Multiphysics anomaly map results for pre-salt area in Campos Basin, Brazil

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Abstract

The Campos Basin, in southeast Brazil, where fractured basalts has been identified as oil reservoirs, is an example of the hydrocarbon exploratory potential in igneous rocks. Recently, new basalt flows in the section below salt was identified as potential reservoirs in this area. Because geophysical interpretation in such scenario is ambiguous and complex, the identification and mapping of such rocks is usually difficult. In such context, geophysical data integration has been largely applied to reduce exploration risk. The integration of interpretation results from multiple geophysical methods in the recently proposed multiphysics anomaly map is a methodology that has proved to be an efficient qualitative tool for a wide range of geological problems. In this methodology, geophysical data from different methods are mathematically treated with a logistic function, a function specially designed to bounds large values, to allow reliable combination. The process emphasizes regions where individual interpretations from different geophysical methods correlate, which represent large probabilities of target occurrence. The effectiveness of the multiphysics anomaly map in the area becomes evident from the correct identification of volcanic rocks sampled in the wells but also from the capacity of providing qualitative estimate of the relative thickness of these volcanic rocks.

Introduction

The occurrence of igneous rocks in the Brazilian offshore sedimentary basins is consequence of magmatic events that have succeeded the rifting and the consequent South America-Africa continental separation. In this context, the Campos Basin, where fractured basalts has been identified as oil reservoirs, is a good example of the hydrocarbon exploratory potential of the igneous rocks.

Recently, three new drilled wells have sampled volcanic rocks in the pre-salt section in Campos Basin (Figure 1). Although two of the wells (WELL-1 and WELL-2) have sampled non-reservoir basaltic flows, the WELL-3 well sampled a potential hydrocarbon reservoir volcanic rocks. In the presence of such scenario, where volcanic rocks can change from non-reservoir to reservoir in short distances, the geophysical mapping of such features becomes a challenge to the interpreter (Santana et al, 2018).

Besides the large variability of these volcanic rocks in the region, the ambiguity inherent to the geophysical interpretation makes the identification and mapping of such rocks complex. The integration of the interpretation results from multiple geophysical methods in the recently proposed multiphysics anomaly map (Lyrio et al, 2019), has proved to be an efficient tool to effectively combine the different outputs bringing confidence to the interpretation.

Multiphysics anomaly map (Lyrio et al, 2019) is a data fusion solution for geophysical data combination where seismic attributes, gravity and magnetic data, for instance, are mathematically processed to allow reliable combination. In each method, anomalous regions of interest are highlighted through the use of a logistic function. Logistic function is a mathematical function specially designed to clip large magnitudes and bound the range of values, which allows maximum discrimination among the data.

In this process, anomalies showing spatial superposition will be emphasized while the remaining anomalies tend to be diminished. The resulting anomalies are then combined in the multiphysics anomaly map, which represents regions of large probabilities of target-occurrence. We applied the multiphysics anomaly map solution to the real problem of identifying and mapping the volcanic rocks in this pre-salt area.

Method

Seismic data interpretation in the area is complex and ambiguous since some volcanic rocks identified in the wells show similar seismic responses to reservoir and non-reservoir rocks. In order to reduce both ambiguity and complexity of the interpretation, it is necessary to integrate the different geophysical methods available in the area. Among several seismic attributes available, the discontinuity attribute (Figure 2a) was chosen as the best to define the lateral distribution of the volcanic rocks (Santana et al, 2018).

The seismic discontinuity attribute (Figure 2a) measures the degree of local similarity between seismic traces. The low similarity values, characterized by dark colors, are believed to bound the lateral extension of the volcanic rocks that were interpreted as lava fans and volcanic craters.

In addition to the seismic attribute, it was also available potential field data like gravity and magnetics. A residual gravity anomaly map calculated to focus on the volcanic rocks depth (Figure 2b) shows strong anomalous values, usually associated to high density sources were interpreted as the gravity responses from the igneous rocks. Similarly, strong anomalous values were also found in the analytic signal amplitude map of the magnetic data (Figure 2c). Such anomalous magnetic values were interpreted as the magnetic responses of volcanic rocks underneath.

Data combination from different geophysical methods usually requires normalization to deal appropriately with the distinct physical units. Normalizing data by dividing it by a chosen constant value is a common practice. However, its linear nature can create large results for bounding values of the dataset, which may lead to undesirable results during anomaly combination. In order to prevent such undesirable results we decided to work with the logistic function.

