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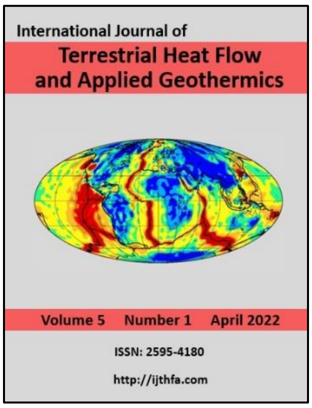

# The Deep South Portuguese Margin: An Attempt to Account for Heat Flow Density Variation in this Region.

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## Abstract

Heat flow data measured in a region characterized by a very high and non-uniform thickness (accretionary prism) of sediments, traversed by strike-slip faults in the E-W direction and thrust faults in the N-S direction, were analyzed. Mud volcanoes have been discovered in the region during the last 20 years. The region includes parts of the borders between the Eurasian and the African plates, at SW of the Iberian Peninsula. Sediment porosity and vertical fluid movements were inferred from thermal conductivity and thermal gradient data. Fault location and boundary of the sediment prism were used to test the results inferred and to explain the scatter in the published heat flow values. Special attention was given to values obtained in regions separating different geologic settings (Gorringe Bank – Horseshoe Plain and Marquês de Pombal fault region). Geoid height values were used to obtain information related with heat flow values from deep parts of the Horseshoe plain and in the Gorringe Bank located in the western part of the region studied outside the accretionary prism of sediments. Information related with the evolution of some transient properties in the region were obtained from geoid height variations using three models made for three different years. Information about the thermal disturbance caused by fluid movements in the region and the heat flow values without them were obtained at the end of the work.

## 1. Introduction

Data used in the present work were obtained in a seismically active region, located S and SW of the Iberian Peninsula in the NE Atlantic Ocean, including the Gulf of Cadiz, the Gorringe Bank and the Horseshoe Abyssal Plain (see Figure 1). The region includes part of the Eurasia-Africa plate boundary located between longitude values -7.5º W and -12º W. The two plates show at present a NW-SE trending convergence (3.8-5.6 mm $y^{-1}$) (DeMets et al, 2010). The plate boundary in the region is diffuse (Sartori et al, 1994) and a deformation band of 600 km with WNW-ESE trending lineaments (strike-slip faults) and NE-SW thrust faults crossing the lineaments, was identified (Zitellini et al, 2009). Tectonically speaking it is a complex region formed by continental crust in the Northern part, Atlantic Oceanic crust in the southern part and oceanic crust from Western Tethys (Martinez-Loriente et al, 2014) in the central part. In the Western part, the Gorringe Bank is a 5000 m high seamount oriented in a ENE-WSW direction, with a length of nearly 200 km and a width of 80 km. Mount Gettysburg the highest peak has it summit at a depth of 24 m under water (Girardeau et al, 1998). The Gorringe Bank is formed by exhumed mantle material of serpentinized peridotite enclosing a 500 m thick gabbro layer, locally cut and partly covered by tholeiitic rocks (Girardeau et al, 1998). A positive anomaly in geoid height and a positive Bouguer anomaly are associated to the Gorringe Bank.

In the eastern part of the region on study, the Gulf of Cadiz has a large sedimentary body emplaced in the region after the westward movement of the Gibraltar domain. Its main unit (the Allochthonous Unit of the Gulf of Cadiz, AUGC) is a mixture of Triassic to Neogene sedimentary units forming the thickest unit of the accretionary wedge’s sedimentary cover (Maldonado et al, 1999). The accretionary prism of sediments is delimited by a front of intense deformation named GCT (Gulf of Cadiz deformation front). A negative gravity anomaly in the region provides the location of the highest thickness of sediments.

Since 1999 (Gardner, J. M.,2001) mud volcanoes have been discovered and studied in the Gulf of Cadiz. Mud volcanoes associated with hydrocarbon-rich fluid venting and mud diapirism confirms the existence of high-pressured layers in the region and the occurrence of vertical fluid migration (Hensen et al,2007). Mud volcanoes located at approximately 4500 m water depth, 90 km west of the deformation front of the accretionary wedge of the Gulf of Cadiz (Hensen et al, 2015) were reported in 2015. Mud volcanoes found in highest water depths (>2500m) are associated to deep strike-slip faults (Hensen et al, 2015) through which fluids circulate.

