with the objective to aid visualization of the location and distribution of the data presented in Fig. 3, besides to distinguish the location of low, medium and high enthalpy sites. Additionally, this helps to characterize with a high accuracy or confidence level the actual thermal status of any particular zone. These energy flux subsets were proposed as follow: 0-120 mW/m^2 (Fig. 4); and 120-1300 mW/m^2 (Fig. 5).

The offshore heat flow data from México (inside the exclusive economic zone) are summarized in the histogram plot of Fig. 3c. Four offshore sections were analyzed: Gulf of California, the Pacific Ocean, the Gulf of México and the Yucatan Basin. Due to space and the scale in the histogram plot, the values of 6250, 7115, 8910 and 15,436 mW/m^2 were not plotted but considered in the analysis of data. Following a similar procedure shown in Fig. 4 and 5, three different energy flux subsets were proposed to analyze the 961 compiled offshore heat flow data, to characterize the heat flow distribution in the ocean crust. Several works have made rigorous analysis of the marine heat flow where they consider that heat flow is in function of the ocean lithospheric age and affected by hydrothermal circulation (e.g. *Parsons and Sclater*, 1977; *Stein and Stein*, 1992, 1994; *Hasterok et al*., 2011; *Spinelli and Harris*, 2011; *Goutorbe and Hillier*, 2013; *Hasterok*, 2013). Fig. 6 presents the 517 heat flow values of the subset 0-150 mW/m^2 including a histogram plot; these values represent approximate heat flow from ocean lithospheric age greater than 10 Ma. The subset 150-600 mW/m^2 is presented in Fig. 7, where 341 heat flow sites are shown in the map and the corresponding histogram. In Fig. 8, 103 high heat flow values from the subset 600-16000 mW/m^2 are located in a map with a histogram.

According to the geographic/tectonic differences, as additional observation, to combine all the data into different heat flow maps and histograms (see Figs. 6-8), this can show us how heat flow vary as a function of oceanic crustal age, because ridges are thought to have higher heat flow and old oceanic crust has low heat flow. However, in this work the purpose of the data combination is to observe with detail heat flow variations in the ocean floor, as well as the location of the thermal anomalies as shown in Figs. 7-8, and their numerical distribution as described in the histograms.

Current technology and production costs in geothermal industry do not allow commercial exploitation of thermal submarine resources presently; however, it may be feasible in a non-distant future; therefore, this data will be highly valuable when this happens (e.g. *Suárez-Bosche et al*., 2000; *Prol-Ledesma et al*., 2008; *Hiriart et al*., 2010; *Torres-Vera et al*., 2010).

As we can observe from Fig. 4 to Fig. 8, several heat flow sites are superimposed or cluster in some areas; hence, the different histograms included in each heat flow map help to visualize the numerical variation according to the different heat flow values subsets defined in this section.

4. Conclusions

A comprehensive update and review of the thermal database from México gives a reliable idea of the current heat flow values and their distribution in México (inland and offshore).

Thermal gradients can be obtained and interpreted in terms of heat reserves stored in subsurface from the regional geothermal heat flow measurements. This interpretation will assist locating low, medium and high enthalpy resources suitable for exploitation and/or utilization (electric or direct use). The exploitation of this energy source depends on the regional requirements and the available technology.

Future steps of this work will include definition of tectono-thermal provinces and their local anomalies, and also analysis of the relationship between borehole measurements and indirect geochemical characterization of heat flow; that will increase the knowledge of heat flow in México, and will allow construction of an updated (and highly necessary) geothermal map of México.

References

Arango-Galván, C., R. M. Prol-Ledesma and M. A. Torres-Vera (2015). Geothermal prospects in the Baja California Peninsula. *Geothermics*, **55**, 39-57. doi: 10.1016/j.geothermics.2015.01.005

Balat, M. (2007). Status of fossil energy resources: A global perspective. *Energy Sources, Part B*, **2**, 31-47. doi:10.1080/15567240500400895

Becker, K., and A. T. Fisher (1991). A brief review of heat-flow studies in the Guaymas Basin, Gulf of California, in *The Gulf and Peninsular Province of the Californias*, edited by J. P. Dauphin & B. R. Simoneit, pp. 709-720, American Association of Petroleum Geologists.

Bertani, R. (2015). Geothermal Power Generation in the World 2010-2014 Update Report. In: proceedings of the *World Geothermal Congress* 2015, Melbourne, Australia, 19-25 April.

Blackwell, D.D., and M. Richards (2004). Geothermal map of North America. *American Association of Petroleum Geologist* (AAPG), 1 sheet, scale 1:6,500,000.

Bullard, E. C. (1939). Heat flow in South Africa. *Proceedings of the Royal Society of London Series A, Mathematical and Physical Sciences*, **173**, 474-502. doi: 10.1098/rspa.1939.0159

Carslaw, H. S., and J. C. Jaeger (1959). *Conduction of Heat in Solids*. Second ed. Oxford Science Publications. 510 pp.

Chamorro, C. R., M. E. Mondéjar, R. Ramos, J. J. Segovia, M. C. Martín and M. A. Villamañán (2012). World geothermal power production status: Energy, environmental and economic study of high enthalpy technologies. *Energy*, **42**, 10-18. doi:10.1016/j.energy.2011.06.005

Chávez, R. E., E. L. Flores, J. O. Campos, M. Ladrón de Guevara, M. C. Fernández-Puga, and J. Herrera (2000), Three-dimensional structure of the Laguna Salada Basin and its thermal regime, *Geophysical Prospecting*, *48*, 835-870. doi: 10.1046/j.1365-2478.2000.00215.x

DiPippo, R. (2015). Geothermal power plants: Evolution and performance assessments. *Geothermics*, **53**, 291-307. doi: 10.1016/j.geothermics.2014.07.005

Epp, D., P. J. Grim, and M. G. J. Langseth (1970). Heat flow in the Caribbean and Gulf of Mexico. *Journal of Geophysical Research*, **75**(29), 5655-5669. doi: 10.1029/JB075i029p05655

Erickson, A. J., C. E. Helsey, and G. Simmons (1972). Heat flow and continuous seismic profiles in the Cayman Trough and Yucatan basin. *Geological Society of America Bulletin*, **83**(5), 1241-1260.

