An Evaluation of the Heat Flow Anomalies in the Espírito Santo Basin, Brazil.

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This paper was prepared for presentation during the 11th International Congress of the Brazilian Geophysical Society held in Salvador, Brazil, August 24-28, 2009.

Abstract

Determination of the Earth's long-term surface heat flow is an important issue in petroleum exploration because it controls the depth / size of the kitchen zones, the amount of generated petroleum, the time of oil expulsion from the source rock, the reservoir temperature, and the oil quality.

The Espirito Santo Basin is a relatively well explored basin, with the main geological characteristics of a typical passive margin. Some thermal anomalies have been identified in the past but plausible explanations have not been demonstrated for their causes. Heat flow estimation is part of the workflow in petroleum system modeling but it is not always correctly estimated and the anomalies are not easily explained due to the large number of parameters involved. Several possible causes are investigated and the main conclusion is the detection of present heat flow values between 70 and 90 mW/m^2, much higher than 41.2 mW/m^2, which is the background value expected after the thermal decay of a 130-120 Ma old rifted margin.

Introduction

Espirito santo is located north of Campos Basin, in the eastern Brazilian margin (Figure 1). Several studies were performed in this basin for academic and exploration purposes (e.g., Costa, 1988). Some comments were made about discontinuities on vitrinite reflectance profiles measured in exploratory wells that were probably caused by thermal variations that existed in depth or time in the basin. However, the thermal condition and its possible causes were never properly discussed.

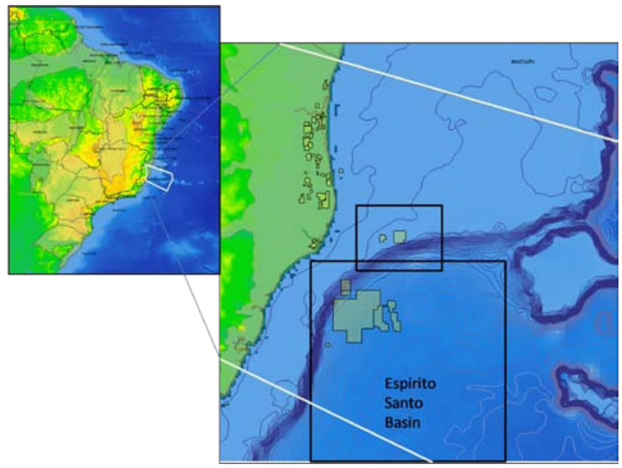

Figure 1- Location of the Espirito Santo Basin. The black polygons represent the two studied areas. The small rectangle in the north is referred here as area 1, whereas the big one is referred as area 2.

A common approach to evaluate the thermal structure of a sedimentary basin in petroleum exploration is the application of deterministic simulation of fluid and heat flow combined with salt restoration. In this study we used PetroMod 3D (vs 10) from IES which takes into account all factors that impact the thermal signature of a basin, like lithospheric heat flow, radiogenic heat content of the crust and the sedimentary rocks, thermal conductivity, fluid effects, erosion and compaction variation. In this study we apply backstripping technique and the resultant theoretical subsidence of the basin is interpreted on the basis of non-uniform stretching models. The results of this approach are heat flow maps that had to be adjusted to honor the temperature and maturation data measured in the basin. The heat flow maps were then applied as boundary conditions in the 3D geological model that HRT & Petroleum built for the Espirito Basin. Several deterministic simulations, that also take into account realistic thermal properties of the sedimentary rocks and geologic-based salt restoration, were processed in order to solve the thermal problem.

Methodology

The boundary conditions that most influence the amount and the distribution of petroleum are basal heat flow, paleowater depths and surface water interface temperature (SWIT). The upper boundary condition is temperature at the sediment/water interface, whereas the lower boundary condition is heat flow. Both vary along the life span of the sedimentary basin. Paleowater depths are important because they control the temperature values at the sea bottom and the tilting of the whole sedimentary section. The tilting is one of the factors that control petroleum migration directions. Basal heat flow is the first order factor that controls the whole temperature configuration of the sedimentary basin, hence temperature of the reservoirs, the amount, quality and timing of hydrocarbon generation. Heat flow values are usually obtained by comparing tectonic subsidence curves in wells with theoretical curves derived from McKenzie type of models (uniform and non-uniform lithospheric stretching models).