The region studied is seismic and tectonic active. The date of the measurements presented in the work may be very important to discuss them and to understand that some changes may be happened since the measurement date until now.

Four works with heat flow values in the area were published by three different teams (Bullard and Day, 1961; Verzhbitsky and Zolotarev, 1989; Grevemeyer et al, 2009; Grevemeyer et al, 2017) including thermal conductivity and thermal gradient values measured in the region. New data about the region obtained and published in recent times are used in the present work to analyze and interpret the published results.

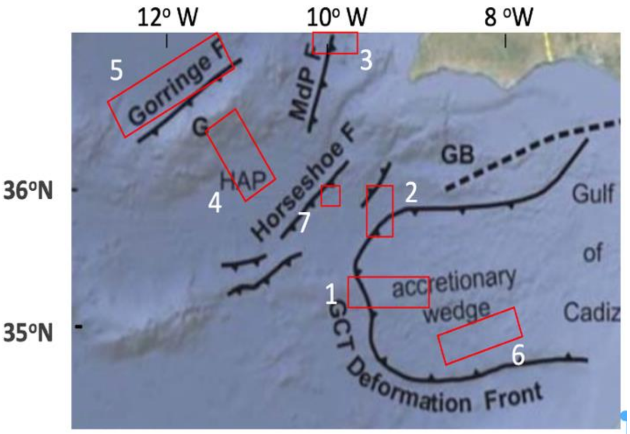

*Figure 1 – Regional map of sites studied in the present work. The red rectangles indicate locations with heat flow measurements. The letters indicate the following: G - Gorringe Bank, HAP - Horseshoe Abyssal Plain and MdP F - Marquês de Pombal fault. Strike slip faults crossing the region with W-E direction are not shown but thrust faults (nearly perpendicular to strike-slip faults) are presented. White numbers identify regions with heat flow density measurements.*

## 2. Thermal data in the region

Due to the scatter of thermal data and different structures in the region heat flow density values were divided into seven regions shown in Figure 1. We will first concentrate our study in data obtained near the borders of different media. The wedge deformation front separating the accretionary prism of sediments from the Horseshoe domain (regions 1 and 2), the Marquês de Pombal fault separating the continental slope domain from the Infante Don Henrique basin (region 3) and the Gorringe Bank and Horseshoe Plain near latitude values of 36 N degree (region 4). Region 5 is located at the western of the Gorringe Bank. The heat flow values obtained in the Cadiz Gulf (regions 1 and 6) and an isolated value (Bullard and Day, 1961) in the Horseshoe valley (region 7) will be studied at the end of the work.

Porosity data is inferred from thermal conductivity values, considering porous or small fractures filled with sea water. A value of 0.65 W $K^{-1}m^{-1}$ was used for thermal conductivity of sea water. Heat flow density data by conduction in the vertical direction were considered and thermal gradient values obtained from heat flow and thermal conductivity data.

Geoid height values in the region are not uniform and their variation from the year 1984 to 2008 was used to obtain information related with thermal transient phenomena in the region. A change in geoid height value in an oceanic region means a change in the mass under the sea in the region. Changes occurring during long periods of time may be due to mantle compensation related to superficial processes. The time interval used in our work is reduced (from 1984 to 2008) and the density variations associated with temperature variations in the region. The evaluation of mechanisms associated with the source of this transient thermal variations is out of scope of the work presented.

## 2.1 The Gulf of Cadiz deformation front

Heat flow measurements were made in regions 1 and 2 in December 2003, at latitudes near 35.5ºN and 35.9ºN (Grevemeyer et al, 2009). Thermal gradient values used in the present work were deduced from heat flow and thermal conductivity data measured in the region and published in 2009 (Grevemeyer et al, 2009). The western group of four measurements made in region 1 at latitude values near 34.5 ºN and longitude values near 9.67ºW shows uniform thermal conductivity values with small heat flow variations related with thermal gradient values. Ocean depths in the region, located on the eastern side of the Coral Patch Ridge (Terrinha et al, 2013-Figure 1) decrease from W to E. Thermal gradient values also decrease from W to E. Figure 2 shows the decrease of ocean depths and thermal gradient values in the region. Geoid height values obtained with GEM84 and GEM96 models (Online geoid calculator-Source Forge) shows identical values and a small increase of nearly 47 cm was found in model EGM2008.