Fisher, A. T., E. Giambalvo, J. Sclater, M. Kastner, B. Ransom, Y. Weinstein, and P. Lonsdale (2001). Heat flow, sediment and pore fluid chemistry, and hydrothermal circulation on the east flank of Alarcon Ridge, Gulf of California. *Earth and Planetary Science Letters*, **188**, 521-534. doi: 10.1016/s0012-821x(01)00310-7

Flores-Márquez, E. L., R. Chávez-Segura, O. Campos-Enríquez, and M. Pilkington (1999). Preliminary 3-D structural model from the Chicxulub impact crater and its implications in the actual geothermal regime. *Trends in Heat, Mass & Momentum Transfer*, **5**, 19-40.

García-Estrada, G., A. Lopez-Hernandez, and R. M. Prol-Ledesma (2001). Temperature-depth relationships based on log data from the Los Azufres geothermal field, México. *Geothermics*, **30**, 111 – 132. doi:10.1016/S0375-6505(00)00039-0

Goutorbe, B., and J. K. Hillier (2013). An integration to optimally constrain the thermal structure of oceanic lithosphere. *Journal of Geophysical Research: Solid Earth*, **118**, 432-446. doi:10.1029/2012JB009527.

Gutiérrez-Negrín, L.C. (2015). Mexican Geothermal Plays. In: proceedings of the *World Geothermal Congress* 2015, Melbourne, Australia, 19-25 April.

Gutiérrez-Negrín, L.C., R. Maya-González and J.L. Quijano-León. (2015). Present Situation and Perspectives of Geothermal in Mexico. In: proceedings of the *World Geothermal Congress* 2015, Melbourne, Australia, 19-25 April.

Hasterok, D. (2013). Global patterns and vigor of ventilated hydrothermal circulation through young seafloor. *Earth and Planetary Science Letters*, **380**, 12-20. doi: 10.1016/j.epsl.2013.08.016.

Hasterok, D., D. S. Chapman, and E. E. Davis (2011). Oceanic heat flow: Implications for global heat loss. *Earth and Planetary Science Letters*, **311**, 386-395. doi: 10.1016/j.epsl.2011.09.044

Henyey, T. L., and J. L. Bischoff (1973). Tectonic elements of the northern part of the Gulf of California. *Geological Society of America Bulletin*, **84**(1), 315-330. doi: 10.1130/0016-7606(1973)84<315:TEOTNP>2.0.CO;2

Iglesias, E. R., R. J. Torres, I. Martínez-Estrella, and N. Reyes-Picasso (2011). Summary of the 2010 assessment on medium- to low-temperature geothermal resources in Mexico. *Geotermia, Revista Mexicana de Geoenergía*, **24**(2), 39-48

Iglesias, E. R., R. J. Torres, I. Martínez-Estrella, and N. Reyes-Picasso (2015). Summary of the 2014 assessment on medium- to low-temperature Mexican geothermal resources. In: proceedings of the *World Geothermal Congress* 2015, Melbourne, Australia, 19-25 April.

International Heat Flow Commission (IHFC). (2011). The global heat flow database of the International Heat Flow Commission [http://www.heatflow.und.edu].

Khutorskoy, M. D., R. Fernandez, V. I. Kononov, B. G. Polyak, V. G. Matveev, and A. A. Rot (1990). Heat flow through the sea bottom around the Yucatan Peninsula. *Journal of Geophysical Research*, **95**(B2), 1223-1237. doi: 10.1029/JB095iB02p01223

Kutasov, I. M. (1999). *Applied Geothermics for Petroleum Engineers*. First ed. Elsevier Scientific Publishing Company. 347 pp.

Lawver, L. A., J. G. Sclater, T. L. Henyey, and J. Rogers (1973). Heat flow measurements in the southern portion of the Gulf of California. *Earth and Planetary Science Letters*, **12**(2), 198-208. doi: 10.1016/0012-821x(73)90115-5

Lawver, L. A., and D. L. Williams (1979). Heat flow in the central Gulf of California. *Journal of Geophysical Research*, **84**(B7), 3465-3478.

Lee, T.-C., and T. L. Henyey (1975). Heat flow through the southern California borderland. *Journal of Geophysical Research*, **80**(26), 3733-3743.

Lonsdale, P., and K. Becker (1985). Hydrothermal plumes, hot springs, and conductive heat flow in the Southern Trough of Guaymas Basin. *Earth and Planetary Science Letters*, **73**(2), 211-225.

Lorenzo Pulido, C., M. Flores Armenta, and G. Ramírez Silva (2011). Characterization of a hot dry rock reservoir at Acoculco geothermal zone, Pue. *Geotermia, Revista Mexicana de Geoenergía*, **24**(1), 59-69.

Lund, J. W. and T. L. Boyd (2015). Direct utilization of geothermal energy 2015 worldwide review. In: proceedings of the *World Geothermal Congress* 2015, Melbourne, Australia, 19-25 April.

Nagihara, S., J. G. Sclater, J. D. Phillips, E. W. Behrens, T. Lewis, L. A. Lawver, Y. Nakamura, J. Garcia-Abdeslem, and A. E. Maxwell (1996). Heat flow in the western abyssal plain of the Gulf of Mexico: Implications for thermal evolution of the old oceanic lithosphere. *Journal of Geophysical Research*, **101**(B2), 2895-2913. doi: 10.1029/95jb03450

Parsons, B., and J. G. Sclater (1977). An analysis of the variation of oceanfloor bathymetry and heat flow with age. *Journal of Geophysical Research*, **82**(5), 803-827. doi: 10.1029/JB082i005p00803.

Prol-Ledesma, R. M., M. A. Torres-Vera, R. Rodolfo-Metalpa, C. Ángeles, C. H. Lechuga Deveze, R. E. Villanueva-Estrada, E. Shumilin, and C. Robinson (2013). High heat flow and ocean acidification at a nascent rift in the northern Gulf of California. *Nature Communications*, **4**(1388), 1-7. doi: 10.1038/ncomms2390

Prol-Ledesma, R. M., and G. Juarez M. (1986). Geothermal map of Mexico. *Journal of Volcanology and Geothermal Research*, **28**(3-4), 351-362. doi: 10.1016/0377-0273(86)90030-2

Prol-Ledesma, R. M., V. M. Sugrobov, E. L. Flores, G. Juárez M., Y. B. Smirnov, A. P. Gorshkov, V. G. Bondarenko, V. A. Rashidov, L. N. Nedopekin, and V. A. Gavrilov (1989). Heat flow variations along the Middle America Trench. *Marine Geophysical Researches*, **11**, 69-76. doi: 10.1007/BF00286248

Prol-Ledesma, R. M., Canet, C., Dando, P. and Hiriart, G. (2008). A new nascent spreading centre at the Wagner Basin in the northern Gulf of California: a possible geothermal resource? In: Proceedings of the *30th New Zealand Geothermal Workshop*. 191- 195.