A logistic function is a common non-linear mathematical function showing a typical sigmoid curve often used in statistics and machine learning techniques. In this approach, we use a modified version of the logistic function specially designed to clip large magnitudes and bound the range of values (Figure 3). The generic form of the logistic function $\boldsymbol{\sigma}$ proposed in this work can be described by the equation:

$$\sigma(x)=\frac{L}{1+e^{-ks(x-x_0)}},$$

where $\boldsymbol{e}$ is the natural logarithm base, $\boldsymbol{x_0}$ is the $\boldsymbol{x}$-value of the sigmoid inflection point, $\boldsymbol{L}$ is the curve maximum value, $\boldsymbol{k}$ is the steepness of the curve, and $\boldsymbol{s}$ is a scaling factor that fits the data domain into the chosen function domain. The asymptotic characteristic of the logistic function as $\boldsymbol{x}$ tends to infinity seems more suitable for getting the desired normalization results since even extreme $\boldsymbol{x}$-values will always result in $\boldsymbol{\sigma}$-values bounded by the logistic function range.

In the multiphysics anomaly map approach each geophysical method needs to be appropriately scaled to the (-24,24) interval, chosen as the function domain. Each dataset have its domain shifted and centered to zero before being rescaled by the scale factor ***s.*** The scale factor $\boldsymbol{s}$ is the ratio between the domain of the logistic function and the data domain.

The choice of the parameter $\boldsymbol{x_0}$ is of fundamental importance and is, indeed, an interpretation task because the selection of significant anomalies in each method is problem dependent. The selection of $\boldsymbol{x_0}$ must be made with care since it is critical for the final results. The resulting datasets after applying the logistic function to each anomalous data are named logistic anomalies.

The logistic anomalies calculated for the geophysical data in Figure 2 are presented in Figure 4. The parameters $\boldsymbol{L} = 2$ and $\boldsymbol{k} = 0.25$ were kept constant for all three geophysical data transformation. The seismic logistic anomaly in Figure 4a was obtained by applying a scale factor $\boldsymbol{s} = 510.64$ and $\boldsymbol{x_0} = 0.007$ to the seismic discontinuity data in Figure 2a. The gravity residual of Figure 2b was processed with scale factor $\boldsymbol{s} = 41.38$ and $\boldsymbol{x_0} = 0.22$ to produce the gravity logistic anomaly show in Figure 4b. Finally, scale factor $\boldsymbol{s} = 4000$ and $\boldsymbol{x_0} = 0.003$ were used to transform the analytic signal amplitude data of Figure 2c into the magnetic logistic anomaly in Figure 4c.

The fusion of all logistic anomalies into the multiphysics anomaly map is accomplished by multiplying all logistic anomalies. As a result, the multiphysics anomaly map highlights regions showing the maximum correlation between major features interpreted from different geophysical methods. In the multiphysics anomaly map, we expect areas showing larger values to represent greater probabilities of target occurrence.

Results

The three logistic anomalies shown in Figure 4 were multiplied together to composed the multiphysics anomaly map exhibited in Figure 5. The computed multiphysics anomaly map shows anomalous regions in the vicinity of the wells WELL-3 and WELL-2, where volcanic rocks were sampled by the wells. Although volcanic rocks have also been identified in WELL-1, no anomaly was detected in this position because the volcanic rocks in WELL-1 are located below the interval were the geophysical data processing was focused.

The amplitude of the anomalous values in the multiphysics anomaly map shows a reduction in intensity from well WELL-3 to WELL-2. The amount of volcanoclastic rocks in WELL-3 (orange color in the well log of Figure 5) associated with the summation of the lava flows thickness in WELL-2 (red colors in the well log of Figure 5) and the absence of the igneous rocks in the well log of WELL-1, strongly correlates with the total thickness of volcanic rocks measured in each well. Therefore, the multiphysics anomaly map was interpreted as a qualitative indicator of the volcanic rocks volume in the area.

Conclusions

The integrated interpretation of geophysical data performed of this area in Campos Basin, based on a recently developed multiphysics anomaly map methodology that combines seismic attributes and potential fields maps, has contributed to the understanding of the volcanic rocks distribution in the area.

The presence of multiphysics anomalies in the regions where wells have detected volcanic rocks brings confidence to extend such interpretation to other surrounding areas as well as in nearby regions showing similar geological context. The strong correlation between the anomaly intensity in the multiphysics anomaly map and the volcanic rocks volume measured in the wells highlights the value of the applied methodology as a qualitative tool to estimate the relative volume of this type of rocks.

