Geothermal fields associated with Tectonic Domains in Campos and Santos Basins: Implications for hydrocarbon generation in the central rift system

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Abstract

The present work is an attempt to examine geothermal fields of the main tectonic domains in the Campos and Santos basins and its implications for oil generation. The structural provinces of these basins, considered for this purpose, include regions of Moho uplift on its western margin, rift basin systems in its central parts and areas of failed spreading ridges in the eastern parts. Observational geothermal data has been used along with estimates in assigning representative heat flow values to these structural elements. The procedure adopted allows for augmented heat flow associated with episodes of uplift and subsidence. The results obtained are consistent with the hypothesis of anomalous geothermal belts, located in the central rift basin systems. Results of model studies indicate that such belts are produced by a recent short-period episode of magma emplacement at shallow depths. Results of model studies have also been used in obtaining estimates of depth and age of long-period magma emplacement episodes. These have promoted differential degrees of thermal maturation and hydrocarbon generation within the tectonic domains of the Campos basin. A consequence of the hypothesis of long-period magma emplacement is that the age of oil generation in the Campos basin is likely to be less than 10 Ma.

Introduction

Inferences as to the characteristics of deep-rooted geologic structures in the Campos and Santos basins are based almost exclusively on results of regional-scale seismic and gravity surveys. On the other hand, it is well known that the present-day structural features maintain close relations with the nature of tectono-thermal processes that took place during the evolutionary history of this basin. In the present work, we examine available data on the geothermal field of the Campos and Santos basins and explore its relations with the structural elements of the passive margin of Southeast Brazil. We also consider the tectonic implications of deep-seated magmatic processes responsible for the geothermal anomalies and examine its consequences for evolution of thermal maturity indices of the main sedimentary formations.

Overview of Structural Setting

The structural framework of the Campos Basin is marked by significant diversity. Along the southwestern border, the pre-rift basement is mostly composed of Precambrian crystalline rocks. The early syn-rift sediments are characterized by siliciclastics intercalated with volcanic rocks dated about 120-130 Ma. This phase of subsidence is contemporaneous with widespread mafic volcanism. In onshore and shallow platform areas, the oldest sediments are clastics, deposited on basalts, or directly over the Precambrian basement. There are indications of basement-involved normal faulting, and associated half-graben development, with depo-centers controlled by antithetic faulting.

In thermo-tectonic studies of sedimentary basins, it is standard practice to recognize three successive subsidence phases namely, rift, sag (referred to also as transitional) and drift. Within areas of Campos and Santos basins the first phase occurs as a series of half-grabens, as has been verified in the Pampo, Badejo, Linguado and Trilha oil field areas. These are rich in clastic terrigenous sediments as they are close to the rift border faults. Also occurring are synthetic and antithetic half-graben form, divided by transcurrent or transfer faults. An example is the region of Espadarte oil field, controlled also by growth faults. The region which extends until the oceanic crust, is covered by siliciclastic sediments. Near the limit between continental and oceanic crusts, its basement section has undergone the highest degree of stretching with asymmetric half-grabens. The overlying post-rift (thermal) marine clastic section shows a more subdued phase of subsidence. These have carbonate deposits with different morphology, and sedimentary geometries.
Within this tectonic context, specific structural provinces have been defined, based on gravity anomalies as well as regional and deep seismic lines (Mohriak & Dewey, 1987; Mohriak et al. 1990; Meisling et al. 2001). The main provinces are regions of Moho uplift (MU), central rift basin systems (RBS), failed spreading ridge (FSR), and stretched continental crust (SCC). Regions of Moho uplift (MU) occurs along a narrow strip near coastal areas. The coastal areas also harbor large systems of dikes, alkaline intrusions, grabens (such as Barra de Sao Joao) and structural highs (such as Badejo high). Farther away from the coastal area are zones of wide (~ 300 km) negative gravity anomalies, which delineate northeast-southwest trending depressions and host the main rift basin systems (RBS). These have been interpreted as half-grabens (Mohriak & Dewey, 1987) and are parallel to the rift system axis. Farther to the east of RBS are regions of positive gravity anomalies trending northeast southwest, which have been interpreted (Demercian, 1996 and Meisling et al, 2001) as failed spreading ridges (FSR).

These coincide with zones considered as pre-salt ridge of eroded volcanic and basement highs (named as Avedis volcanic pre-salt high). Between FSR and the stable oceanic crust is the region of highly stretched continental crust (SCC).

