Two-layer lithospheric stretching model applied on the source rock maturity prediction: a 2D BPSM example in Central Santos Basin.

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Abstract

The knowledge of the generation process of the petroleum system strongly depends on the temperature history of sedimentary basins. Especially for basins originated by lithospheric stretching, some quantitative models were created to predict their thermal evolution. In this work the Two-layer model of Royden and Keen (1980) and Hellinger and Sclater (1983) were applied in order to estimate the thermal evolution of a section interpreted from a 2D regional seismic data.

The method applied consists first in building a 2D section based on a depth seismic interpretation, 1D extraction in order to create some pseudo-wells, backstripping the pseudo-wells in order to estimate the tectonic subsidence, predicting of the stretching factors that best fit the tectonic subsidence curve and at last the calculation of conducting heat flow. The second part is the 2D numerical basin and petroleum system modeling (BPSM) that includes a series of input data in which the calculated heat flow is one of them.

The results show an increase in the heat flow towards the oceanic crust, but locally there are particular structural features that change this pattern. The mantle stretching factor play a very strong control in high heat flow values, especially in deep water.

Introduction

The quantitative temperature history in a sedimentary basin is difficult to predict because it involves the estimation of the heat from astenosphere, crustal and sedimentary radiogenic input, and water pore convection over geological time. The petrophysical characteristic as porosity and thermal conductivity also impact the estimation of temperature throughout the time.

It is known that heat from astenosphere is conducted across the lithosphere and is one of the most important sources of temperature in sedimentary basins.

Since the end of 70's geologists and geophysicists have applied a constant temperature history on the prediction of thermal evolution of source rocks. Just a few of them have applied thermomechanical models that quantified the thermal evolution in sedimentary basins. Some quantitative models were proposed since the end of 70's and early 80's. Especially for basins originated by lithospheric stretching, in which the Santos Basin is included, the so-called plate model (Mckenzie, 1978; Jarvis & Mckenzie, 1980; Royden and Keen, 1980; Hellinger and Sclater, 1983) was the most used model to estimate paleotemperatures distribution in sedimentary basins worldwide.

The Santos Basin was formed by extensional process during Early Cretaceous when rift sediments were deposited and not much longer after that the thermal subsidence process took place and typical marine sediments were deposited (Macedo, 1989; Cainelli and Mohriak, 1999; Meisling *et al.,* 2001; Pinto, 2008). This pattern indicates that the Two-layer model could be satisfactorily applied in the Santos Basin.

Subsidence of the Two-layer model

The Two-layer model was first applied by Royden and Keen (1980) to explain the absence of rift sediments in the Labrador and Nova Scotia Margins; furthermore this model better explains the tectonic subsidence of those margins when compared with the uniform stretching model (Mckenzie, 1978). The physics behind that model is very similar to the Mckenzie (1978) and geologically assumes that there are two phases, one related to the rift stage which is controlled by mechanical process and a drift stage that is controlled by thermal process. Besides, the model assumes that the igneous intrusion may affect the subsidence and the heat flow history.

The subsidence of the mechanical or rift phase can be found assuming that the pressure at the base of the stretched area is equal to the unstretched area in order to maintain the isostatic equilibrium (local isostasy) as shown by equation (01), where (y) indicates thickness (ρ) density, (g) the gravitational acceleration and (β) the stretching factor. The indices indicates (c) for crust, (sc) for subcrust, (m) for mantle, (l) for lithosphere and (s) for sediment.

$$y_c\rho_c g+(y_l-y_c)\rho_m g = y_s\rho_s g+\frac{y_c}{\beta_c}\rho_c g+\frac{(y_l-y_c)}{\beta_{sc}}\rho_m g+\left(y_l-y_s-\frac{y_l}{\beta_l}\right)\rho_m g. \quad (01)$$

Rearranging the equation to obtain the depositional space created, in order words, the thickness of the sedimentary basin (y_s) and applying the effect of thermal expansion on density, the equation becomes

$$y_s=\frac{\left[(\rho^*_m-\rho^*_c)y_c\left(1-\alpha_v\frac{T_m}{2}\frac{y_c}{y_l}\right)-\frac{\alpha_v T_m\rho^*_m y_c}{2}\right]\lambda_c-\left[\frac{\alpha_v T_m\rho^*_m(y_l-y_c)}{2}\right]\lambda_l}{\rho^*_m(1-\alpha_v T_m)-\rho_w}, \quad (02)$$

where $\lambda = 1-\frac{1}{\beta}$. (03)

In that case there are two (λ), one for lithosphere (l) and another for the crust (c).