Reiter, M. and Tovar, J.C. (1982). Estimates of terrestrial heat flow in northern Chihuahua, Mexico, based upon petroleum bottom-hole temperatures. *Geological Society of America Bulletin,* **93**, 613-624. doi: 10.1130/0016-7606(1982)93<613:EOTHFI>2.0.CO;2

Rosales Rodríguez, J. (2007). Evaluación Integral de los flujos de calor en el golfo de México. Instituto Politécnico Nacional. Master thesis, 104 p.

Sanchez-Zamora, O., P. Doguin, R. W. Couch, and G. E. Ness (1991). Magnetic anomalies of the Northern Gulf of California: Structural and thermal interpretations. In *The Gulf and Peninsular Province of the Californias*, edited by J. P. Dauphin & B. R. T. Simoneit, pp. 377-401, American Association of Petroleum Geologists, Tulsa, Oklahoma, USA.

Smith, D. L. (1974). Heat flow, radioactive heat generation, and theoretical tectonics for northwestern Mexico. *Earth and Planetary Science Letters,* **23**, 43-52. doi:10.1016/0012-821X(74)90028-4

Smith, D. L., C. E. Nuckels III, R. L. Jones, and G. A. Cook (1979). Distribution of heat flow and radioactive heat generation in northern Mexico. *Journal of Geophysical Research*, **84**(B5), 2371-2379. doi: 10.1029/JB084iB05p02371

Spinelli, G. A., and R. N. Harris (2011). Effects of the legacy of axial cooling on partitioning of hydrothermal heat extraction from oceanic lithosphere. Journal of Geophysical Research, **116** (B09102). doi:10.1029/2011JB008248.

Stein, C. A., and S. Stein (1992). A model for the global variation in oceanic depth and heat flow with lithospheric age. *Nature*, ***359***, 123-129. doi:10.1038/359123a0

Stein, C. A., and S. Stein (1994). Constraints on hydrothermal heat flux through the oceanic lithosphere from global heat flow. *Journal of Geophysical Research*, **99**(B2), 3081-3095. doi: 10.1029/93JB02222.

Suárez-Bosche, N., K. Suárez-Bosche, and M. C. Suárez A. (2000). Submarine geothermal systems in México. In: proceedings of the *World Geothermal Congress*. Kyushu-Tohoku, Japan, May 28 - June 10, 3889-3893.

Von Herzen, R.P. (1963). Geothermal heat flow in the Gulfs of California and Aden. *Science*, **140**, 1207-1208. doi:10.1126/science.140.3572.1207

Von Herzen, R.P. (1964). Ocean-floor heat-flow measurements west of the United States and Baja California. *Marine Geology*, **1**, 225-239. doi:10.1016/0025-3227(64)90061-1

Von Herzen, R. P., and A. E. Maxwell (1964). Measurements of heat flow at the preliminary Mohole site off Mexico. *Journal of Geophysical Research*, **69**(4), 741-748. doi: 10.1029/JZ069i004p00741

Wilhelm, H., Y. Popov, H. Burkhardt, J. Šafanda, V. Čermák, P. Heidinger, D. Korobkov, R. Romushkevich, and S. Mayr (2005). Heterogeneity effects in thermal borehole measurements in the Chicxulub impact crater. *Journal of Geophysics and Engineering*, **2**, 357-363. doi: 10.1088/1742-2132/2/4/S09

Williams, D. L., K. Becker, L. A. Lawver, and R. P. Von Herzen (1979). Heat flow at the spreading centers of the Guaymas Basin, Gulf of California. *Journal of Geophysical Research*, **84**(B12), 6757-6769. doi: 10.1029/JB084iB12p06757

Ziagos, J. P., D. D. Blackwell, and F. Mooser (1985). Heat flow in southern Mexico and the thermal effects of subduction. *Journal of Geophysical Research,* **90**, 5410-5420. doi: 10.1029/JB090iB07p05410

(Figures in the following pages)

