Structural control of the São Francisco River Delta from the aeromagnetic data, Brazil.

ABSTRACT

The São Francisco River delta is a Quaternary sandy plain built on a structural low of the Sergipe-Alagoas Basin, known as the São Francisco Low. The inner limit of the São Francisco River delta is defined by rectilinear cliffs between the delta plain and the Barreiras Formation, which coincide with important faults delimiting the São Francisco Low. Moreover, on the continental shelf, the deltaic clinoform developed over a topographic low limited by rectilinear scarps that present compatible orientation with the Sergipe-Alagoas structural framework. Thus, based on a theoretical background that indicates the existence of structural control over the formation of delta systems in general, and previous knowledge of this area, it is possible that the Sergipe-Alagoas Basin structure has influenced the delta. This relationship can be inferred using adequate methodology. Magnetometric was integrated in the present study with the geological information on the area. The main objective was to evaluate the existing structural controls over the formation of the São Francisco delta and neighboring areas. The first stage of the present study consisted of a thorough bibliographic review and the search for pre-existing geophysical data in the region.

Keywords: Delta; San Francisco; Aeromagnetic Data; Edge Detection.

1. INTRODUCTION

Deltas are defined as a shoreline protuberance caused by the insertion of the fluvial system into a lower energy environment, in a context where the sedimentary supply is greater than the capacity of the basin to distribute [3]. Deltatic environments are of great importance since these areas offer various facilities for the populations that settle in them. As an example are the fertile land regions for agriculture, the proximity to river courses and the coastal zone [11].

Nowadays, many studies are carried out in deltas that target the oil and gas industry, but studies that are concerned with the environmental aspects of these regions have also been developed [11]. The significant increase in the environmental impacts caused by the increase of the population in these areas has generated an increasing concern with them, very susceptible to problems such as coastal erosion, subsidence, floods and salt intrusion [17].

There are several factors that are widely found in the literature, which are identified as those responsible for delta sedimentation: climate, river discharge, tidal amplitudes, wave energy, relative sea level variation, wind patterns ([4], [7], [8], [9]). Another important factor in the deltaic sedimentation is the tectonics of the area, which although little approached as one of the determining factors in this process presents evidences of its control in deltas around the world.

Some works present in the literature analyze the tectonics as the main controlling agent in the formation of the deltas. [12], in a work on the Ganges-Brahmaputra delta, emphasized the influence of Himalayan tectonics on the sedimentation rates, magnitude and characteristics of the sedimentary deposits on the delta banks. [5] wrote about the Pos Delta and the influence of glacial cycles and tectonic processes on the natural subsidence of this delta.

[1] developed a study that shows the influence of the presence of reactivated growth faults in the Mississippi Delta, and [19] developed a study that attempted to understand subsidence processes in the Nile Delta, where he concluded that subsidence rates were accelerated due to the neotectonic present in the region. Finally, [15] conducted a study in the São Francisco Delta that focused on the study of the reactivation of faults in the Quaternary as the main controlling agent of sediment deposition and morphology of this delta.

The São Francisco River Delta (DSF) is a sandy, quaternary-level plain (Figure 1) built on a low basement of the Sergipe-Alagoas basin, known as Baixo do São Francisco [18]. Knowledge about DSF is basically restricted to its superficial outcrop portion. [11] was the first to provide subsurface information of the area, which allowed to advance in the knowledge of the depositional architecture of this system. A preliminary analysis of published works and existing data suggest some kind of tectonic control in the development of DSF.

The Sergipe-Alagoas Basin, located in the states of Sergipe and Alagoas, is distributed both on land and in the submerged region, extending towards the sea beyond the 2,000 m isobath, in a total area of approximately 34,600 km², being 12,000 km² in the emergent portion. This basin is limited by the parallels 9ºS and 11º30'S and by the meridians 34º 30'W and 37º 30'W.