The equation (01) is demonstrated by Hellinger and Sclater (1983). By the empirical formula (equation 5), it is also possible to change the equation (02) and include the effect of the dike intrusion, that could terminate in a total "oceanization", and modeling the lithosphere in the case that the depth of ductile and ruptil transition do not necessarily coincides with the Moho depth (Royden and Keen, 1980).

$$\Delta H=\left[\left(1-\frac{1}{\beta_{sc}}\right)+\left(\frac{z^2}{y_l^2}-\frac{2z}{y_l}\right)\left(\frac{1}{\beta_c}-\frac{1}{\beta_{sc}}\right)\right](1-\gamma)+\gamma \quad (05)$$

The (γ) parameter indicates the "oceanization" in which zero means that no intrusion has occurred and one means that oceanic crust had been taken place. The (z) parameter indicates the depth of ductile-ruptil transition.

The thermal subsidence (S_t) is controlled by a time-temperature dependent function given by

$$S_t = E_o\sum_{m=0}^{\infty}\frac{x_{(2m+1)}}{(2m+1)}e^{\frac{-(2m+1)^2 t}{\tau}}, \quad (06)$$

where,

$$E_o=\frac{4y_l\alpha_v T_m}{\pi^2}\frac{\rho^*_m}{(\rho^*_m-\rho_w)},$$

$$x_n=\frac{2}{n^2\pi^2}\left[(\beta_c-\beta_{sc})sen\left(\frac{n\pi y_c}{y_l\beta_c}\right)+\beta_{sc}sen\left(\frac{n\pi}{\beta_l}\right)\right],$$

$$\tau=\frac{y_L^2}{\pi^2\kappa}.$$

In the same way as discussed in mechanical phase, it is possible to consider the (z) and (γ) parameter discussed in Royden and Keen (1980), but the use of these parameters veil the simplicity of the physics concept of the model, because of this it will be not applied in this works. Besides that, there are no evidences of dike intrusion in the seismic section (Pinto, 2008).

The total tectonic subsidence modeled is obtained summing the mechanical subsidence (y_s) and the thermal subsidence (S_t)

Heat flow of the Two-layer model

In the Two-layer model, the heat is assumed to flow by conduction according to the Fourier's Law (equation 07).

$$Q=-K\frac{\partial T}{\partial y} \quad (07)$$

Considering the 1D heat conduction equation (08) and applying the boundary condition (equation 09) and initial conditions (equation 10), it is possible to obtain the analytical solution for the problem (equation 11).

$$\frac{\partial T}{\partial t}=k\frac{\partial^2 T}{\partial y^2} \quad (08)$$

$$\begin{aligned}&\textit{Lower boundary condition}: \quad T=T_m \quad em \quad y=0\\ &\textit{Upper boundary condition}: \quad T=0 \quad em \quad y=y_l\end{aligned} \quad (09)$$

$$\begin{aligned}&T=T_m && for \quad 0\le y\le y_l\lambda_l\\ &T=T_m\left[1+\beta_{sc}\left(\lambda_l-\frac{y}{y_l}\right)\right] && for \quad y_l\lambda_l\le y\le y_l-\frac{y_c}{\beta_c}\\ &T=T_m\beta\left(1-\frac{y}{y_l}\right) && for \quad y_L-\frac{y_c}{\beta_c}\le y\le y_l\end{aligned} \quad (10)$$

$$T(y,t)=T_m\left(1-\frac{y}{y_l}\right)+\sum_{n=1}^{\infty}x_n\ sen\left(\frac{n\pi y}{y_l}\right)\exp\frac{-n^2t}{\tau} \qquad (11)$$

The heat flow equation (12) is easily obtained by the first derivative of temperature equation (11) and by multiplying the thermal conductivity according to the Fourier's Law (equation 07).

$$Q=K\frac{T_m}{y_l}\left\{1+\sum_{n=1}^{\infty}(-1)^{n+1}n\pi x_n e^{-\frac{n^2t}{\tau}}\right\} \qquad (12)$$

Using the equation (12) is possible to predict the heat flow at the top of the model, in other words, at the top of the basement. This equation shows clearly the variation of the heat with time and is made of two terms, one the steady-state that is the Fourier's Law itself, and a transient term in the summarization that must be added to the first one.