According to Meisling et al. (2001), the offsets across gravity anomalies indicate transfer zones (TS) or transform faults. These lie in a west-northwest to east-southeast orientation, and according to Mohriak et al. (1995), are synchronous with extensional faulting during the Neocomian rifting. The plate tectonic reconstruction of the early stage of the Atlantic opening in the Campos and Santos basins shows extension in east-west direction. However, the transfer zones are oblique to this direction. The inherited basement structures trending northwest - southeast are about 45º degrees to each other.

A map of the main structural elements of the Campos basin is presented in Figure (1). The focus of the current work is in outlining the thermal fields associated with tectonic processes that affected these structural elements, hence have remarkable features in their present surface heat flow values.

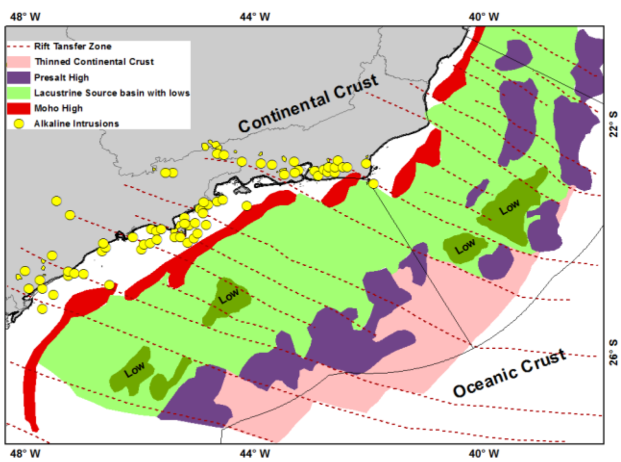

Figure (1) Main structural elements of Campos and Santos basins (Modified after Meisling et al., 2001).

Geothermal Data

The available geothermal data sets for areas of Campos and Santos basins are based mostly on results of bottom-hole temperature (BHT) measurements carried out as part of geophysical logs of oil wells. Meister (1973), Ross and Pantoja (1978), Rossi Filho (1981) and Zembruscki (1982) reported values of geothermal gradient values derived from these data sets. However, these values were not corrected for the perturbing effects of drilling disturbances. In addition, incorrect values were assumed for surface temperatures. Cardoso (2007) and Cardoso and Hamza (2014) reported results of later compilations where corrections for drilling disturbances and surface temperatures were incorporated. Observational data sets employed in these studies made use of measurements of bottom-hole temperatures for 72 wells. These results indicated that geothermal gradients fall in the range of 25 to 40ºC /km, the mean value being 30 +/- 3ºC/km. The heat flow values fall in the range of 60 to 85mW/m^2, the mean values being 74+/- 7mW/m^2.

More recently, Vieira and Hamza (2014) modified the database allowing use of estimated values based on the empirical heat flow – age relation (Hamza and Verma, 1969) as complements to observational data sets. This procedure allowed them to derive representative maps of geothermal gradient and heat flow for the offshore areas of southeast Brazil. Vieira and Hamza (2014) presented maps of geothermal gradient and heat flow derived on the basis of these data sets.

In analysis of geothermal data, it is convenient to setup a suitable grid system for the study area. The sizes of grid elements chosen are such that the interpolation system employed in graphical representations preserves the dominant spatial variations in observational data sets. It is well known that large grid sizes lead to excessive smoothing, leading to obliteration of variations related to secondary physical processes. On the other hand, too small grid sizes lead to systems where the number of cells with estimated values is higher than those having observational data, which is undesirable. Trial runs indicated that a grid system with cell dimensions of 0.5º x 0.5º is adequate in representing the large-scale variations of heat flow in the study area. The geographic distribution of this cell system is illustrated in the map of Figure (2), along with locations of wells considered in the present work.