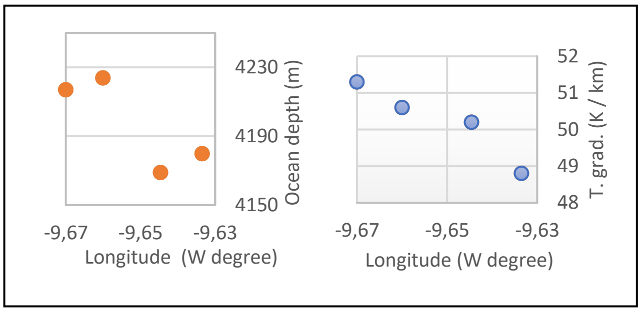

*Figure 2 - Ocean depth and thermal gradient values obtained in region 1 –Point D.*

Six heat flow density values were measured in region 2 (Grevemeyer et al., 2009). Thermal conductivity values obtained in the front are 5.3% higher than values obtained in region 1. Ocean depths and thermal gradient values of four points can be seen in Figure 3. The transition between the two sides of the front seems to be associated with a low thermal gradient and a high thermal conductivity values. Heat flow density values on the western side of the front are lower than values in the eastern side (high thickness of sediments). Geoid height values obtained with GEM96 and GEM 2008 shows differences of ≈6-7 cm but from GEM84 to GEM96 the decrease found is ≈ 1.7 -1.9 m.

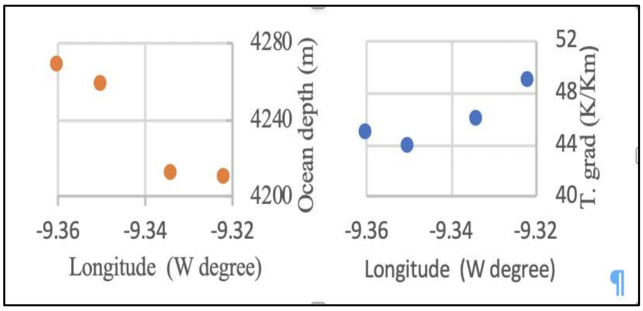

*Figure 3 - Ocean depth and thermal gradient values obtained at four points of region2.*

## 2.2. Marquês de Pombal (MP) Fault

Marquês de Pombal fault is a compressive tectonic structure located between Cape St. Vincent and the Bank of Gorringe (Region 3 in Figure 1). This fault has surface rupture and a total length of about 60 km (Gràcia et al., 2003). The heat flow data, measured in 2003 (Grevemeyer et al, 2009), were obtained in the northern part of the fault. Ocean depths between points in the western side of the fault and points in the eastern side of the fault shows a maximum value of 1467 m. Deepest ocean depths are located in the western side of the profile and thermal gradient and heat flow values present highest values in this region. High thermal conductivity values (the highest values in this work) were found in the eastern side of the profile. The values indicate clearly two media with different thermal properties separated by the fault. Figure 4 shows some ocean depth and thermal gradient values found in the region. Geoid height values obtained with the three models shows a decrease of ≈0.8 m from 1984 to 1996 and an increase from 1996 to 2008. Figure 4 shows thermal gradient and geoid height increase values from EGM96 to EGM2008 models in the region.

