Determination of fluid flow in Deep Sedimentary Layers in the Campos Basin

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Abstract

Results of regional-scale geothermal studies are presented, providing new insights into the characteristics of fluid flows within deep sedimentary layers of the Campos basin. The study is based on bottom-hole temperature data sets for 76 oil wells, the depths of which vary from 2000 to 4000 m. The techniques employed in data analysis have allowed identification of upflow of fluids in both shallow and deep sedimentary layers. Specifically, temperature profiles of 15 wells are found to have non-linear features indicative of upflow. The geographic distributions of these wells indicate presence of two distinct groups of flow systems that operate in shallow and deep depositional environments. According to the results obtained vertical velocities of fluid flows are found to fall in the range 10^{-10} to 10^{-9} m/s, while the horizontal velocities are considerably higher, of the order 10^{-8} m/s.

Introduction

A common characteristic feature of basins in the continental margin of Southeast Brazil is the widespread occurrence of turbidity currents. Results of deep drilling have revealed the presence of turbidite deposits at depths greater than 5000 meters (Posamentier & Walker, 2006; Mutti et al, 2009). Such deposits are formed by turbidity currents which are rapid, downhill flow of sediment water mixtures. It is believed that such currents have been set into motion when mud and sand on the continental shelf are loosened by influx of fluvial discharge, earthquakes, collapsing slopes, and other geological disturbances. Influxes of fluvial discharge are believed to be intense along the continental slopes during periods of low level sea stand. Turbidity currents are considered responsible for changes in the physical shape of the continental shelf and slope by eroding large areas, carving out underwater canyons and creating channel systems on the sea floor. For example, Castro (1992) reported an overview of channel systems carved out by turbidites in the area of the off-shore segment of the Campos basin.

The processes responsible for turbidity currents belong to the general class of subsurface flows in permeable media. Occurrences of headless canyons have been cited in some studies (Covault, 2011) as marks of turbidity currents triggered by subsurface flows.

Cases of regional scale subsurface flows have been reported in several parts of continental interiors. In Brazil such flows have been identified in the Amazon, Parnaiba and Paraná basins (Pimentel and Hamza, 2013). Pimentel and Hamza (2012) reported subsurface flows in the Taubate basin and in the on-shore segment of the Campos basin. In this latter case there are indications of subsurface discharge into the submerged parts of the continental shelf. Cases of such submarine discharge of groundwaters have been reported for coastal areas in several parts of the world (Buddemeier, 1996; Taniguchi et al, 2002).

Considerable advances have been made over the last few decades in understanding the geological characteristics of turbidite deposits (see for example Bouma, 1962; Mutti et al, 2003; Shanmugam, 2003). Nevertheless few efforts have been made in estimating fluid flow characteristics in turbidites after their final stages of deposition. In the present work we report progress obtained in the use of geothermal methods for identifying present day fluid flows in sedimentary layers that include turbidite deposits in the Campos basin. The main advantage of this approach is the ease with which it is possible to determine characteristics of advective fluid flows at depths extending to several kilometers. The relative locations of the basins in the continental margin of southeast Brazil are indicated in the map of Figure 1.

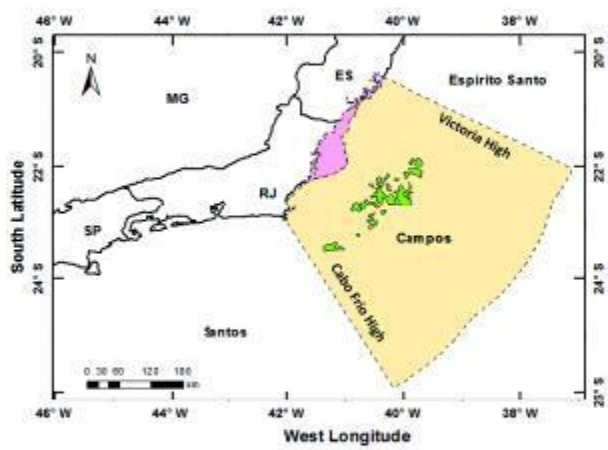

Figure 1 - Locations of sedimentary basins (Santos, Campos and Espirito Santo) in the continental margin of southeast Brazil. The ash and pink colored areas indicate the on-shore and off-shore segments of the Campos basin and the dotted lines their approximate limits. The green colored patches are locations of the main oil fields in the Campos basin.