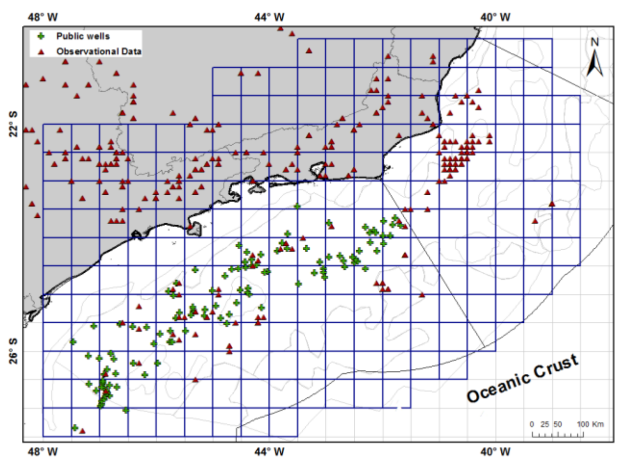

Figure (2) Geographic distribution of cell system employed in analysis of geothermal fields of tectonic domains. The symbols indicate locations of wells considered in the present work.

Thermal Fields of Tectonic Domains

Tectonic domains are envisaged in the present work as regions where the presence of specific geological activity can be recognized. For example, the area affected by Moho uplift (MU) may be considered as a narrow belt along the western border of the Campos basin. This episode has not affected the ages of rock formations at the surface. On the other hand, areas associated with subsidence of central rifted region (RBS) are much wider. To the east of this rift basin system is the region of stretched continental crust (SCC).

Thermal regimes of structural units, unaffected by recent tectonic activities, are usually considered as stable. Crustal temperatures in such areas may be determined on the basis of observational data or by making use of estimated heat flow values. These latter ones are derived from the well-known empirical relation between heat flow and tectonic age. In the present case, this approach is unsuitable as there are areas where transient changes in heat flow have taken place as a result of recent tectonic activities. Under such conditions, it is necessary to take into consideration contributions of transient components in heat flow, not related to the age pattern in near surface rocks. For example, processes such as uplift and subsidence are accompanied by transient perturbations of the local geothermal fields. Such perturbations arise from displacements of subsurface layers, accompanied in some cases also by thermal effects of magma intrusions. Exact evaluation of transient changes in heat flow associated with such episodes is a difficult task, but results of thermal models may be used in setting useful limits. Numerical simulations by Vieira et al (2017) reveal that perturbations in surface heat flow arising from moderate uplift episodes are likely to be small, with magnitudes smaller than 20mW/m^2. In addition, the lateral extent of such perturbations extends only to distances of the order of few tens of kilometers from the belt of gravity anomalies. On the other hand, thermal perturbations accompanying subsidence episodes of the central rift basins are likely to have much higher magnitudes, in the range of 20 to 50mW/m^2.

Here we limit the discussion to procedures employed in determining transient heat flow associated with tectonic processes. Under this scheme, 26 cells covered areas affected by Moho uplift, adjacent to the western side of the continental margin. In the area of central rift-basin system, 53 cells had observational data and estimated values were assigned for the remaining 47 cells. In areas of highly stretched continental crust there are 20 cells, all of them have been assigned estimated values. The task of assigning estimated heat flow values has been restricted to cells for which observational data are unavailable. Also, mean values were assigned for cells with multiple observational data. Heat flow map derived for this grid system is illustrated in Figure (3), along with locations of observational data (triangles in black color) and estimated values (triangles in blue color)

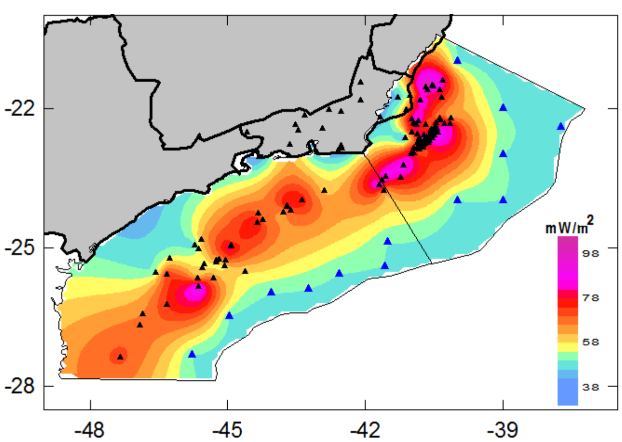

Figure (3) Revised heat flow map of the Campos and Santos basins along with locations of observational data (black triangles) and estimated values (blue triangles).