The incorporation into the multiphysics anomaly map of structural and stratigraphic features, for instance, should amplify its usefulness as integrated interpretation tool and contribute to the expansion of its multimodal nature.

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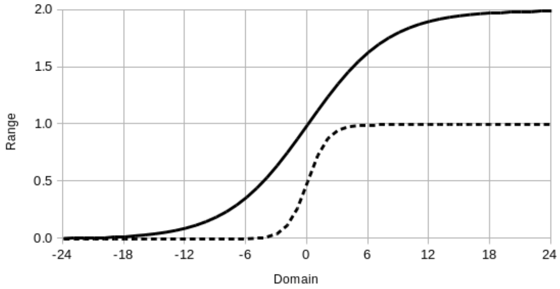


Figure 3 – Example of logistic functions. In dashed line is the standard sigmoid function while the modified logistic function is shown by the solid line.

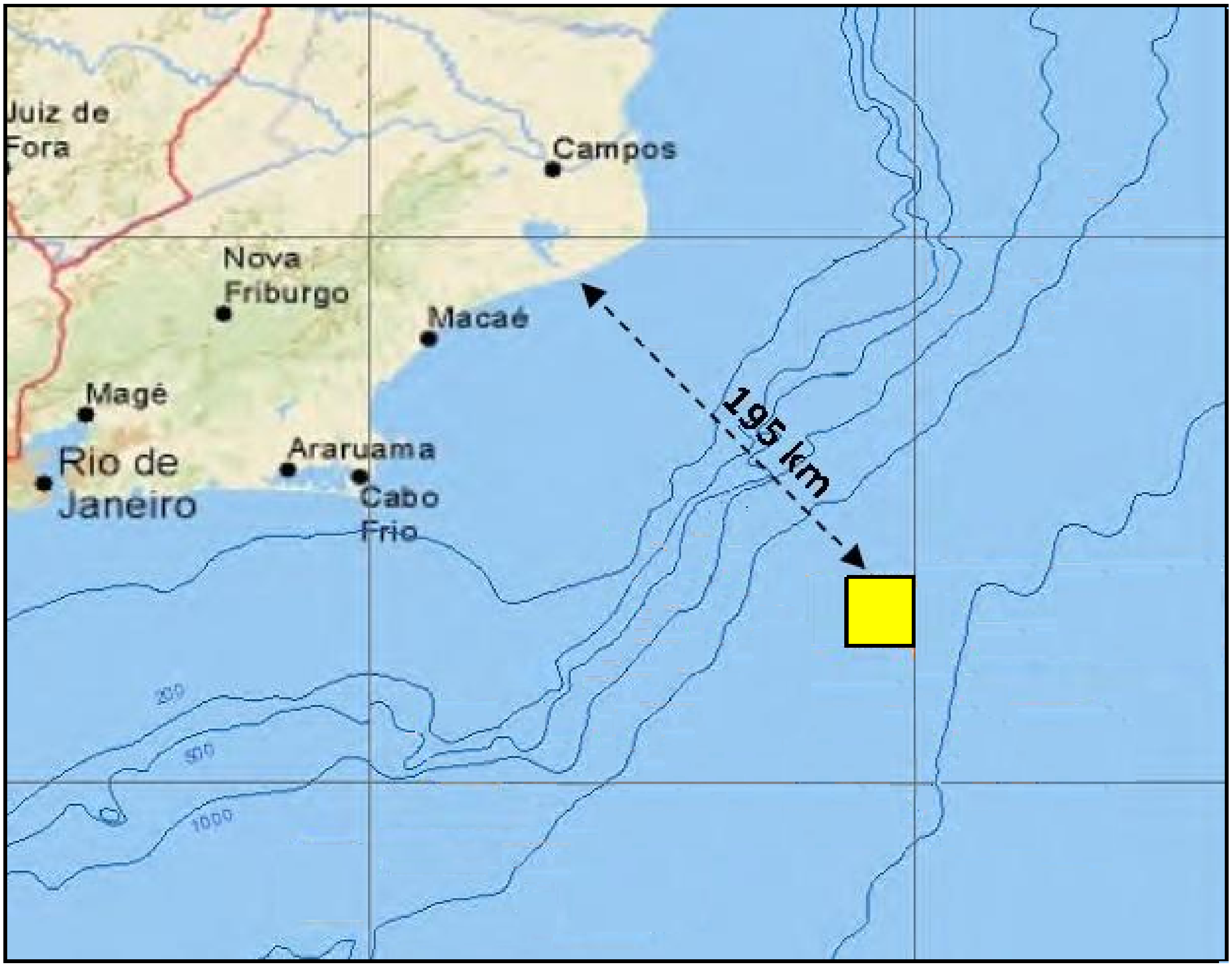
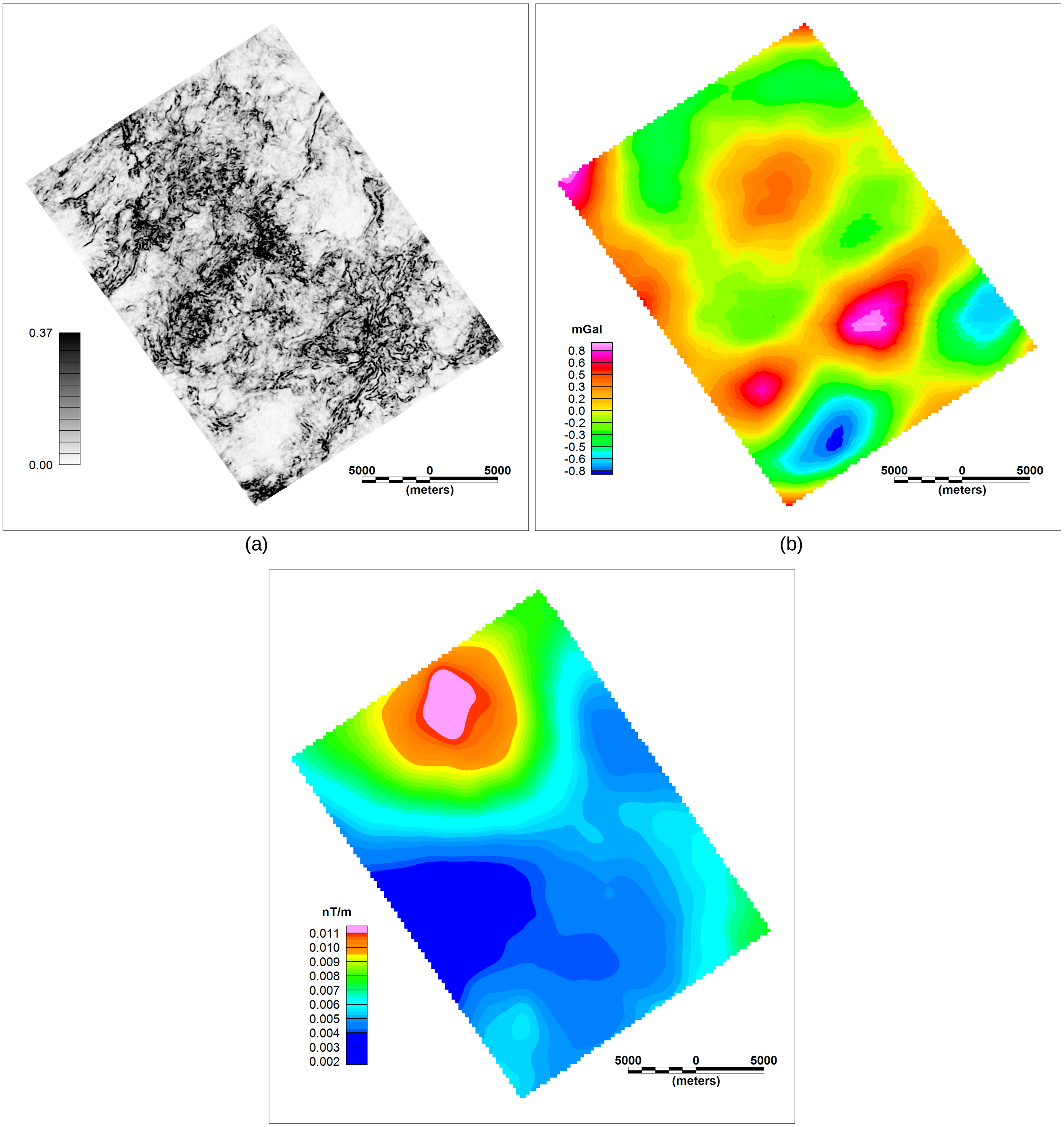