Petroleum System in Santos Basin

It's known that the Santos Basin is a typical basin originated by extensional process where two phases are identified and proved by their depositional stratigraphic sequences. The first is the rift phase controlled by large faults, originated mainly by mechanical process and the other one is the drift phase, where predominates sediments deposited in a marine environment, where the subsidence is controlled mainly by thermal process.

The source rock maturation, as well as the petroleum system elements and process (Magoon and Dow, 1994) vary with time and location what does not allow giving a general petroleum system definition for the entire Santos Basin. But it is known from the literature that it is possible to identify at least four petroleum systems for which four main source rocks (SR) are identified, two related to the rift section (Buracica and Jiquia local stages), and two related to the drift section (Albian and Turonian in age) (Mello and Maxwell, 1990; Milani et al., 2000). The main reservoirs (RES) are Aptian, Albian and Santonian in age.

Method

The method adopted here can be resumed in two main steps. The first one is the estimation of the heat flow history across the section (figure 1 and 4) and the second one is the Basin and Petroleum System Modeling (BPSM).

The estimation of the heat flow history in the 2D section follows a well known workflow. It consists in backstripped a well, in this case twenty pseudo-wells extracted from the 2D model, in order to obtain the tectonic subsidence according to equation 13 (Watts, 2001), where, W_{di}, S_i, Δ_{sli} and Y_i are respectively, water depth, the decompacted sedimentary thickness, sea level change and the tectonic subsidence of the (i) stratigraphic layers.

$$Y_i=W_{di}+S_i^*\left[\frac{\left(\rho_m-\bar{\rho}_{si}\right)}{\rho_m-\rho_w}\right]-\Delta_{sli}\frac{\rho_m}{(\rho_m-\rho_w)} \qquad (13)$$

The next step consists in changing the stretching factors parameter to fit the modeled tectonic subsidence with the calculated tectonic subsidence (Y_i) as shown in figure 2.

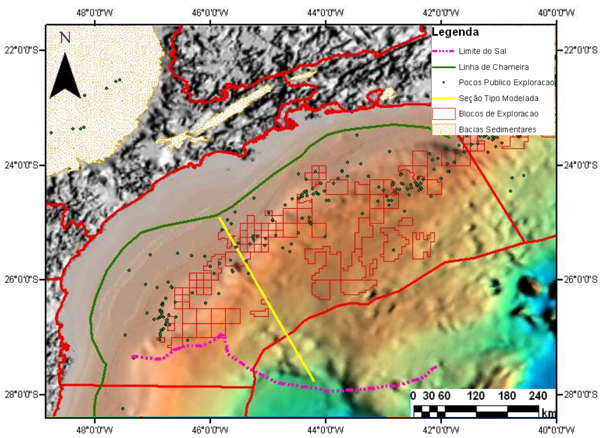

Figure 1. Location map. The yellow line indicates the seismic section took from Pinto (2008) that has been used in the modeling.

After that, the stretching factors were applied in the heat flow equation (12). In this step it is also necessary to set up the time of the beginning and the end of the rift phase that in this works is 135-122 Ma (Figure 2), as well as define the parameter found in the Two-layer model equation (table 1). This procedure described was used in all 20 pseudo-wells that were extracted along the 2D section (figure 3 and 4).