Referring to the map of Figure (3) it is important to point out that the elements of this grid system, for which observational data are not available, were assigned heat flow values in accordance with the thermal perturbations of tectonic domains. In the present case, cells within crustal segments to the west of continental margin (where basement rocks are mostly Precambrian in age) were assigned heat flow values, generally in the range of 40 to 60mW/m^2. This region has been assumed free from perturbations arising from basin formation. Cells within the region of Moho uplift (MU) were assigned slightly higher values, in the range of 60 to 70 mW/m^2. Similarly, cells within the central rift basins, which have ages less than 80 Ma, were assigned higher heat flow, in the range of 70 to 90mW/m^2, depending on the depth of ocean floor. For regions of stretched continental crust (SCC) and for the oceanic crust, the assigned heat flow values are based on the empirical heat flow – age relation (Hamza, 1967; Hamza and Verma, 1969). These areas are assumed to have a near constant heat flow value of 50mW/m^2.

The map of Figure (3) points to the existence of an anomalous geothermal belt in the central parts of the Campos and Santos basins, where temperature gradients are higher than 30ºC/km and heat flow in excess of 70mW/m^2. The width of the belt is somewhat variable, but most of it falls within the range of 100 to 300km. It is relatively large in the central parts, when compared with those in the northern and southern parts. It is confined between zones of relatively low to normal heat flow in the neighboring continental region to the west as well as the stable oceanic region to the east.

Thermal effects of magma emplacement

The characteristics of the heat flow anomaly, illustrated in Figure 3, indicates that the width of the thermal source region is narrow and it is located at relatively shallow depths. Magma emplacement at shallow depths in the crust is usually considered as the most probable mechanism generating such geothermal anomalies. Some insights into the nature of this mechanism can be gained through model studies. In the present work, we make use of models discussed by Vieira et al (2017) in investigating the nature of thermal effects of magma emplacement in the crust beneath Campos and Santos basins. The discussion here is limited to the application of this model and its consequences for the occurrence of anomalous heat flux in the central parts of the Campos and Santos basins.

Numerical simulations of magma emplacement episodes were carried out using the model of Vieira et al (2017). The purpose has been to select the model that best fits the observed heat flow anomaly. The results of model studies indicate that the origin of the anomalous geothermal belt is related to recent episodes of magma emplacement at depths of approximately 20km. The model results also indicate that the age of magma emplacement is no more than 2Ma.

It is important to point out that such magma emplacement need not necessarily give rise to intrusions in the upper crust. The ductile behaviour of heated mantle can allow for emplacement of magma beneath the crust as an under-plate, without giving rise to intrusives reaching upper crustal levels. Such a process may be envisaged as the end-member of the differential stretching process proposed by Royden and Keen (1980). In such cases, the crustal stretching becomes very small, while sub-crustal stretching accommodate most of the lateral flow of mantle.

Supporting evidence for magma emplacement

Occurrence of widespread seismic activity at shallow depths in areas of Campos and Santos basins may be considered as indication of near surface manifestations of tectonic processes accompanying magma emplacement. According to data acquired by the Brazilian Seismographic Network (2015) frequency of seismic activity is higher in the region between Moho and Pre-salt Highs. In addition, magnitudes of earthquakes seem to be relatively higher near transfer zones, identified in gravity surveys. The body wave magnitudes of earthquakes are relatively small, varying from 2 to 4.8 on the Richter scale. Focal depths of these events vary from 1 to 17km, the mean value being about 5km. Such characteristics of seismicity appear to be compatible with the hypothesis of tectonic activity resulting from magma emplacement at depths of about 20km in the central parts of Campos and Santos basins.

Implications for Thermal Maturation

Thermal effects of magma emplacements in crust beneath sedimentary layers are superimposed on that produced by crustal stretching events that occurred during the early stages of basin development. Understanding the nature of such multiple tectonic events is a complex task. However, available information on the evolution of thermal maturity indices of organic matter within the main sedimentary formations may be used in extracting useful information. Cardoso (2007) and Cardoso and Hamza (2007; 2014) reported palinspastic reconstructions illustrating the evolutionary history for five sites in the Campos basin. However, their calculations of paleo-temperatures, based on the method proposed by McKenzie (1978), did not take into consideration potential contributions of heat flow associated with episodes of recent magma emplacement at deep crustal levels. Here we discuss results of model studies that incorporate thermal effects of recent magma emplacements, superimposed on thermal consequences of previous crustal stretching events. The details of the procedures adopted are presented in the recent work of Vieira et al (2017). Here we limit the discussion to an example for the site of the well RJS-13. The relevant results of including the thermal effects of magmatic events on paleo-temperatures is illustrated in Figure (4),