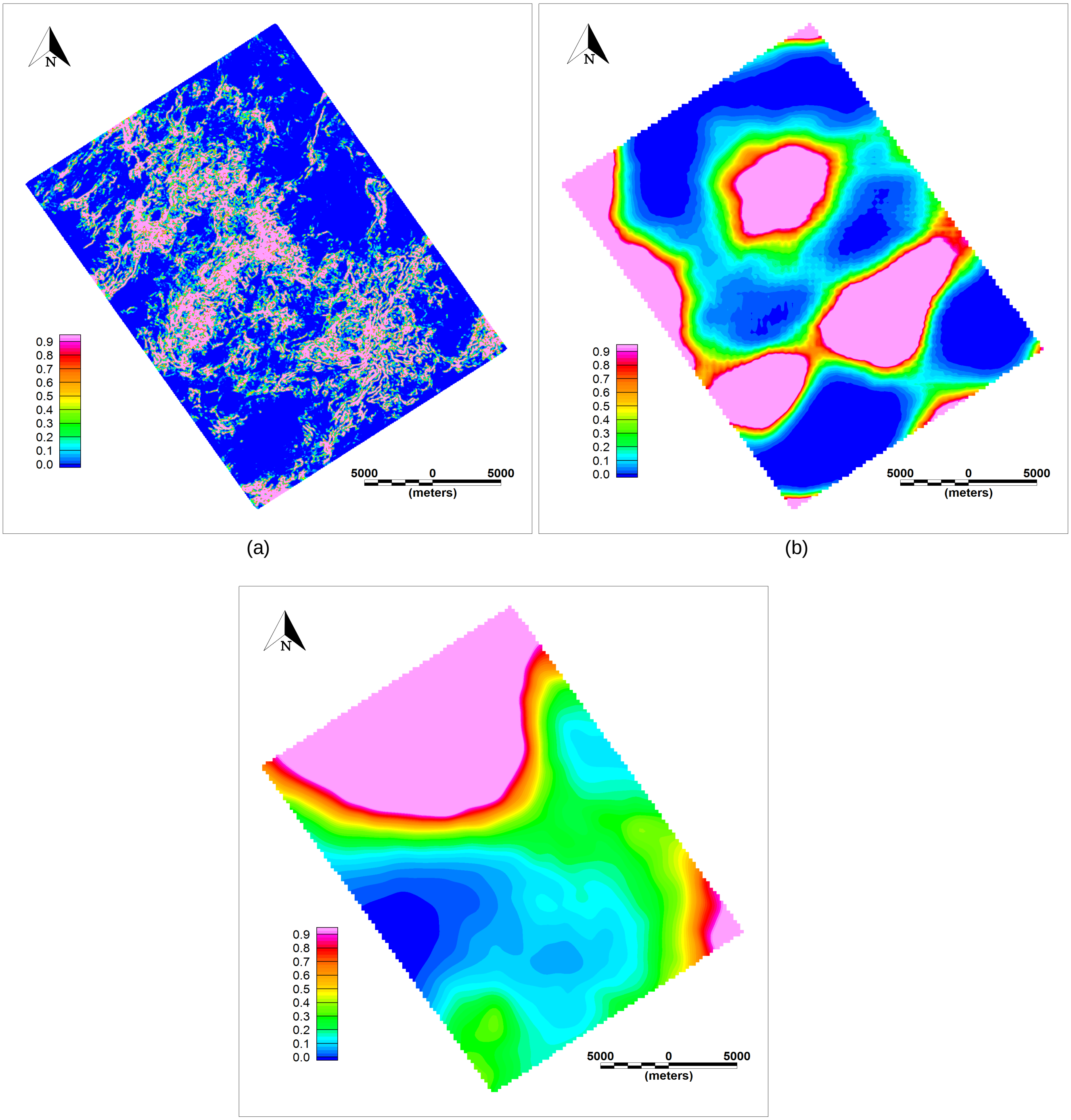
Figure 1 – Location of study area. The yellow box shows the position of the study area in Campos Basin, Brazil.



(a) (b)

(c)

Figure 2 – Anomalies selected for construction of the multiphysics anomaly map in an area of Campos Basin, Brazil. In the seismic discontinuity in (a) the dark areas were interpreted as indicative of volcanic rocks. The gravity residual in (b) shows positive anomalies, usually related to high density rocks, which can be indicate presence of igneous rocks. The strong magnetic anomaly in the amplitude of the analytic signal in (c) may also represent the response of volcanic rocks.



(a)

(b)

(c)

Figure 4 – Logistic anomalies calculated applying the proposed modified logistic function to the selected geophysical anomalies shown in Figure 3. In all three results, the logistic seismic anomaly shown in (a), the logistic gravity anomaly in (b) and the logistic magnetic anomaly in (c), the higher values represent the regions with large probability of occurrence of volcanic rocks.