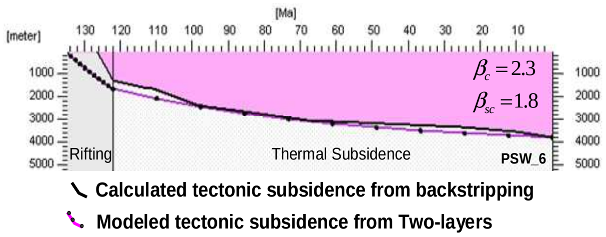

Figure 2. Estimation of the stretching factors. The figure shows an example of the estimation of the stretching factors in one of the twenty pseudo-wells modeled. Changing β_c and β_{sc} stretching factors values is

possible to fit the modeled tectonic subsidence curve from Two-Layer model with the calculated tectonic subsidence from the pseudo-well backstripped.

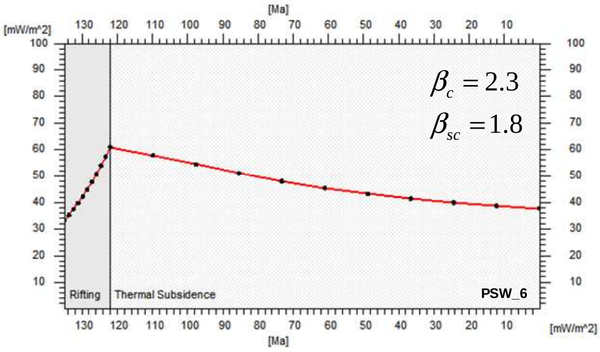

Figure 3. Heat flow curve. The figure shows a very characteristic curve of the model, in which there is a linear rising of the heat flow at the rift phase (also known as mechanical) and an exponential decrease at the thermal subsidence phase.

Parameter	Value	Description
y_l	125,000 m	Lithospheric thickness
y_c	32,000 m	Crustal thickness
ρ_m	3,330 kg/m^3	Mantle density
ρ_c	2,800 kg/m^3	Crustal density
ρ_w	1,030 kg/m^3	Water density
α_v	3.28 x 10^{-5} $^oC^{-1}$	Thermal expansion coefficient
T_m	1,333 ^{o}C	Asthenospheric temperature

Table 1. Parameters used in the Two-layer model.

After the estimation of the heat flow trends they were assigned to the 2D BPSM software (Petromod ®). The prediction of maturity strongly depends on temperature and time that was calculated basically using the 2D heat flow equation, in the sedimentary section, and the Sweeney and Burnham (1990) algorithm.

Results

The method discussed above allowed the identification of the maturity of the section extracted from Pinto (2008) showed in figure 3. It is possible to see in the section three source rocks, two related to rift section and one from Turonian. According to Pinto (2008), the Albian source rock was not considered because it was not possible to identify it in the seismic section. The depth of the rift source rocks were chosen to simulation purposes since no well reached such depth in the section.

The basal heat flow calculated by the Two-layer model (figure 5) presents higher values at the beginning of the thermal subsidence and decays exponentially until the present day. In distances greater than 200 km the heat flow history is higher than in the distances lower than 200 km. This is caused by the stretching factors predicted. This basal heat flow works as a lower boundary condition for the top of the basement showed in figure 4.

The figure 6 shows the present day heat flow distribution in the sedimentary section estimated based on the 2D heat flow equation. In this picture is possible to notice high heat flow values at top of the salt domes and low heat flow values at the sides of salt domes. This is caused by the thermal conductivity of the salt (6 W/m/K) that is twice the shales conductivity. Laterally to the salt diapirs it is easily seen the influence of the 2D heat flow equation where the heat at the sides of the diapirs flows into it.

The temperature can be established based on the Fourier's law and will control the maturity (figure 7) that can be estimated using the Sweeney and Burnham (1990) algorithm. It is possible to observe, in figure 6, that the rift section in almost all area is in late oil to gas windows whereas the Turonian source rock is immature to oil window.

Conclusions

Using the Two-layer model it is possible to better adjust the calculated tectonic subsidence curve when compared to the uniform stretching model. This is due mainly by increasing the mantle stretching factor, that in this case will raise heat flow values.

The 2D BPSM modeling gives a good idea of the maturity of the source rocks and its evolution throughout the geological time. But in order to obtain satisfactory results, calibration data as temperature (e.g BHT), vitrinite reflectance, spore color index, surface heat flow measurements, must be used to calibrate the thermal history of the basin. In this work the calibration data was not used because the main objective is the methodology of a relatively new tool that is the BPSM.

