A Source of Error in McKenzie Model of Lithospheric Extension and Its Implications for Petroleum Play in Sedimentary Basins

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Abstract

An improved thermal model of the lithosphere extension is proposed and its influence in the petroleum system in sedimentary basins examined. The new model assumes existence of time dependent variation in the lithosphere thickness during the post-rift period, which was not take account in the formulation of the Mackenzie model (1978). In the present work we assume that the asymptotic growth of the lithosphere thickness, during the post-rift period, may be represented by a relation of the type:

$$L(t) = \frac{L}{\beta} + \left(L - \frac{L}{\beta}\right) erf(\gamma t)$$

where L(t) is lithospheric thickness at post-rift time t, β the stretching factor as defined in the McKenzie model, *erf* the error function and γ a suitable scaling constant. According to the above equation the syn-rift value of L is (L/β). For large times the thickness of the lithosphere approaches asymptotically the pre-rift value of L. The value of γ can be determined by calculating the time necessary for the stretched lithosphere (L/β) to return to original thickness. The results of numerical simulations indicate that the heat flux derived from the new model is substantially lower than the values predicted by the McKenzie model. The new model was used in calculating evolution of thermal maturity indices for the Santos Basin, situated in the offshore area of southeast Brazil. Petroleum generation rates calculated on the basis of new model predicts significantly less oil generation for Albian and Turonian source rocks. More significantly, the windows for peak oil generation are shifted to relatively recent times for Barremian and Albian source rocks.

Introduction

Thermo-mechanical models of tectonic processes often provide a suitable frame work for assessment to petroleum play in sedimentary basins. According to the extension model of McKenzie (1978) subsidence and development of sedimentary basin occur in response to extension of the lithosphere. Consequent upwelling of the asthenosphere leads to a rapid rise in surface heat flow, which returns gradually to equilibrium value during the post-extensional period.

The thermal models of extensional processes (McKenzie, 1978; Royden & Keen, 1980) have been widely used over the last few decades as a tool in understanding the evolutionary history of petroleum generation-migration-accumulation processes. Nevertheless, these models have lead to systematic overestimates of organic maturation indices (Pepper and Corvi, 1995; Pepper and Dodd, 1995; Makhous et al, 1997), often incompatible with geochemical evidences (Sweeney and Burnham, 1990; Tsuzuki et al, 1999). The problem has been ignored over the last three decades and in many cases erroneously attributed to the uncertainties in model parameters.

The extension model proposed by McKenzie (1978) to describe the thermal history of sedimentary basins is, in fact, an outgrowth of the Plate model of the oceanic lithosphere, proposed earlier (McKenzie, 1967). The validity of the Plate model has recently been questioned, because of the large discrepancies between model values and observational oceanic heat flow data (Hofmeister & Criss, 2005; Cardoso et al, 2009). The main drawback of the Plate model is that it ignores the possibility of variations in heat input into the base of the lithosphere (Hamza et al, 2008b; Cardoso et al, 2009).

A similar problem is also found to exist in the extension model of McKenzie (1978), which is widely used in describing the thermal evolution of sedimentary basins. In the present work, we point out the need to introduce corrections in such extension models of sedimentary basins, and examine their implications for determining thermal maturation of organic matter in subsurface strata.

McKenzie Model

Consider first the problem of heat transfer in a rectangular lithospheric plate that has undergone extension. The equations describing vertical distribution of temperatures and surface heat flow (q) as functions of depth (z) and time (t) in such a lithosphere of thickness (L) may be derived on the basis of the relevant heat conduction equation (see for example Carslaw and Jaeger, 1959). The relation for heat flow deduced by McKenzie (1978) is:

$$q_p(z,t) = \frac{\lambda T_1}{L}\left\{1 + 2\sum_{n=1}^{\infty}\left[\left(\frac{\beta}{n\pi}\right) sen\left(\frac{n\pi}{\beta}\right)\exp\left(-n^2 t/\tau\right)\right]\right\} \quad (1)$$

where T_1 is temperature at the base of the lithosphere, κ the thermal diffusivity and β the stretching factor. The Fourier coefficients are given by:

$$a_n = \frac{2\beta}{(n\pi)} sen\left(\frac{n\pi}{\beta}\right) \quad (2)$$

The term τ in the exponential term is the thermal time constant of the lithosphere, defined as:

$$\tau = L^2 / \left(\pi^2 \kappa\right) \quad (3)$$

This definition of τ implies that the decay of the transient components of temperature and heat flow during the period following extension is determined by the initial thickness (L) of the lithosphere.