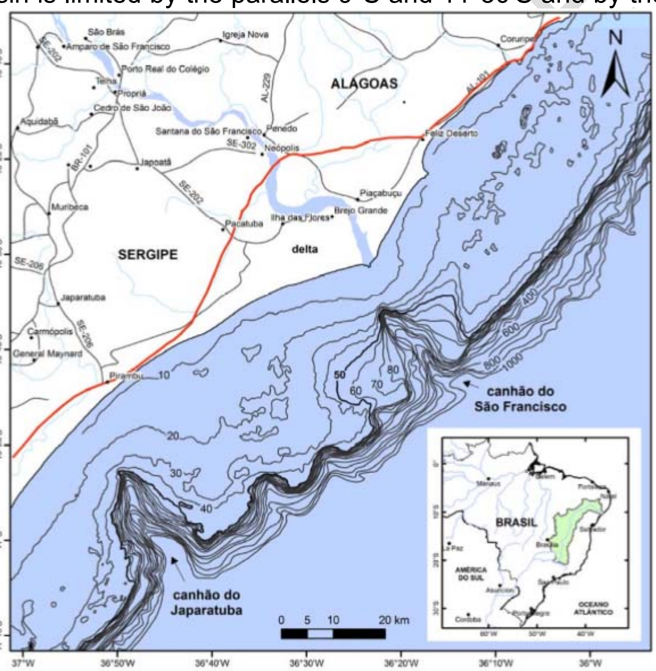


__Figure 1:__ Location map of the study area. Source: [11].

In a more recent work, [15] carried out a study in DSF that had as main focus the process of reactivation of faults in the Quaternary, considered by the author as the main controlling agent of sediment deposition and delta morphology. This control would occur from the generation of new space for sediment accommodation, through the reactivation of faults. This work using well data, optical and radiocarbon dating and seismic data proposed the existence. From three main stratigraphic units (Figure 5): 1) Barreiras Formation deposits (fb) dated from the Miocene; 2) fluvial deposits and flow of debris (dffd) dated to the Late Quaternary; 3) inter bedded braided stream (bsb) deposits also dated from the Late Quaternary. Data from pre-existing seismic surveys in the region show that the internal boundary of the DSF coincides with the N-S and NE-SW direction of Cretaceous faults (Figure 6). These faults form several cliffs and most of these are at the base of the uncontaminated sedimentary rocks of the fb and the dffd unit.

The author concludes that at least two major faults were reactivated during the Miocene. In Figure 6 it is possible to verify the Cretaceous faults with a parallel orientation to the internal boundary of the delta plain plunging toward the basin. Figure 2 shows an increase in the thickness of the Barreiras Formation, crossing these faults, suggesting a sediment deposition contemporary to the failure processes, with reactivation of these faults during the Miocene. [15] also presented evidence of other reactivations during the Pleistocene-Holocene that affected or created additional accommodation space for the deposition of the other units. The Figure 3 shows the geological map evidencing the present failures in the region and the limits of the DSF.