Data base of the present work

Most of the earlier studies on the geothermal field of the Campos basin have been based on results of bottom-hole temperature measurements in oil exploration wells (e.g., Meister, 1973; Rossi Filho, 1981; Zembruscki and Chiang, 1989). Ross and Pantoja (1978) reported results of a work with focus on local subsurface temperature fields. Jahnert (1987) presented maps of regional variations deep isotherms and thermal gradients in areas of oil fields and discussed their eventual correlations with regional scale structural features and gravity anomalies. Unfortunately, the details of data base employed by Ross and Pantoja (1978) and Rossi Flilho (1981) are not available for public domain analysis. In addition, very little information is available in these reports on the methods employed in data reduction and error analysis.

More recently, Gomes and Hamza (2005) reported geothermal data for the adjacent coastal region of Rio de Janeiro. In addition, Vieira et al (2010) and Vieira and Hamza (2011) reported estimates of heat flow values for the oceanic crust adjacent to the Campos basin. A summary of geothermal gradient and heat flow values is given in Table 1.

Table 1 Mean values of geothermal gradients (Γ) and heat flow (q) in the offshore basins of SE Brazil

Basin	Γ (^oC/km)	q (mW/m^2)
Espirito Santo	30.8	74
Campos	30.3	75
Santos	31.0	70

Methodology

The general principle of the geothermal method in studies of groundwater flows is based on consideration of the role of advection heat transfer on the conductive regime of subsurface layers. The equation for simultaneous heat transfer by conduction and convection in a porous and permeable medium of homogeneous thermal properties has been discussed by Carslaw and Jaeger (1959), Suzuki (1960) and Stallman (1963). In obtaining simple analytical solutions it is common practice to assume that the medium is homogeneous with constant physical properties and uniform flow velocities. Bredehoeft and Papadopulos (1965) presented a solution for the case in which flow is dominantly in the vertical direction. This solution has been employed widely in the geothermal literature (see for example Cartwright, 1970; Mansure and Reiter, 1979). Lu and Ge (1996) considered the case where the flow has both horizontal (x) and vertical (z) components. The differential equation relevant in this case for a medium with vertical temperature gradient (η) and horizontal temperature gradient (γ) may be expressed as:

$$\frac{d\eta}{dz} = \frac{\beta}{L}\eta + \frac{\alpha}{L}\gamma \qquad (1)$$

where L is the thickness of the medium. In Eq. (1) the quantities $\alpha = c_w \rho_w v_x L/\kappa$ and $\beta = c_w \rho_w v_z L/\kappa$ represent dimensionless Peclet numbers, in which v_x and v_z are the velocities of the circulating water in the x and z directions.

Lu and Ge (1996) derived a solution for Eq. (1) in which the medium is assumed to be homogeneous. For layered media this solution (referred to in the present work as the LUGE-model) may be expressed as:

$$\frac{T_i - T_0}{T_L - T_0} = \left\{ \frac{\exp[\beta(z_i/L)] - 1}{\exp(\beta) - 1} + \frac{\alpha\gamma}{\beta\eta}\left[\frac{\exp[\beta(z_i/L)] - 1}{\exp(\beta) - 1} - \frac{z_i}{L} \right] \right\} \qquad (2)$$

where T_i is temperature of the i^{th} layer at depth z_i within the medium and the subscripts *0* and *L* refer to the top and bottom of the medium where water flow occurs. Note that in the absence of fluid movement in the horizontal direction and/or horizontal temperature gradient, Eq. (2) simplifies to the case considered by Bredehoeft and Papadopulos (1965). Also, the left hand side of this equation represents the dimensionless temperature (θ). Its variation with depth z allows use of curve-matching methods for determination of the flow parameter β and the quantity δ (= α γ / β η). This in turn may be used for determination of the velocity components v_x and v_z.