The problem in the McKenzie model lies in the definition of the thermal time constant (equation 3) which determines the post-rift thermal recovery. The nature of this problem can be understood by considering the variations in the thickness of the lithosphere during the post-rift period, a schematic illustration of which is provided in Figure (1).

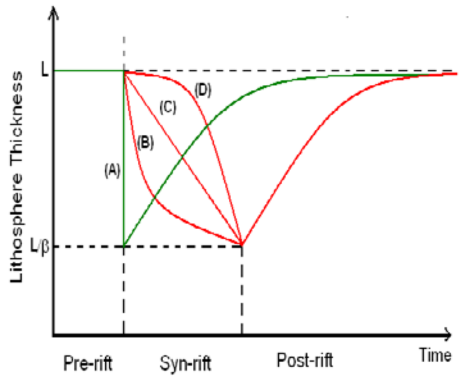

Figure (1) – Schematic representation of thickness variations of the lithosphere during pre-rift, syn-rift and post-rift periods. Curve (A) refers to the case of instantaneous stretching while curves (B), (C) and (D) refer to the case of finite stretching.

Note that even the description of the post-rift recovery provided by McKenzie assumes that lithosphere thickness returns to the original pre-rift value. However, equation (3) does not conform to this assumption. In the following sections we present a modification of the post-rift recovery that incorporates the thickness variations assumed in the extensional model.

Post-Rift Recovery Allowing Variable Time Constant

In the present work we assume that the asymptotic growth of the lithosphere thickness, during the post-rift period, may be represented by a relation of the type:

$$L(t) = \frac{L}{\beta} + \left(L - \frac{L}{\beta} \right) erf(\gamma t) \qquad (4)$$

where L(t) is lithospheric thickness at post-rift time t, β the stretching factor as defined in the McKenzie model, *erf* the error function and γ a suitable scaling constant. According to equation (4) the syn-rift value (i.e.: at time t = 0) of L is (L/β). For large times (i.e.: for $t \to \infty$) the thickness of the lithosphere approaches asymptotically the pre-rift value of L. The value of γ can be determined by calculating the time necessary for the stretched lithosphere (L/β) to return to original thickness. For this propose, we assume that the solidification of asthenospheric segment just beneath the remnant part of the stretched lithosphere behaves as a *thermal boundary layer*. This is the region of significant temperature changes during the post-rift period. The thickness of this confined boundary layer requires an arbitrary definition, since the temperature *T* at the top of this layer drops to the initial syn-rift temperature T_b instantaneously at the beginning of the post-rift period but at large depths approaches the asymptotically the temperature T_m of the asthenosphere. The form of temperature variation is illustrated in Figure (2).

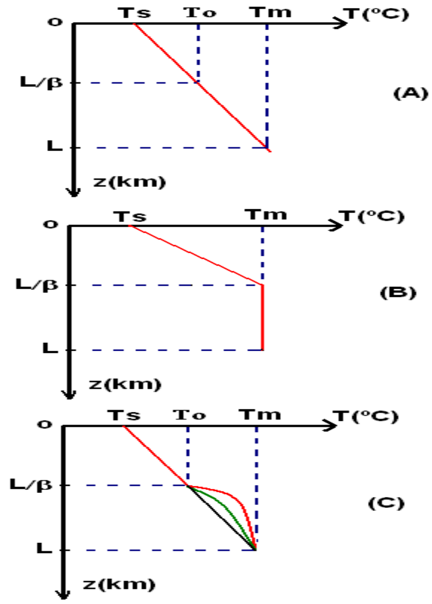

Figure (2) – Schematic representation of temperature variations of the lithosphere during pre-rift, syn-rift and post-rift periods.

According to the premises of the McKenzie model lithospheric temperatures adjust instantaneously to changes in the bottom temperatures (induced by changes in the height of the asthenospheric column). The implication is that the response time of the solid part of the lithosphere is small compared to its thermal time constant. This simplification may also be extended to the problem of cooling of asthenospheric layer beneath the solid part of the extended lithosphere. The thickness of the boundary layer may be defined as that corresponding to 90% of the temperature difference (Carslaw and Jaeger, 1959; Turcotte and Schubert, 1982):

$$Z(t) = 2{,}35\sqrt{kt} \qquad (5)$$

Equation (5) means that the change in thickness of the asthenospheric layer beneath the stretched lithosphere is given by the relation:

$$Z(t) = L - \frac{L}{\beta} = 2{,}35\sqrt{k\,t} \qquad (6)$$

Thus, the time necessary for the lithosphere to come back to original thickness is:

$$t' = \frac{(L - L/\beta)^2}{5{,}36\,k} \qquad (7)$$

Substitution of equation (7) in (4) leads to:

$$L = \frac{L}{\beta} + \left(L - \frac{L}{\beta} \right) erf(\gamma t') \qquad (8)$$