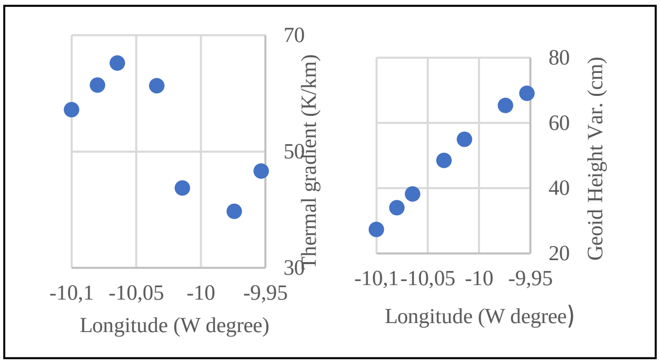

*Figure 4 - Thermal gradient values and differences in geoid height values obtained with models EGM 2008 and EGM96 in region 3 (near Marquês de Pombal fault).*

## 2.3 The Gorringe Bank and the Horseshoe Plain

This section located in the western side of the area studied is named as region 4 in Figure 1. The heat flow values used were obtained by two different teams. The older data were published in 1989 (with unknown date of measurement) (Verzhbitsky and Zolotarev,1989) and new data were measured in 2003 and published in 2017 (Grevemeyer et al, 2017). The information used was obtained between latitude values 36.1ºN and 36.4ºN. Three heat flow values are analyzed in this region. The western point shown in Figure 5 is located in the Gorringe Bank, mainly formed by peridotites and serpentinites covered by a small thickness of sediments. Heat production due to radioactive elements in these types of rocks are low and heat flow and thermal gradient values are lower than values found in the Horseshoe plain. Ocean depths in the Horseshoe plain show the highest values used in the work. Ocean depths and thermal gradient values measured in the three points (Verzhbitsky and Zolotarev, 1989) are shown in Figure 5. Thermal conductivity values between 1.09 and 1.11 W $K^{-1}$ $m^{-1}$ were obtained (Verzhbitsky and Zolotarev,1989). The highest heat flow value measured in the region is 66 mW $m^{-2}$.

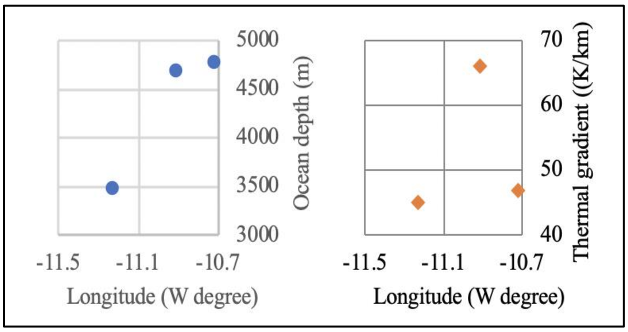

*Figure 5 - Ocean depth and thermal gradient values obtained in the Gorringe Bank and in the Horseshoe plain (Data from* Verzhbitsky and Zolotarev, 1989).

In addition to heat flow data, measurements of $He^4$ content were made in two points (Verzhbitsky and Zolotarev, 1989) with positive anomalies. The $He^4$ content is highest in the point with the highest heat flow value. The helium measurements were made before 1989 geoid values in the region were obtained with models EGM84 and EGM96. The geoid height value found on Gorringe Bank point (Longitude of 11.23 W) is ≈ 50.5 m. A decrease was found between EGM84 and EGM96 data with the highest value (≈ 3.9 m) at longitude value of 10.72 W degree.

Two heat flow density values were published (Verzhbitsky and Zolotarev 1989) in zone 5 of Figure 1. Thermal conductivity data found in this region present low values, but a high thermal gradient was found at the point located in the southern part of the region (latitude 36.93ºN and longitude 12ºW) suggesting a region with large water content (implying high porosity). Ocean depth values in this region are higher than values obtained in the horseshoe plain. Heat flow density values of 56 and 65 mW $m^{-2}$ were found (Verzhbitsky and Zolotarev 1989). Geoid height values decrease from the model value of GEM84 to that of GEM2008, but the difference is ≈ 3 m in the southern parts and ≈ 60 cm in the northern parts. The decrease observed between model values of EGM96 to EGM2008 is ≈12 cm and ≈ 96 cm respectively.

## 2.4 The Cadiz Gulf

Region 1 and region 6 of Figure 1 are located in the Cadiz Gulf. Four groups of four heat flow measurements were made at latitude values near 35.5ºN (Grevemeyer, et al. 2009). The western group, denominated in this work as group D, was included in section **2.1**. The data groups E, F and G are located to the east of group D. The lowest heat flow density value in the region was obtained in G due to a thermal gradient value of 29.5 K/km and a thermal conductivity value of 1.09 $WK^{-1}m^{-1}$. Thermal gradient values of 43-45 K/km were obtained in Group F.