Paleowater depth maps were estimated based on structural and isopach maps integrated with well data. In deep water area, the maps were restored based on tectonic subsidence trends, which were estimated via the Crustal Heat Flow tool. With this methodology the paleowater depth maps reflect correctly the deepening of the basin through time. Temperature at the surface water interface: is estimated via the automatic mode in PetroMod 3D (based on WYGRALA, 1989). This program estimates the temperature at the sea bottom through time of the 3D framework and takes into account the reconstruction of the drift movements of the South Atlantic continent through time. The program also takes into account the decrease of temperature of the sea bottom as it gets deeper.

The thermal properties of the basin are introduced in the 3D model as part of detail facies maps that were defined based on seismic and well data. A comprehensive set of well data, 2D and 3D seismic data were used to depict the structural framework and to map the main stratigraphic sequences in the two studied areas of the basin (Figure 1). The 3D geological framework of the basin has high resolution features (cell size is 250m in area 2) and it was used as input for the tectonic subsidence analysis.

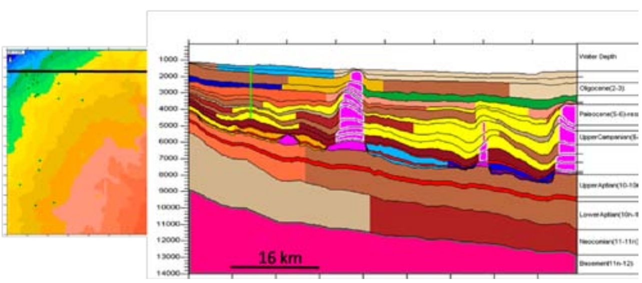

Figure 2 – Illustration of an east-west cross-section along the southern studied area 2.

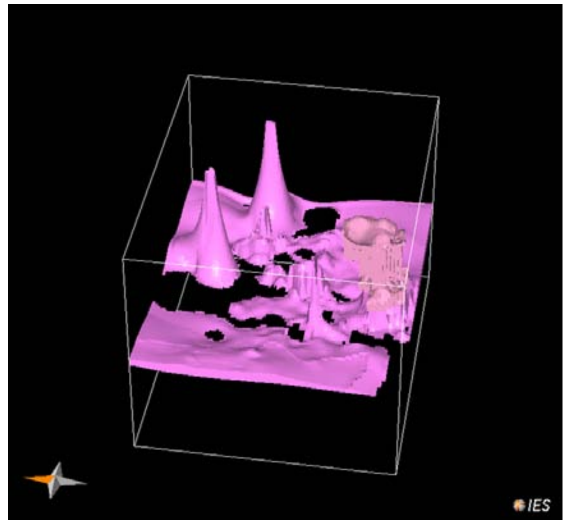

Figure 3. 3D view of the salt layer at present day in the area 1 (north). Note an overhang salt structure in the southeast corner of the area. The volcanics of Abrolhos might have influenced the formation of salt diapirs in this area (Guerra, 1989).

Figure **2** and Figure **3** gives a partial view of how salt is distributed in the basin. Numerous salt pillows exist in the proximal areas, whereas salt diapirs are better developed in deep water. To achieve salt restoration the total mass of halite was kept constant along the basin history. Particular attention was given to the estimation of the original salt distribution and to the opening of salt windows during the geological evolution of the basin. The distribution of the salt in the past and in the present day is important because halite has high thermal conductivity. Thick salt layers and large diapirs facilitate the heat conduction to the upper sequences, and as such remove the heat and lower the temperature in the sub-salt sequences (see *Figure 8*).