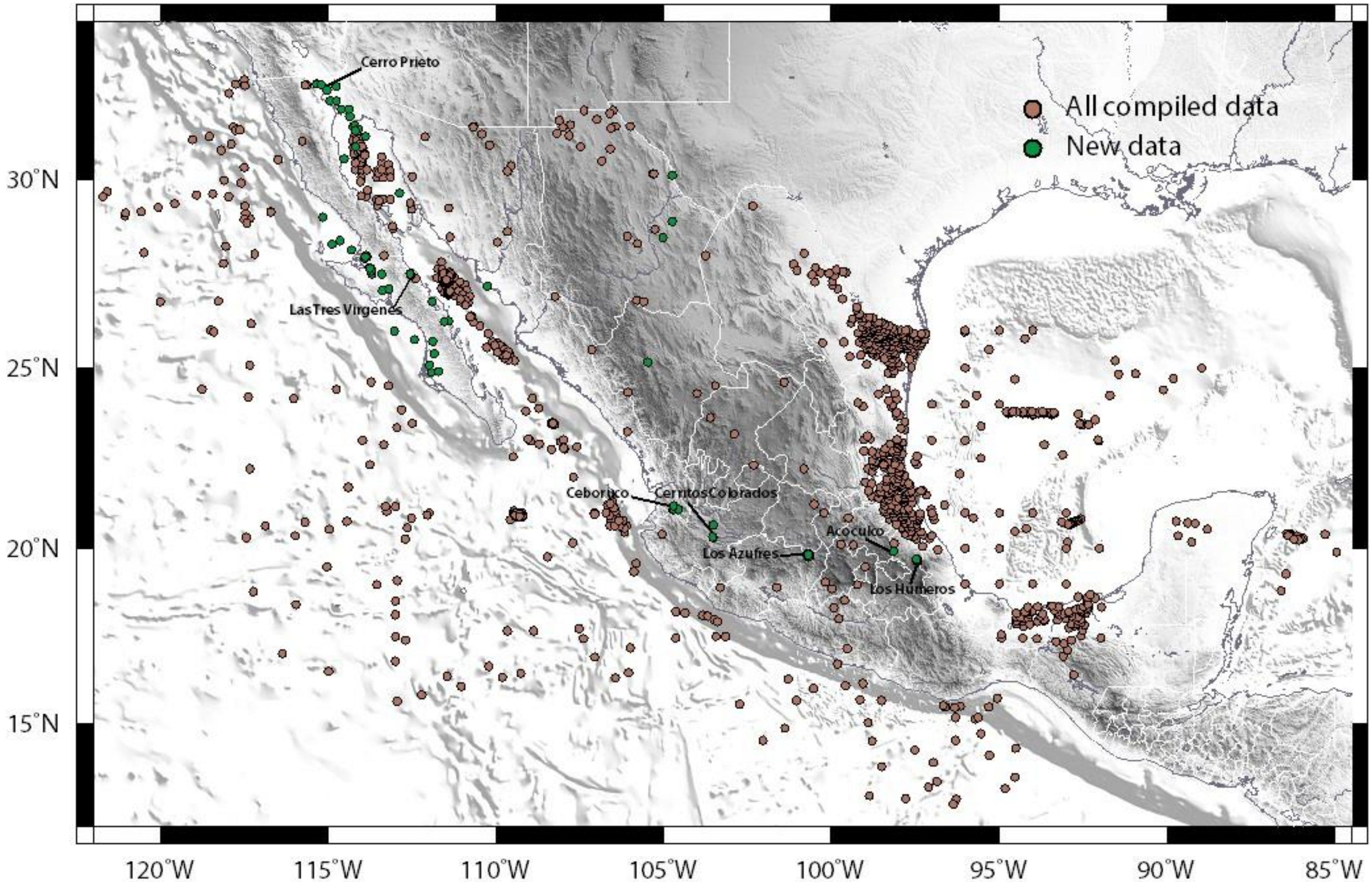

Fig. 1. The updated heat flow data base: Green (new heat flow sites); Brown (All compiled continental and off-shore sites). Location of the Mexican geothermal fields (Cerro Prieto, Las Tres Virgenes, Los Azufres and Los Humeros) and zones with possible exploitation energy (Ceboruco, Cerritos Colorados and Acoculco) are shown as reference of the areas with known thermal anomalies.

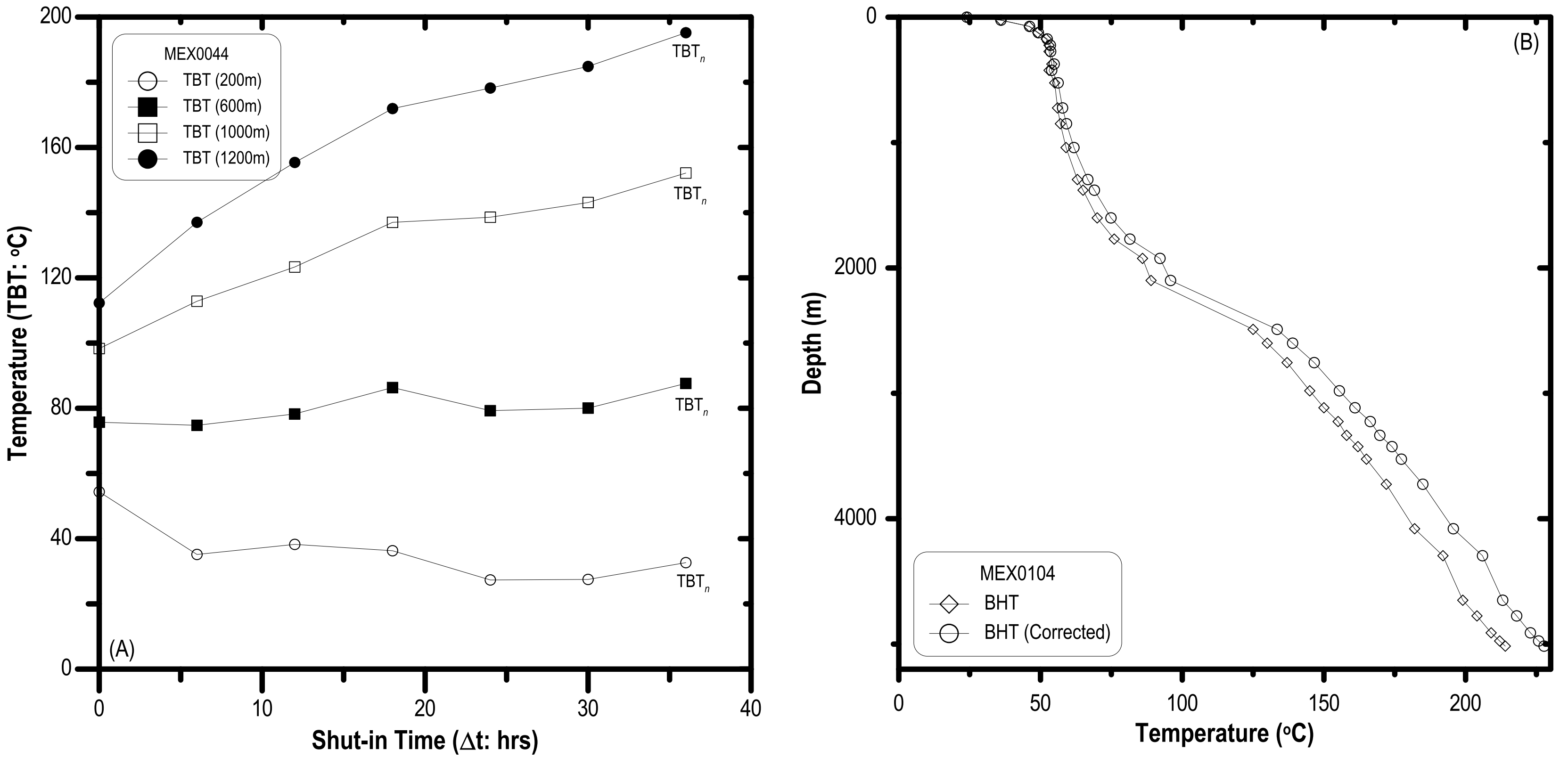

Fig. 2. (A) Plots of the transient borehole temperature (TBT) from the MEX0044 borehole. Last measured Transient Borehole Temperature (TBT_n). (B) Plot of the Bottom Hole Temperature (BHT) logged during drilling activities and the BHT corrected.