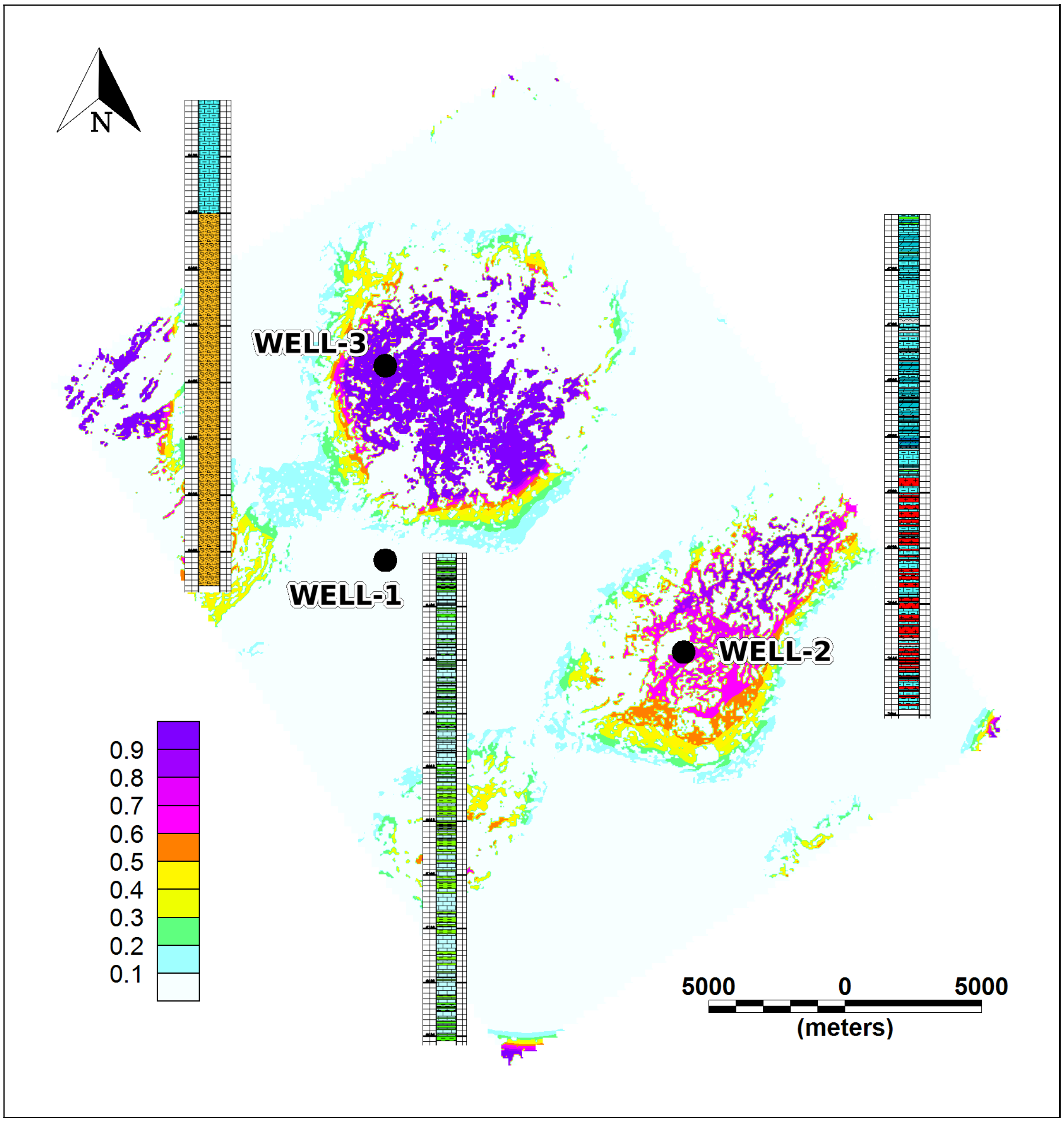


Figure 5 – The multiphysics anomaly map resulting from the fusion of the three logistic anomalies shown in Figure 4. The position of the main anomalies correspond to the presence of volcanic rocks sampled by the wells. The amount of volcanoclastic rocks in WELL-3 (orange color in the well log) associated with the summation of the lava flows thickness in WELL-2 (red colors in the well log) and the absence of the igneous rocks in the well log of WELL-1, makes clear that the intensity of the anomalous values directly correspond to the total thickness of volcanic rocks in each well.