Tectonic Subsidence

The 1D backstripping technique consists in estimating the depth to basement through time by removing other factors that are not tectonic related like compaction, density effects, sea level and the loading effect of the sedimentary rocks without their associated isostatic consequences (Steckler & Watts, 1978). This way the tectonic effects in the basin can be isolated and their implications in terms of heat flow can be understood by means of theoretical lithospheric stretching models (Hellinger & Sclater, 1983). There are two main tectonic events that are expected to exist in subsidence plots. The first and most prominent is the rifting event that took place during the early Cretaceous. The second is the large-scale igneous event that formed the volcanic province in the Early Tertiary known as Abrolhos.

Figure **4** and Figure **5** illustrate the backstripping technique built in the Crustal Heat Flow tool from PetroMod. It is an advanced tool that estimates heat flow based on: tectonic subsidence calculated by traditional backstripping of layers (1D) (Steckler and Watts, 1978) and theoretical subsidence calculated by non-uniform stretching models. The tool incorporates also salt thickness variation in time. The results of this tectonic processing are tectonic subsidence maps and a complete set of heat flow maps that correspond to each stratigraphic age of the model. The non-uniform stretching model of Hellinger and Sclater (1983) was used, with rift duration equal to 131-120 Ma. Original crustal thickness was considered as uniform in the area and equal to 40 km. The pre-rift mantle was considered 125 km thick.

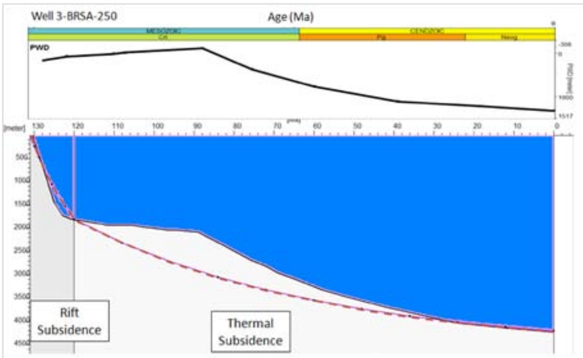

Figure 4 – Tectonic subsidence plot of the well 3-BRSA-250 (blue area). The dashed line is the theoretical subsidence associated with crustal stretching δ= 3 and mantle stretching β=3.5. The black continuous line in the top is the paleobathymetric evolution.

The observed subsidence curve does not match very well the theoretical curve between 110 and 60 Ma, probably related to inaccurate paleowater depth data. Some errors related to compaction correction might also be included.

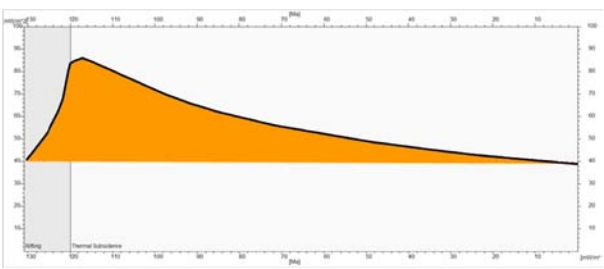

Figure 5 - Heat flow evolution for the well 3-BRSA-250, as a consequence of the stretching and tectonic subsidence shown in the previous figure. The heat flow peak is 85 mW/m^2 at 117 Ma.

Based on mass balance of the lithosphere and isostatic considerations, it is clear that the degree of extension of the crust is the controlling factor of total (and final) subsidence of sedimentary basin. However, the subsidence rate and the magnitude of the rift subsidence are also controlled by the mantle stretching. Therefore, isopach of the rift sequences play an important role in this analysis.

The sensitivity analysis performed in this study revealed that if the rift is 20% less thick than interpreted in this reference model, than the stretching factors are smaller, δ= 2.25 and β=3.15. The associated heat flow peak in this case is 10 mW/m^2 smaller and takes place 5 ma after the end of rifting (115 Ma). Note that the heat flow peak takes place during Albian times and not during rifting because of the natural delay related to heat conduction throughout the entire lithosphere. Heat flow peak taking place in Albian times has been erroneously interpreted as a longer rift period, extending into post-salt period.