For large times the value of the error function approaches unity, which means that:

$$erf\left(\gamma \frac{(L - L/\beta)^2}{5{,}36\,k} \right) = 1 \qquad (9)$$

We choose the value corresponding to the argument of the error function of 1.9 (erf(x) = 0.993) as the asymptotic limit. This leads to:

$$\gamma = \frac{10{,}9\,k}{(L - L/\beta)^2} \qquad (10)$$

Note that the value of the constant γ depends on the initial lithosphere thickness (L), the stretching factor (β) and the thermal diffusivity (k). For values of β close to 1 (i.e. for very small stretching factors) the denominator in equation (10) is small and the value of γ approaches infinity. This is the limiting case represented by the McKenzie model. Results of numerical simulations illustrating the heat flow variation for low stretching factors are presented in Figure (3). Obviously, in such cases the differences between the McKenzie model and the case considered in the present work are relatively small.

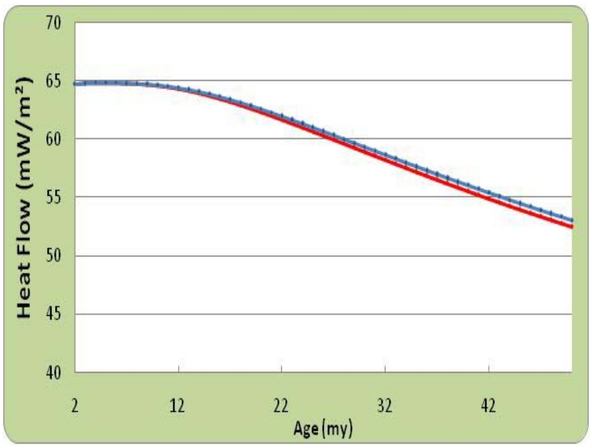

Figure (3) – Comparison between Mackenzie model and the present work, for β = 1.8.

The situation is however quite different for the case in which the stretching factor (β) is greater than 2. An example of heat flow variation for β = 2.5, illustrated in Figure (4), reveal that post-rift heat flow values are substantially less than those predicted by the McKenzie model.

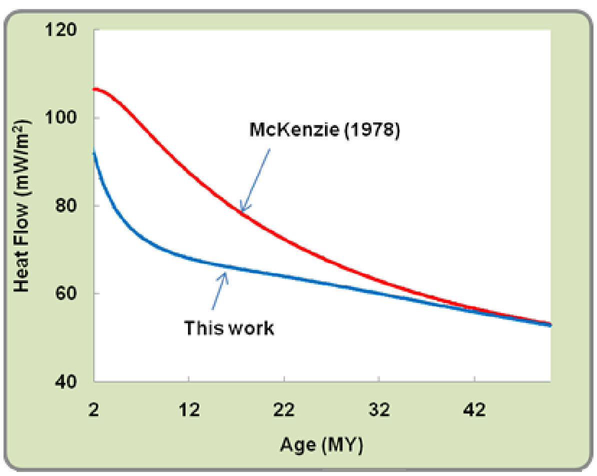

Figure (4) – Heat flow variations for the post stretch period, for the case in which the stretching factor is 2.5.

Implications for Thermal Maturity Calculations

We now proceed to examine the implications of the model of post-rift recovery, allowing variable time constant, on the thermal maturity calculations. As an illustrative example consider the evolution of maturity indices for the Santos basin, located in the off-shore area of southeast Brazil. Petroleum generation rates were calculated using the program PETROMOD (PETROMOD, 2008). This program implements the scheme for oil generation outlined by Sweeney and Burnham (1990). Two different models were employed in determination of maturity indices: the homogeneous stretching model of McKenzie (1978) and the two-Layer model of Royden & Keen (1980). The model values of petroleum generation (normalized to the maximum value predicted by the McKenzie model) are presented in Figures (5A), (5B) and (5C) for Barremian, Albian and Turonian source rocks respectively. The results reveal that the rates of petroleum generation are lower than those predicted by the homogeneous stretching model of McKenzie. Also, the time window for peak generation is shifted to recent times, when compared with predictions based on the McKenzie model.