In graphical representations of thermal profiles (with the depth axis pointed vertically downward and temperature on the horizontal axis), the effect of advection heat transfer manifests itself as a characteristic curvature in the vertical distribution of temperatures. In cases where fluid movement is vertical only, the sign of the flow parameter (β) may be positive or negative depending on the direction of v_z. Thus, positive values of β generate curvatures that are indicative of down flow, while negative values lead to curvatures that indicate up flow. In cases where fluid flows have both vertical and horizontal components, the analysis of curvatures in temperature profiles is a more complicated task. According to the convention adopted by Lu and Ge (1996), γ is taken as positive when the heat flux is leftward (or negative, when it is rightward). In addition, the parameter α is considered positive when the fluid flux v_x is rightward (or negative, when it is leftward) and the parameter β is positive when the fluid flux v_z is downward (or negative, when it is upward). Fit of Eq. (2) to observational data on temperature distribution may be used for determining the values of α and β and the velocity components of ground water flows. The values of parameters employed in model simulations are presented in Table 2.

Table 2 Values of parameters employed in model simulations.

Parameter	Value	Unit
Fluid Density	1000	Kg/m^3
Specific Heat	4200	kJ/kg/^oC
Thermal Conductivity	2.5	W/m/^oC
Thickness of the flow medium	5000 -8000	m
Top Boundary Temperature	5 - 15	^oC
Bottom boundary Temperature	170 - 220	^oC
Horizontal thermal Gradient	0.00020	^oC/km
Vertical Geothermal Gradient	0.025 – 0.040	^oC/km

Some comments on the potential sources of error in attempting model fits to temperature profiles observed in wells is in order before presenting the details of the results obtained. Foremost among these is the non-uniqueness in curve-matching procedures, which arise from the compound effects of horizontal and vertical fluid flows in vertical distribution of temperatures. Reiter (2001) recommends use of piezometric data to constrain the model solutions. This option, however, is impractical in the present case. In cases where the vertical dimensions of the flow domain are relatively small compared to its lateral dimensions the probability that the stream lines cross isotherms is small. This condition may lead to uncertainties in the estimates of horizontal velocities. In the present work, the thicknesses of strata considered are relatively large and hence the probability that the streamlines run parallel to isotherms is small. Also, results of numerical solutions reveal that the range of combinations of vertical and horizontal velocities that can provide statistically good fits is narrower for data sets that cover large depth values. Thus, relatively reliable estimates of velocities can be obtained in curve-matching procedures, provided the depth ranges of flow systems are reasonably large. The relatively large depth intervals of BHT data, and the wide geographic distribution of oil wells, mean that the results obtained provide useful information on deep flow systems.

Another problem with the curve matching procedure of the LUGE method is that it requires estimates of the depths of the top and bottom boundaries of the flow system. In the present work, available information on the hydrogeological characteristics of the basin was employed in setting depth values of the flow interval. Clearly, geological uncertainties as to the top and bottom boundaries of aquifers contribute to the problem of non-uniqueness in data analysis. Results of numerical simulations reveal that errors of up to 10% in the depth level of the bottom boundary has only a minor influence on the estimates of flow velocities. However, the important point is that the restriction imposed by geologic data for the depth to bottom boundary of the flow interval limits the domain of non-uniqueness. Moreover, it allows selection of values of velocity components that minimize mean square deviations of the fits to experimental data. This approach was adopted in the present work. An example of the results obtaining in applying this procedure is illustrated in Figure 2. It illustrates the variations of mean square deviations as a function of the adopted value of basal temperatures in model fits. The numbers besides the curves refer to the thickness of the flow medium. Note that for any particular value of the thickness of the flow medium the mean square deviation has a minimum. In the resent case best fit values were obtained for temperatures in the range of 180 to 200 ^{o}C, at depths of 5500 to 6500 meters.

It is clear that velocity values, for which statistically robust solutions can be identified falls within a narrow interval. Obviously, the magnitude of this interval is related to the quality of observational data. BHT data sets are in general “noisy” and hence lead to larger domains of non-uniqueness. High precision temperature measurements are, in principle, useful in limiting the domains of non-uniqueness. However, availability of such data is in general scarce, especially for depths greater than a few kilometers.