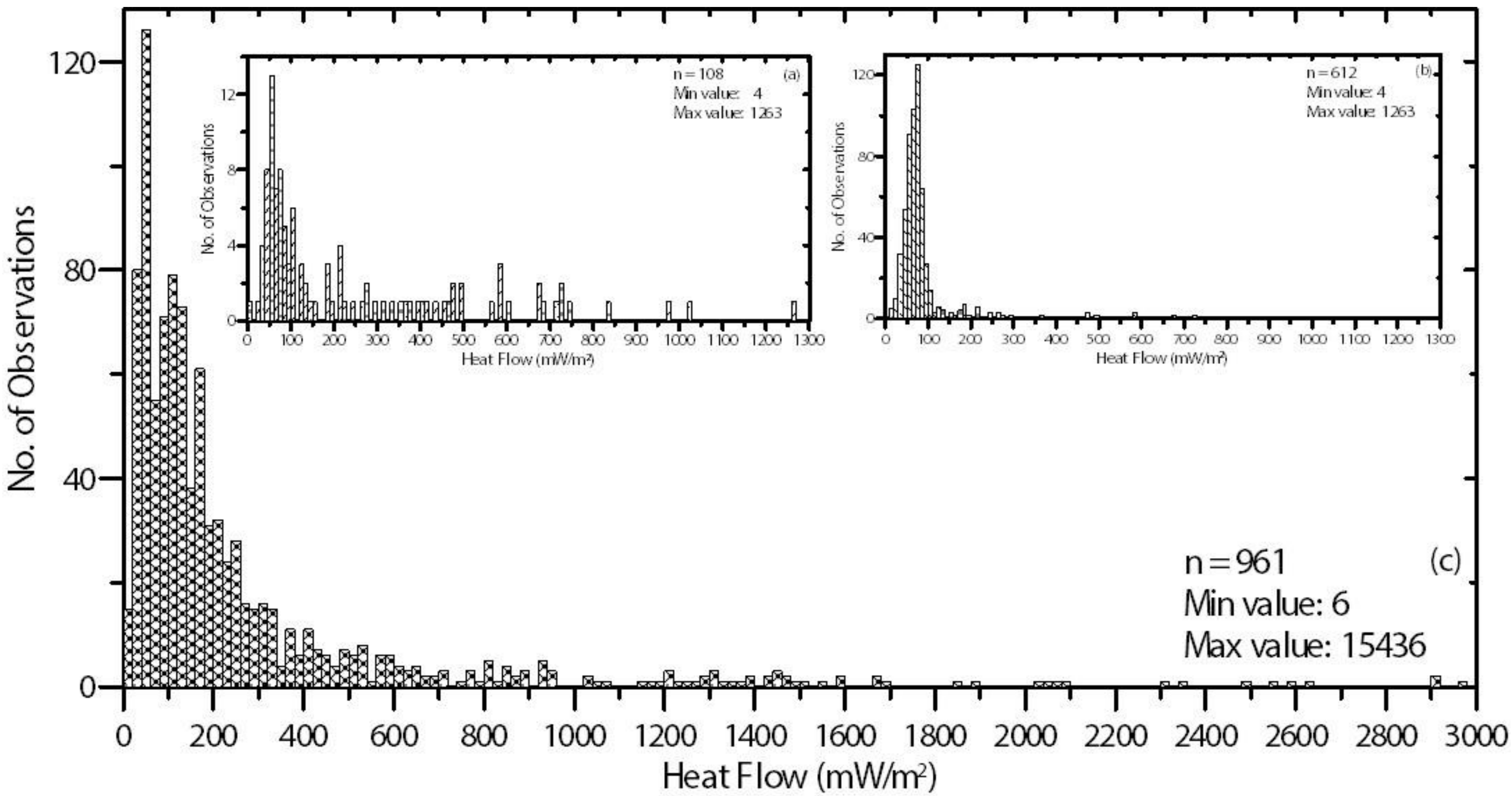

Fig. 3. Histogram plots of the overall heat flow measurements from México: (a) the new heat flow calculations; (b) all compiled continental heat flow values; and (c) all the compiled off-shore heat flow observations (due to space and the scale in the histogram plot, the values of 6250, 7115, 8910 and 15436 mW/m^2 were not included but considered in the analysis of data). The plots include the number of data (*n*), and the maximum and minimum numerical values.