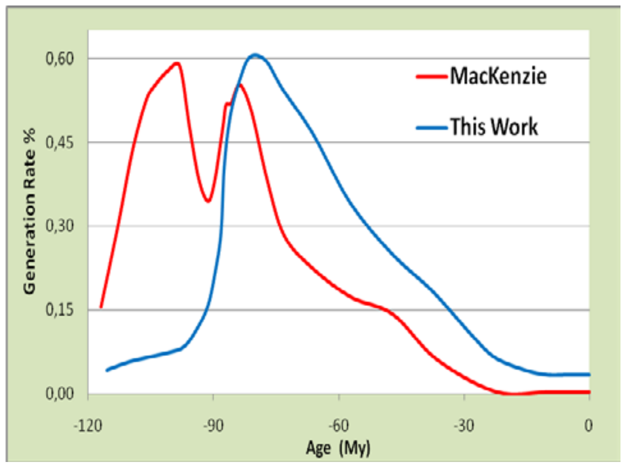

Figure (5A) – Evolution of the rate of petroleum generation for Barremian source rocks.

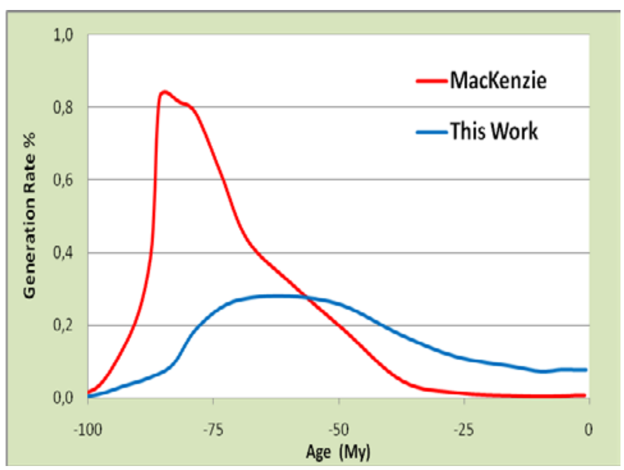

Figure (5B) – Evolution of the rate of petroleum generation for Albian source rocks.

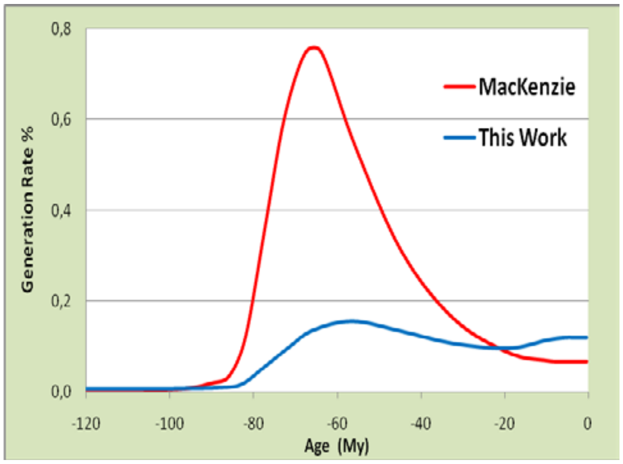

Figure (5C) – Evolution of the rate of petroleum generation for Turonian source rocks.

Comparison with Geochemical Studies

According to the results of geochemical studies, vitrinite reflectance of rock samples of Turonian age from the Santos Basin is around 0.65%. This is in reasonably good agreement with the value of 0.67% calculated using the new model, based on the procedure of Sweeney & Burnham (1990). The values derived from the homogeneous and Two-Layer models are 0.79% and 0.84% respectively.

Conclusions

It is clear from the results of the present work that the modified thermal model of the lithosphere for post-extensional periods has a strong influence on the prediction of hydrocarbon maturation and generation processes. The failure to take into consideration the increase in thickness of the extended lithosphere in the McKenzie model has led to overestimates of heat flow during the period following the stretching event. According to results of figure (5) the new model predicts significantly lower rates of oil generation for Albian and Turonian source rocks, when compared with the predictions based on the McKenzie model. Also, the beginning of the time window for oil generation is shifted to later times in the new model. It starts at 90m.y. for Barremian, 85m.y. for Albian and 70m.y. for Turonian source rocks and continues to present times. In the McKenzie model the time window for oil generation starts at 110m.y. and ends at 60m.y. for Barremian. The corresponding interval for Albian is 90 to 60m.y. For Turonian source rocks the window starts at 80m.y. and continues to present day. Such differences in time windows are significant and needs to be corrected for a better understanding of the space-time framework of petroleum play in sedimentary basins.

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