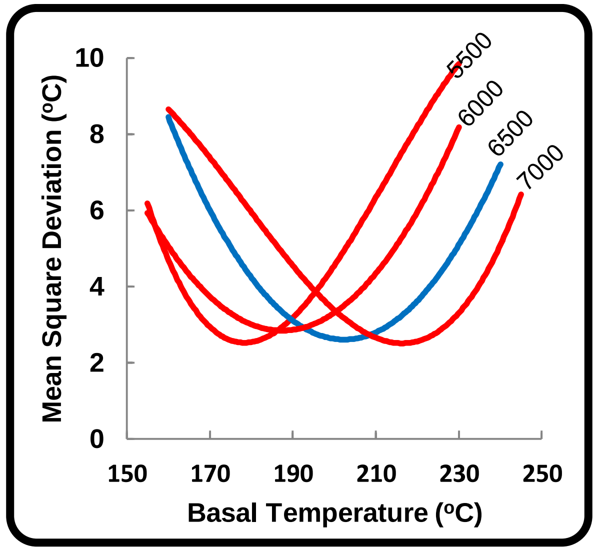

Figure 2 - Variations of mean square deviations with basal temperatures for model fits. The numbers besides the curves refer to the thickness of the flow medium.

Results

Out of 76 wells studied in the present work 15 were found to have significant deviations from the linear trends, which were considered as indicative of the thermal effects of advective fluid flows. The coordinate locations of these wells are given in Table 3 along with depths of bottom-hole temperature measurements. AAPG procedure (AAPG, 1976) was adopted in making corrections for drilling disturbances in temperatures. The corrected values are given in the last column of this table.

Table 3 Data sets for wells with non-linearity in temperatures, indicative of upflow of interstitial fluids.

Well	Coordinates		Depth	Temperature (^{o}C)	
	Lon	Lat	(m)	Meas.	Cor.
RJS44	40.657	22.613	2804	98	108
RJS50	40.473	22.454	3218	107	119
RJS56	40.387	21.594	5000	154	168
RJS57	40.544	21.490	4202	148	162
RJS58	40.635	21.604	3796	125	138
RJS70	40.995	22.230	2355	83	91
RJS79	40.513	21.524	3761	134	147
RJS80	40.478	22.444	3170	103	114
RJS82	40.809	21.824	2282	86	94
RJS83	40.540	22.504	3252	106	118
RJS91	41.176	23.211	2890	96	106
RJS94	40.682	21.533	2704	111	121
RJ96A	40.316	21.383	4003	144	158
RJ101	40.583	22.477	4603	167	181
RJ106	40.740	22.764	2780	99	109

The results of curve matching procedures for the set of data in Table 3 are illustrated in Figure 3. For this set of data the vertical velocities of fluid flow are found to be of in the range of 10^{-10} to 10^{-9} m/s. The horizontal velocities were however found to be nearly an order of magnitude higher. No significant departures from non-linearity in temperatures were observed for the set of remaining 61 wells considered in the present work. Such cases have been considered as indicative of the absence of fluid flows in local sedimentary deposits.

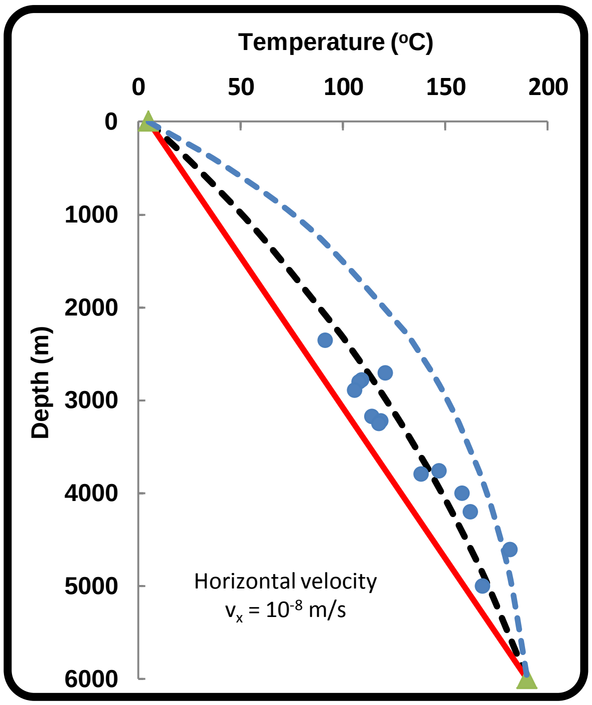

Figure 3 - Distribution of temperatures in turbidity deposits at sites of 15 wells.