The backstripping was applied in multiple wells and the results were contoured in order to get stretching factors and heat flow maps (Figure **6**).

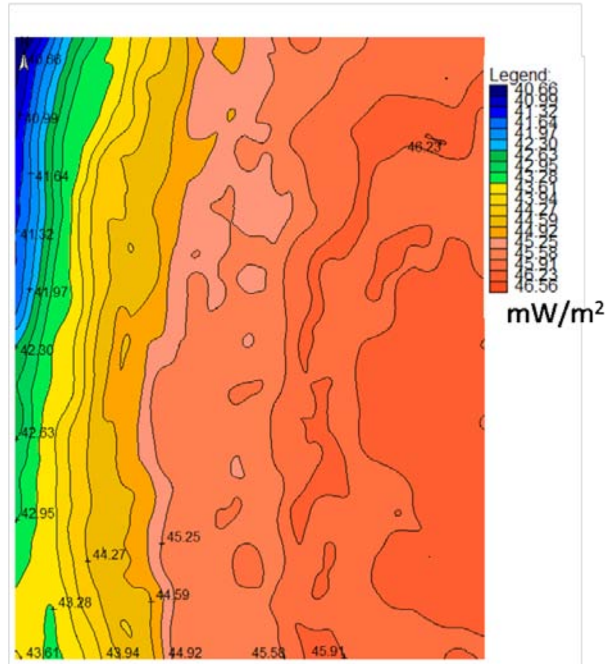

Figure 6 – Present day heat flow map of the area 2 estimated with the Crustal Heat Flow Tool. The heat flow values increase from shallow to deep waters and the values above 41.2 mW/m2 represent the thermal residue of the rifting process.

The heat flow map of *Figure **6*** does not calibrate the temperature data measured in exploratory wells of the area. The map that matches the well data does not follow only the trend of the figure above. There are other factors creating heat flow anomalies in the basin. An optimized heat flow map will be presented.

Calibration of the Thermal Model

The heat flow maps, for the past and present day, are then applied as boundary condition in the 3D model, which is a basic requirement for a heat flow simulator.

To calibrate the simulation results, several wells that cover a wide range of depth and area of the basin were selected from HRT database (BrazilGeodata) in order to check the model. Measured values of vitrinite reflectance, BHT temperature data, Tmax and oil geochemistry were used to check those parameters estimated by the simulator (e.g., Figure **7**).

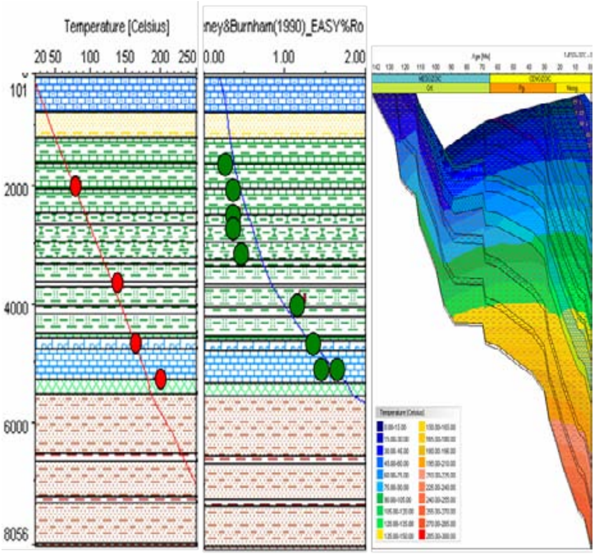

Figure 7 – Temperature and vitrinite reflectance (%Ro) depth profiles of a well in the Espirito Santo area.

The heat flow variation throughout the basin was evaluated in order to distinguish influences caused by salt diapirs (e.g.: Figure **8**) from those originated from the crust.