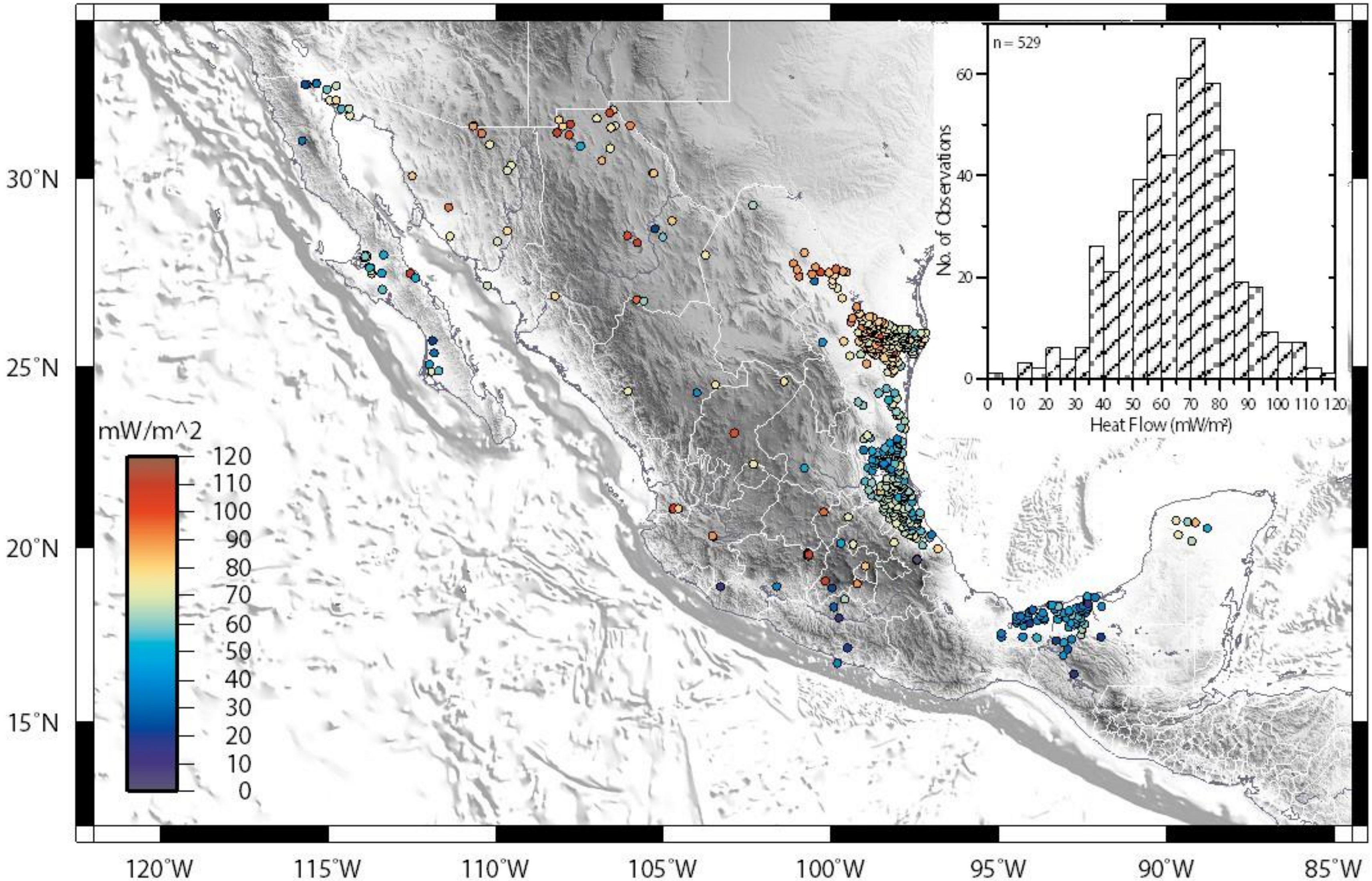

Fig. 4. Continental heat flow map of México (Update 2015). Histogram plot, location and distribution of the heat flow sites considered in the interval 0-120 mW/m².

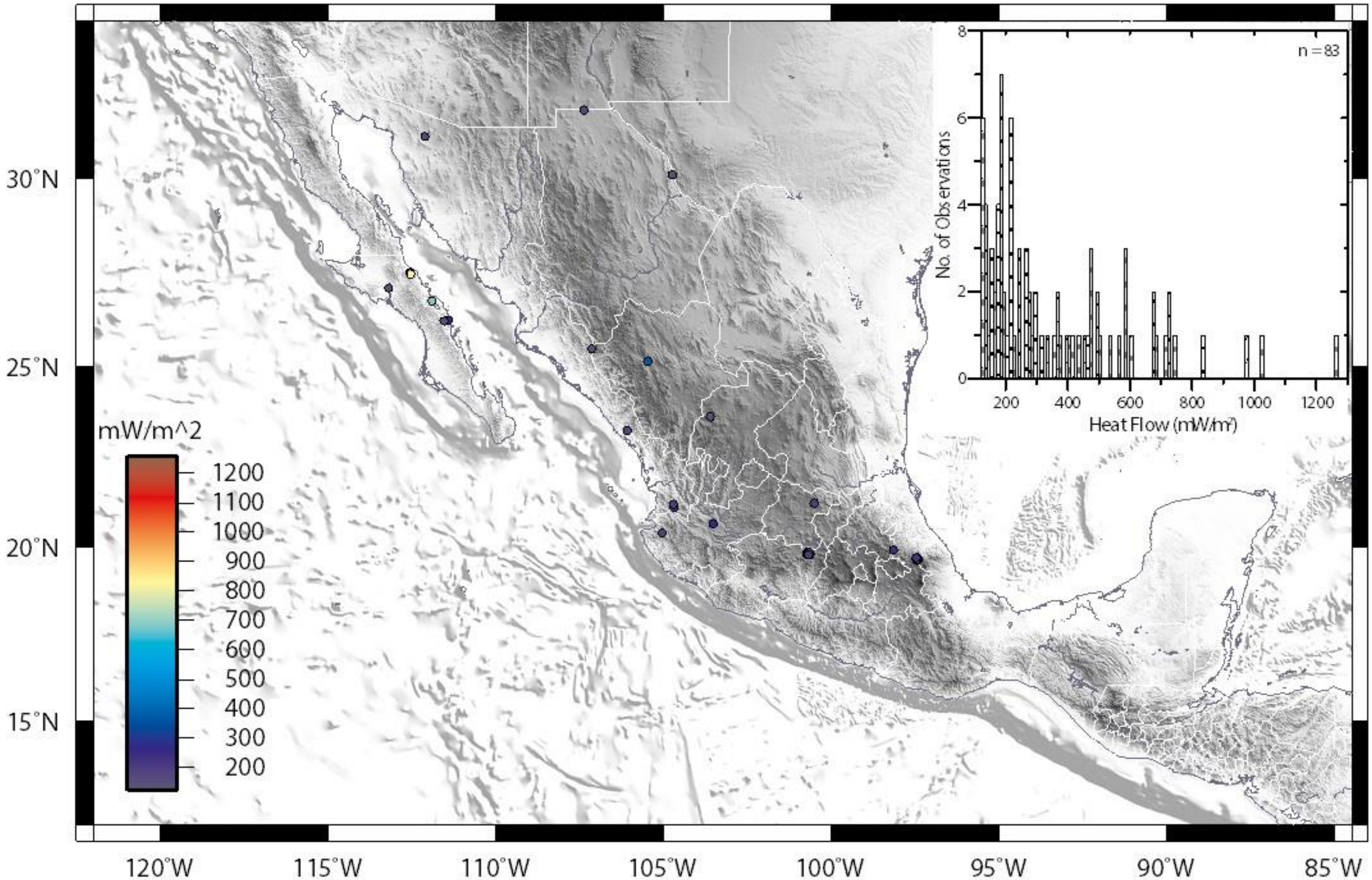

Fig. 5. Continental heat flow map of México (Update 2015). Histogram plot, location and distribution of the heat flow sites considered in the interval 120-1300 mW/m^2.