The maturity results presented is in good agreement with the knowledge of the Santos Basin where the Mexilhão gas field is present in proximal area. The occurrences of petroleum related to Turonian source rock in the area has not been reported yet in the literature. It is possible that this source rock is immature along the interpreted horizon and further thermic calibration has to be done.

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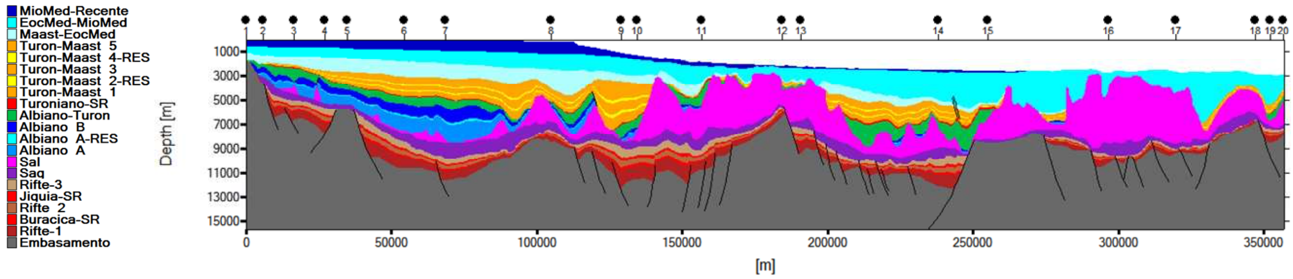

Figure 4. 2D model. The figure shows the stratigraphic interval used in the numerical modeling. It was considered three source rocks, two in the rift section and one in the marine section that is related to the Turonian. The black dots show the location of the 20 pseudo-wells extraction. The interpretation was extracted from Pinto (2008).

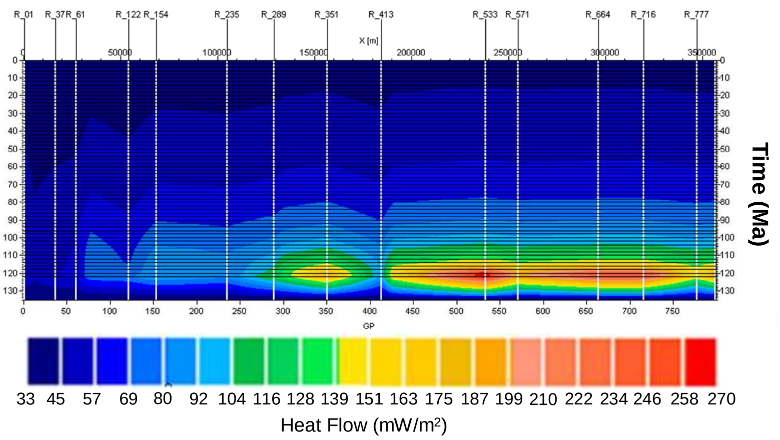

Figure 5. Basal Heat Flow trend. This picture shows the basal heat flow (HF) estimated by the Two-layer model. In the upper x-axis is possible to the distance in meter, in the lower x-axis are the grid points (GP), in the y-axis are the ages that goes from 135 Ma until 0 Ma. The colors indicate the heat flow with high values near to the beginning of the thermal phase (122 Ma) and decrease exponentially until the present day (0 Ma).