A thermal conductivity value of 1.06 $WK^{-1}m^{-1}$ suggest a water content increase due to the low thermal conductivity of water. Low thermal gradient values may be associated with vertical downward movements of water. Looking to a tectonic map in the region (Hensen et al, 2015) it is possible to note that G is located in the region of a strike-slip fault with possible water entry and vertical movement from the top (ocean bottom) to larger depths. F is located close to Bonjardim mud volcano characterized by fast fluid movement in the vertical direction and open pores allowing fluid content sufficient to lower the thermal conductivity values in the region (1.08-1.09 W $K^{-1}$ $m^{-1}$). Geoid Height values found in groups F and G decrease from EGM 84 to EGM 2008, but the differences found are very small and negligible compared to those observed on other points of measurement. The values found for Group E shows a small increase of ≈20 cm from EGM96 to EGM 2008.

Sixteen heat flow measurements were measured over Profile Seismar-16 (Grevemeyer et al, 2009) in the region 6 of Figure 1. Two heat flow values (171 and 112 mW/$m^2$) located to the east of profile SISMAR 16 (Grevemeyer et al. 2009) seems to be associated to hot water entry in the region. The southern group of data denominated A is formed by three heat flow values in the range 47-49 mW/$m^2$ and thermal gradient values of 42-43 K/km. The central group, denominated B, is formed by nine heat flow measurements with values from 47-52 mW/$m^2$ and thermal gradient values of 36-55 K/km. The northern group, denominated C, is formed by two heat flow values obtained at latitude values close to 35.18° N, with thermal gradient values of 47 K/km and heat flow values of 53 mW $m^{-2}$. Ocean depth values near 3700 m were found in group A, while values from 3200m to 2800 m were found in group B and value near 2240 m was measured in group C. Geoid height values found in points of region 6 are the lowest values found in this work. They increase from values of EGM 84 to EGM96 models, but the differences found are lower than ≈ 64cm in group C, 50 cm in group B and 30 cm in group A.

## 2.5 Region 7

A single value of heat flow (36 mW /$m^2$) located near 36ºN latitude and 10ºW longitude (Bullard and Day, 1961) was measured in November 1954. This low value is due to a low thermal gradient of 37.5 K/km and a thermal conductivity value of 0.97W $K^{-1}$ $m^{-1}$. The ocean depth in the area is 4534 m. The low thermal gradient value suggests possible downward movement of cold water. A strike-slip fault was identified in the region close to this point of measurement (Duarte et al. 2010; Corela et al. 2017; Martinez-Loriente et al. 2021). Geoid height values in the region decrease from those of EGM84 to EGM 2008. The difference obtained is ≈2,.7 m. The heat flow measurement was made in the year of 1954. No information about geoid height values was found for this date.

## 3. Discussion

The highest values of thermal conductivity were obtained near the sedimentary wedge deformation front (region 2). This fact was attributed to high pressure values and possible closure of pores that gave rise to low water content.

The lowest thermal conductivity value presented in the work (excluding values of region 5) is 0.97 W $K^{-1}$ $m^{-1}$ (Bullard and Day,1961). Using 1.19 W $K^{-1}$ $m^{-1}$ as the thermal conductivity of sediments and 0.65 W $K^{-1}$ $m^{-1}$ for the thermal conductivity of seawater, a value close to that referred is obtained with a water content of 40%. This value is in accordance with the published thermal conductivity data (Bullard and Day,1961). Using the same method, it is possible to find a water content of ≈11 % in the points of group D (region 1).

The data obtained in the two profiles traversing the Gulf of Cadiz deformation front (Figure 2 and Figure 3) clearly shows the transition from the two domains, but some differences can be seen in thermal gradient and heat flow data values of the two profiles. We must note that values obtained at 35.5° N latitudes are located in a region with mud volcanoes (Hensen et al, 2015). Porto mud volcano is located slightly north of 35.5ºN latitude and in longitude values located between groups D and E. Low thermal gradient values obtained in the eastern parts of group D and the first western point of group E may be due to vertical movement of water. No mud volcanoes are known near the profile located at 35.9ºN latitude (region 2). The heat flow values are clearly higher in the eastern part of the profile.