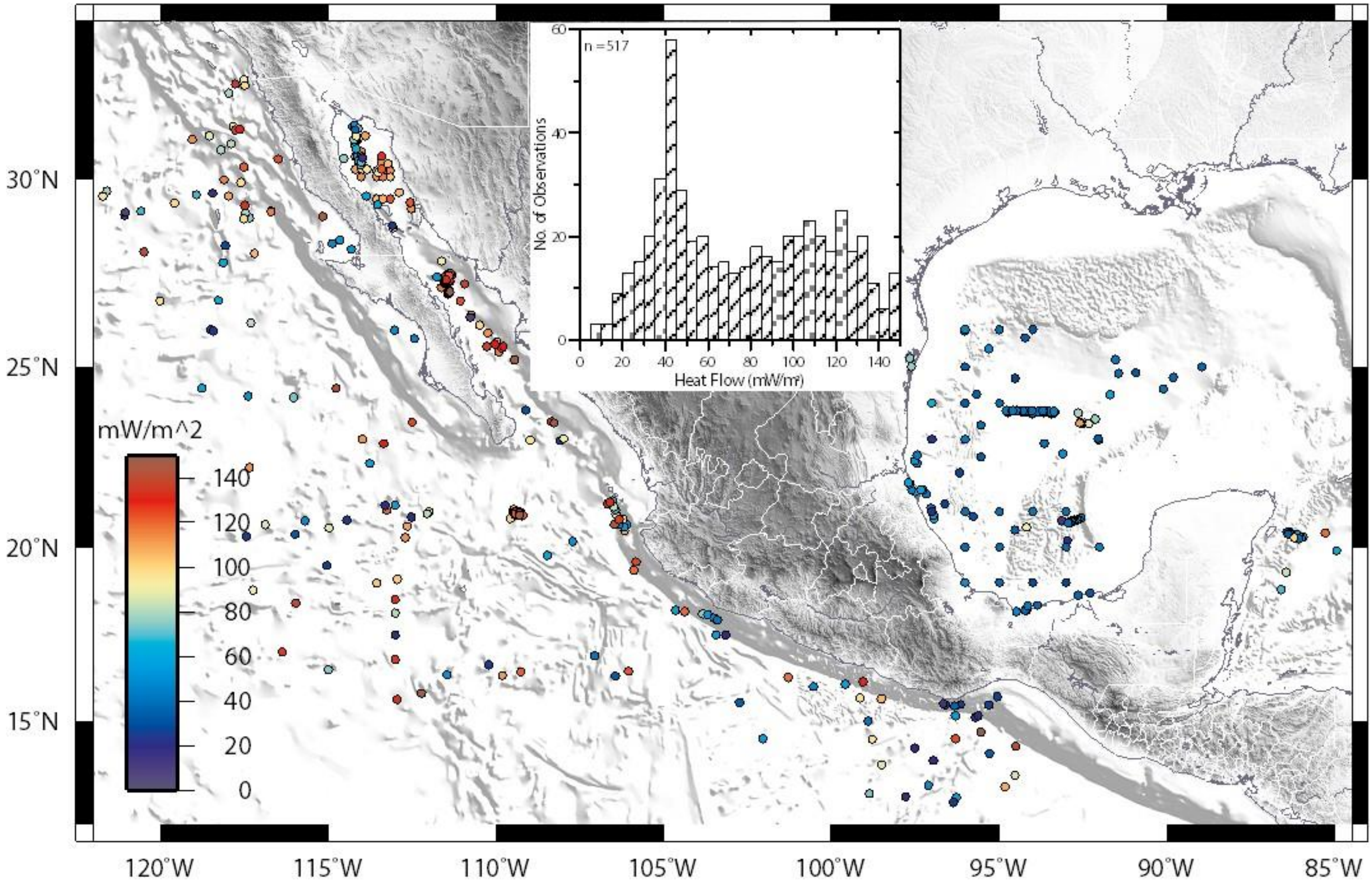

Fig. 6. Offshore heat flow map of México (Update 2015). Histogram plot, location and distribution of the heat flow sites considered in the interval 0-150 mW/m^2.