Discussion and Conclusions

The geographic distribution of the sites of wells where fluid flows have been identified is illustrated in Figure 4. It is clear that the locations fall into two distinct groups both with orientations of NE – SW. The first one is close to the coastal area where water depths are less than 1000 meters. The second one is located also in the continental shelf but water depths are greater than 1000 meters. The channels appearing in this map are associated with turbidite flows in quaternary sediments (Castro, 1992; Gonthier, 2003). Lack of suitable data have prevented us from identifying similar channel systems that developed during earlier times and have contributed to the evolution of paleophysiolography of the primitive sea floor.

Though the results obtained in this work have allowed determination of ascend velocities of pore fluids in turbidite deposits the processes responsible for such upflow systems remains largely unknown. Self compaction of unconsolidated sediments can give rise to upflow systems but this possibility has been ruled out as there are no indications of systematic decreasing trends in upflow velocities.

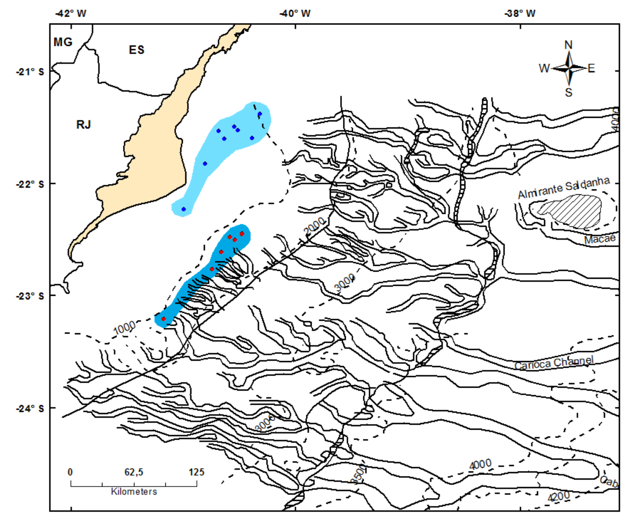

Figure 4 - Distribution of sites where fluid flows have been identified relative to the turbidite channels in Quaternary sediments (Adapted from Castro, 1992).

On the other hand, the fact that regions of upflow systems are located in the continental shelf opens up an intriguing possibility. During periods of low level sea stand the sedimentary layers in coastal areas harbour significant recharge movements of groundwater, originating from fluvial discharge and associated subsurface flow systems. Much of these are in fact similar to the underground flow systems described in the recent works of Pimentel and Hamza (2012; 2013). On the other hand, during periods of high level sea stand the connection between fluvial discharge and sedimentary layers in the continental shelf are cut off. As a result the pressure heads driving the recharge flows in deep sedimentary layers become extinct. In addition, the extra pressure head on the sea floor generated by high sea levels lead to a reversal in the directions of subsurface flow systems. The recharge zones become areas of upflows during periods of high sea levels. A schematic of this flow system is illustrated in Figure 5. In the present context, we advent the hypothesis that upflow systems observed in the continental shelf of Campos basin are related to recent changes in sea levels.

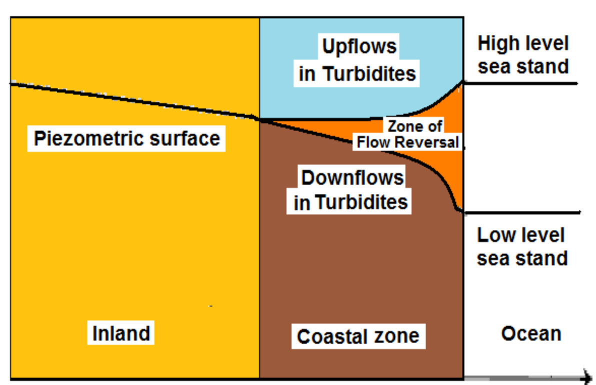

Figure 5 - Schematic illustration of flow reversal in turbidites.

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