The Bonjardim mud volcano is located slightly south of 35.5ºN at longitude values of group F. Low thermal conductivity values measured in this group (1.06-1.09 W $K^{-1}$ $m^{-1}$) suggest the presence of water contents of 18.5-24.0 % using the method described.

Geoid height variations obtained with models EGM84 and EGM2008 in the regions of mud volcanoes Bonjardim, Porto are very small and may be considered null compared with values obtained in other points in the region.

Group G is located near a strike –slip fault and thermal conductivity values of 1.08-1.10 W $K^{-1}$ $m^{-1}$ were measured suggesting water contents of 17-21 % in the region. Thermal gradient values suggest the presence of vertical descending water movements in the region (probably through the fault).

A good correlation was found near the borders of Marquês de Pombal fault (Region 3 in Figure 1) between ocean depth and thermal conductivity data with highest thermal conductivity values obtained in the eastern side of the fault where lowest ocean depths were found. Thermal gradients and heat flow values are lower Thermal gradients and heat flow values are lower in the eastern side of the fault despite the higher values of thermal conductivity. Geoid height values are similar in both sides of the fault, suggesting that the heat flow difference obtained between eastern and western sides of the fault may be due to a local and crustal heat production anomaly.

The heat flow values obtained in 1989 in regions 4 and 5 presumed to be imprecise values due to the decrease of the geoid values since 1984 to 2008 (see Figure 6 and Figure 7). The decrease of geoid height values found with models EGM84 and EGM2008 (Online geoid calculator-Source Forge) is ≈ 3.56m in the eastern point (longitude 10.72ºW) and ≈ 3.26 m in the point near Gorrindge Bank (longitude 10.91ºW) but the geoid height values found in model EGM2008 is higher in the point with the highest heat flow value (see Figure 6).

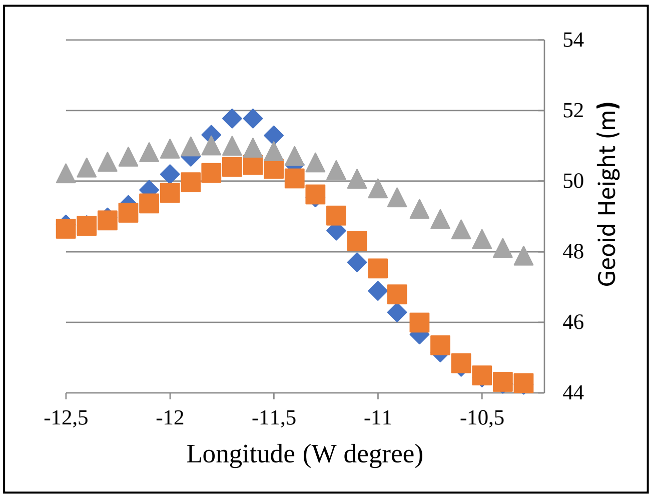

*Figure 6. Geoid height values at longitude 36.3ºN obtained with models EGM84 (grey triangles) EGM96 (orange squares) and EGM2008 (blue diamonds). (Values obtained with* Online Geoid Calculator –GeographicLib, Source Forge)

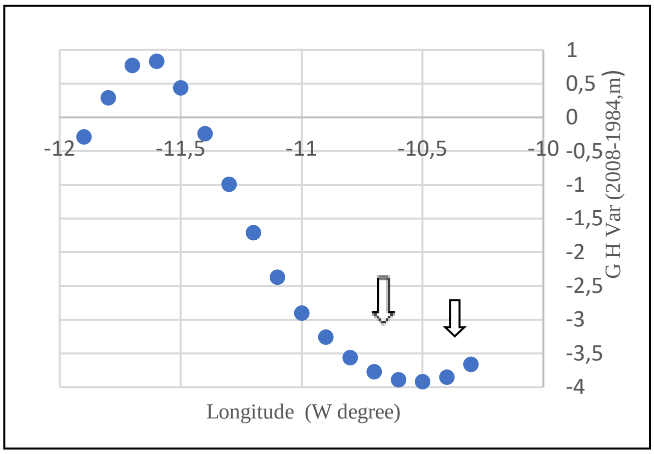

*Figure 7. Geoid height variation from EGM84 to EGM2008 in latitude values36.3ºN. (Values obtained with* Online Geoid Calculator – GeofraphicLib Source Forge). *Arrows indicate the position of the two points with heat flow measurements in the Horseshoe plain.*