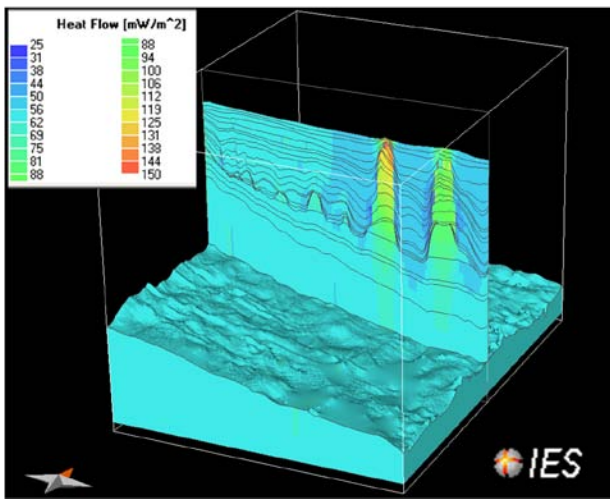

Figure 8 - Heat flow anomalies associated with salt domes structures in the area 2. Note the high values (above 100 mW/m^2) at the top of the diapirs and low values in the areas around them.

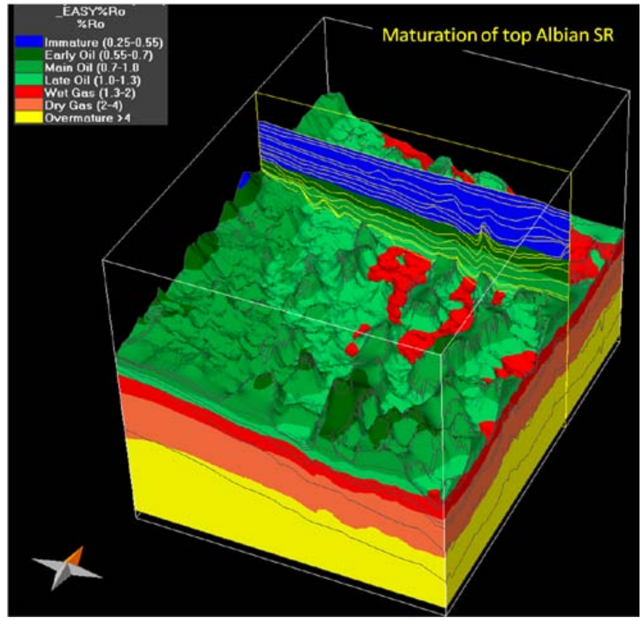

Figure 9 – A 3D view of the maturation map of top Albian source rock. The maturation was estimated using the Sweeney and Burnham (1990) %Ro kinetic. The heat flow maps used as basal boundary conditions have strong influence on the maturity maps.

Important source rocks in the basin are the Mariricu-Cricaré formations. They are thermally immature in most of the onshore part of the basin and are mature to highly mature in a belt along the present-day shelf zone. The source rocks from the rift sequence on the outer shelf are deeply buried and have reached an overmature stage of thermal evolution, suggesting today to be a gas to condensate-prone area.

Oils derived from the Peroá/Cangoá and Fragata gas-condensate fields are composed of mixtures of highly thermally cracked oils derived from deep sources in the pre-salt sequences, although there is influence of less mature black oils sourced by shallower source rocks of the marine sequences. These are first order observations consistent with the heat flow maps estimated in this study.

Temperature well data are presented from south to the north part of the basin in order to identify remnant thermal anomaly related to the Abrolhos Volcanics. This study will show what parts of the basin have normal heat flow values and others that are anomalous.

This work is of great value for the exploratory works on the basin, since it has impact on the prediction of the distribution, amount and mainly on the oil quality expected in the pre-salt layers. Additionally, this kind study if extended to the onshore parts areas might enhance or rule out the potential of geothermal energy in the basin.

Acknowledgments

We are grateful to all HRT staff involved in the development of BrazilGeodata, which has allowed the data retrieval and integration performed in this study. We also thank Maria Gabriela Vicentelli who was responsible for the seismic interpretation of the studied areas. We express our gratitude to IES/Schlumberger for the use of PetroMod 3D, without which this paper would not be possible.

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