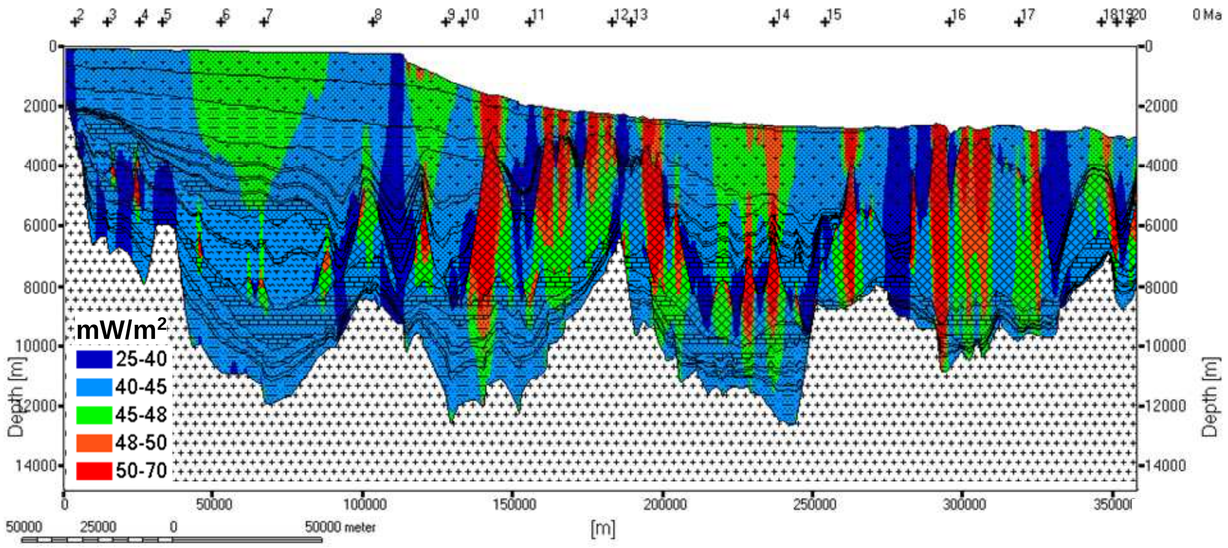

Figure 6. Heat flow in the sedimentary section. The red colors represent high heat flow values that are occurring in the salt diapirs. The dark blue represent low heat flow values that can be found meanly at the sides of the salt diapirs.

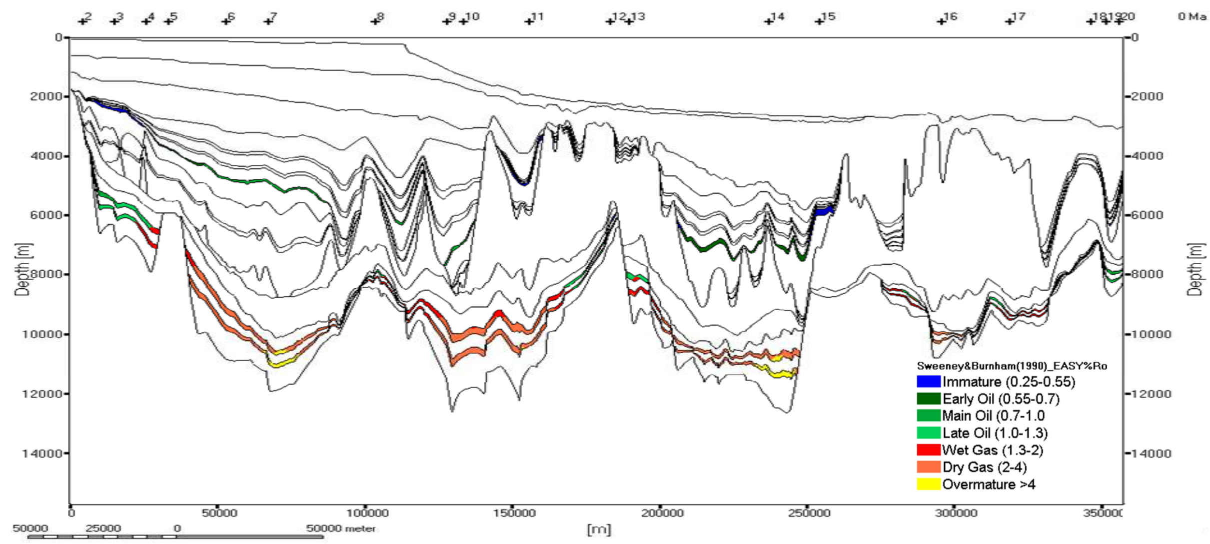

Figure 7. Maturity of the source rocks. The estimated maturity section shows that the rift source rocks are predominately in late oil to gas window and the Turonian is immature to early oil window.