In this figure, the dashed curves (in blue color) indicate paleo isotherms for the range of 20 to 90ºC, at intervals of 10ºC. These are the isotherms for the case where the evolution of temperatures is determined exclusively by the stretching mechanism. The curves in red color indicate isotherms for the case where thermal effects of magma emplacement at depth of 20km is superimposed on that arising from stretching. The black lines indicate the sequences in the subsidence history of the main sedimentary formations (Emborê, Macaé, Lagoa Feia, Cabiúnas), reconstructed by back-stripping methods.
A notable feature of the case illustrated in figure (4) is that it includes thermal effects of two distinct magma emplacement events. The first one is a relatively long period episode, responsible for higher values of paleo-temperatures, over the last 20 Ma. The age value of this event has been chosen such that the effects of magma emplacement produce thermal maturity indices that are compatible with extensive occurrences of oil fields in the central rift system of the Campos basin. Note that thermal effects of stretching events, that took place during early period of basin formation, are in many cases insufficient in producing adequate maturity levels. For example, the indices of maturation reported by Cardoso (2007) as well as Cardoso and Hamza (2014) are too low for oil generation, at four out of the five sites within the central rift system of the Campos basin. We conclude that maturity indices compatible with large-scale occurrences of oil deposits in Campos and Santos basins are possible only under the thermal effects of magma under-plating that occurred in the last 20 Ma.

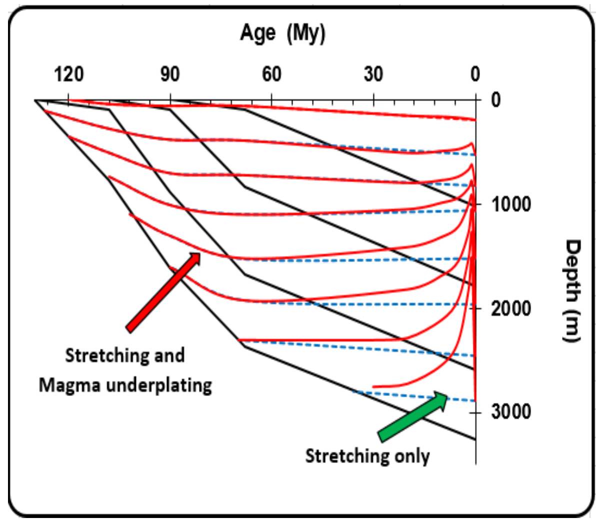

Figure (4): Paleo-temperatures at the site of well RJS-13 during the evolutionary history of the Campos basin. The dashed curves indicate isotherms for the case where the thermal regime is determined only by the stretching mechanism. The lines in red color indicate the case where thermal effects of under-plating are superimposed on that by stretching.

Conclusions

In the present work, we have examined the nature of thermal fields associated with the main tectonic domains of Campos and Santos basins. The structural provinces of the basin, considered for this purpose, include regions of Moho uplift on its western margin, rift basin systems in its central parts and areas of failed spreading ridges in the eastern parts. Observational geothermal data has been used along with estimates in assigning representative heat flow values to these structural elements. The anomalous geothermal belts are located in the central rift basin systems. There are indications that the origin of the geothermal belt is related to recent episodes of magma emplacement in the upper crust. According to results of model studies, the depth of magma emplacement is approximately 20km and its age no more than 2Ma.
At this point, it is useful to point out that a single magma episode cannot account simultaneously for maturity levels needed for oil generation in the central rift system and at

the same time produce anomalous heat flow in the central parts of the basins. Increasing the duration of the long period event would lead to unacceptably high maturity levels in the central rift system. On the other hand, an episode of short duration is necessary to account for the characteristics of the observed heat flow anomaly, which is limited to the axial regions of the basin. Increasing the duration of this short period event would lead to high heat flow in the adjacent continental regions, due to lateral thermal diffusion in the continental crust adjacent to the basins. Such a situation contradicts the observed heat flow pattern, and is therefore unacceptable. Hence, the need for two distinct magma episodes, one of relatively long period (20Ma) and the second one of relatively short duration (2Ma). This observation has important implications in analysis of periods of oil generation in the Campos basin. Thus, allowing for additional effects of magma under-plating imply that the period of oil generation in the Campos basin is likely to be no more than 10Ma.

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