The vertical profiles presented for the region by many authors suggest the presence of serpentinites under the sediments layers and, in some parts of the horseshoe plain some ridges of this rocks were detected (Martinez-Loriente et al. 2014) and this fact (differences in height from bottom of the ocean to the top of the basement) could be a reason for the differences found. Heat flow values obtained by other author in the same region (Grevemeyer, I., et al. 2017) are between the two values presented in 1989 and the geoid height decrease obtained with values from EGM84 and EGM2008 models are ≈ 3.4 m. This value is located between the value obtained for the point with the highest heat flow and the value obtained for the point with the lowest heat flow value.

He$^4$ measurements (Verzhbitsky and Zolotarev, 1989) show a positive anomaly over points located in the horseshoe plain suggesting a connection with deeper zones. The He$^4$ positive anomaly was not found at points in region 7.

The values of the thermal gradients and uncorrected heat flow seems to increase from East to West.

The highest heat flow value obtained in the region is 66 mW m$^2$ but this value was published in 1989. Since then until 2008 a decrease in Geoid height values occurred in the region at longitude values with heat flow measurements suggesting cooling of the region. Figure 8 shows the geoid height variation in latitude values 36.9ºN.

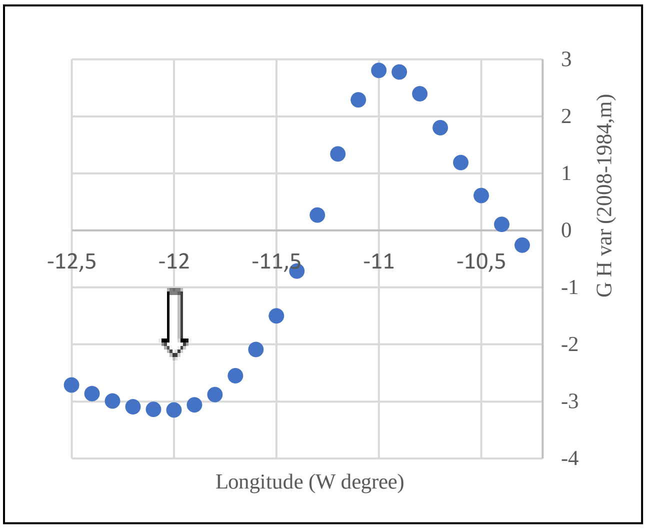

*Figure 8. Geoid height variation from EGM84 to EGM2008 in latitude values 36.9ºN. (Values obtained with Online Geoid Calculator – GeographicLib, Source Forge). The arrow indicates the position of the points with heat flow measurement in the southern part of region 5 (see Figure 1).*

## 4. Conclusion

The scatter of the heat flow density data in the Gulf of Cadiz can be explained by water content (and its influence on thermal conductivity values and effects of vertical upward/downward movements of water on thermal gradient values). This conclusion is supported by the existence of mud volcanoes in the region and low thermal conductivity and heat flow values in measurements made close to strike-slip faults. Heat flow values of 58-59 mW m$^{-2}$ may be found in points of the Cadiz Gulf where mud volcanoes are absent.

Higher values of heat flow were obtained in the Horseshoe Plain region. The main difference between heat flow values seems to be related with thermal gradient values decreasing when distance to Gorringe Bank increases. An inverse relation was found between heat flow and geoid height values in the Horseshoe plain.

Geoid height values obtained with model EGM84 are high values in the entire region but a decrease happened in EGM96. The highest value of this decrease was obtained in the Horseshoe Plain. Nearly zero variation was found in Bonjardim mud volcano and Porto mud volcano points.

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