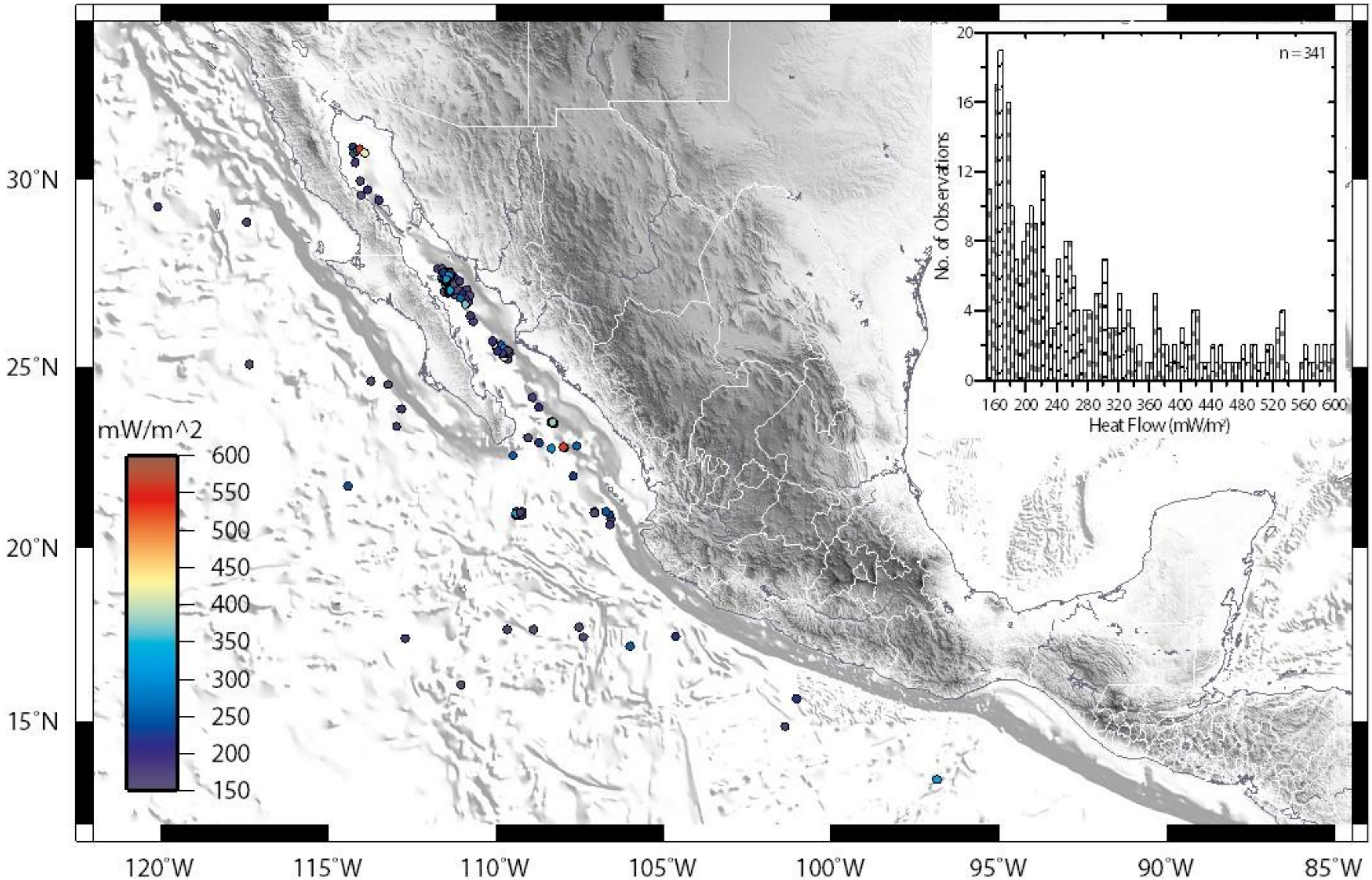

Fig. 7. Offshore heat flow map of México (Update 2015). Histogram plot, location and distribution of the heat flow sites considered in the interval 150-600 mW/m².

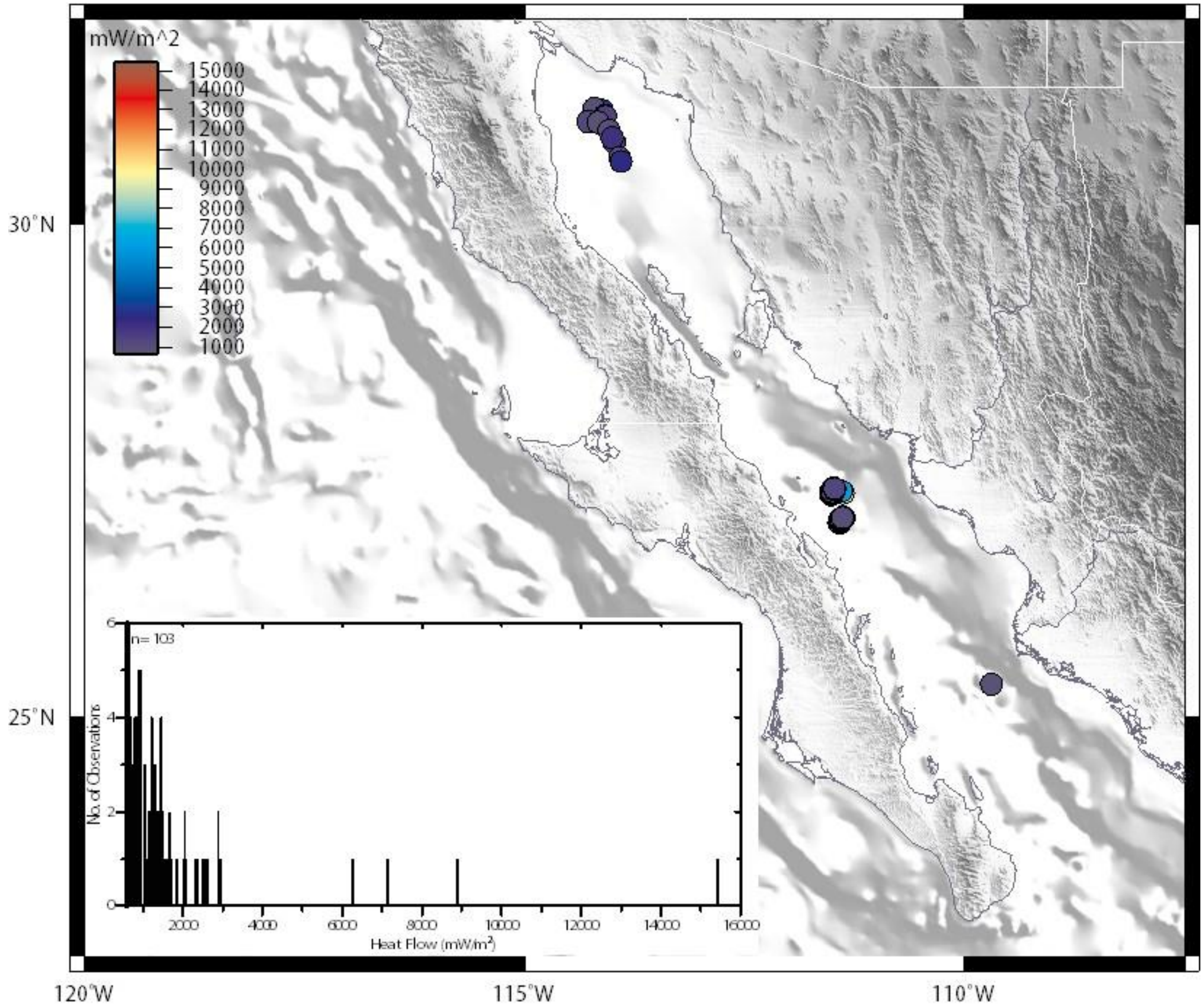

Fig. 8. Offshore heat flow map of México (Update 2015). Histogram plot, location and distribution of the heat flow sites considered in the interval 600-16000 mW/m.