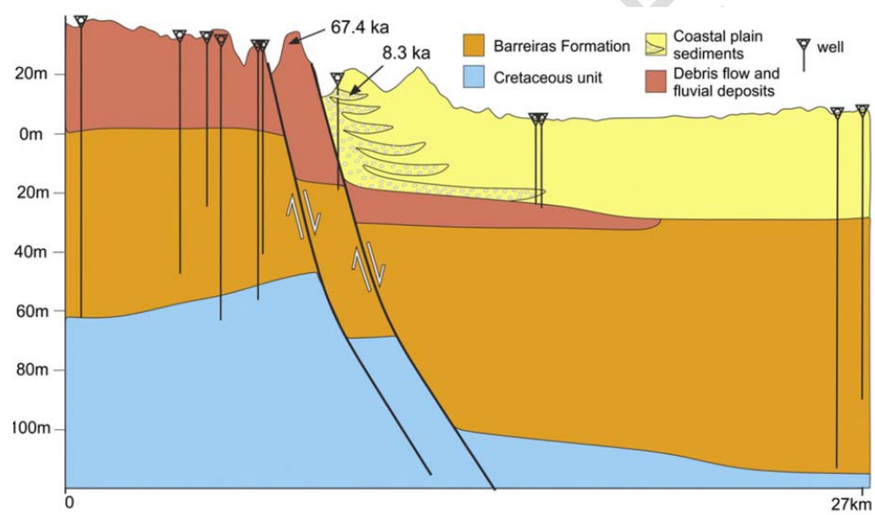


***Figure 2**: Main stratigraphic units found in the area: 1) Barreiras Formation deposits (fb); 2) Fluid deposits and flow of debris (dffd); 3) Braided stream (bsb) deposits. (Source: [15]).*

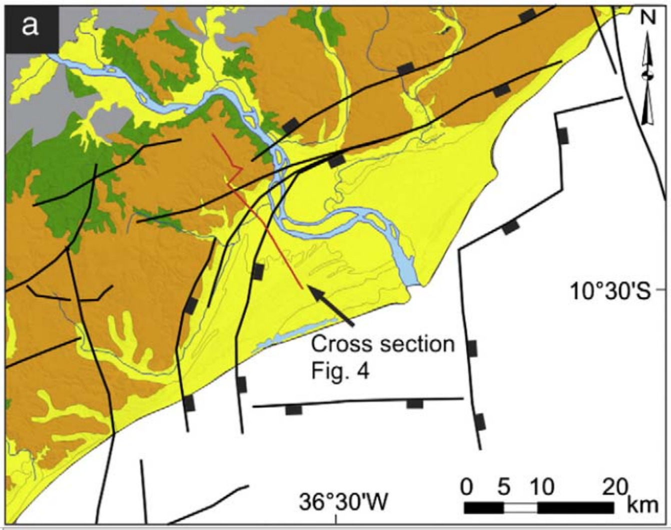


Figure 3: *Simplified geological map evidencing the present failures in the region and the limits of the DSF. The cross section in red represents the section shown in Figure 2 (Source: [15]).*

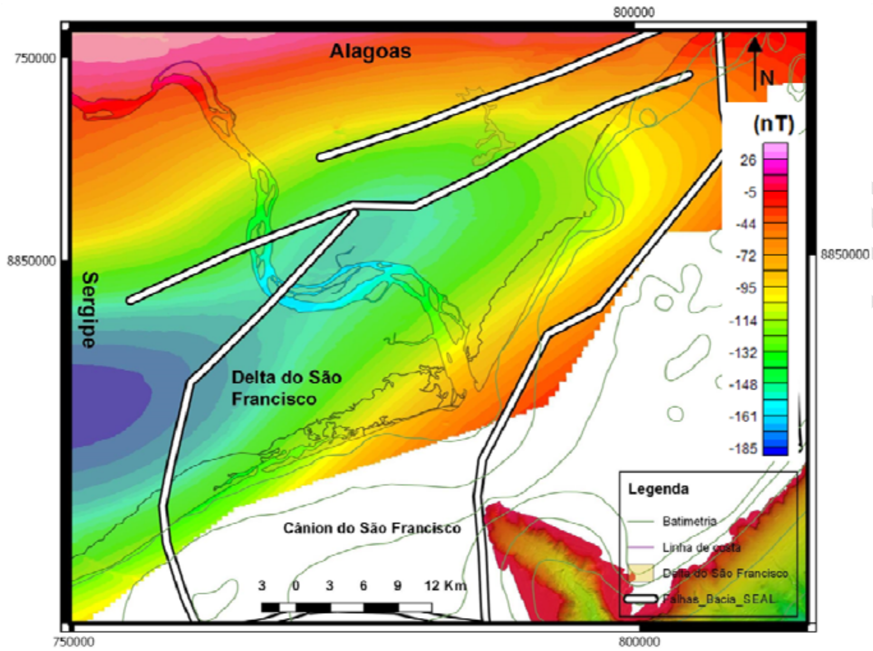
The present work consists in the use of the integrated magnetometry method to the geological data about the study area, having as main objective the evaluation of the structural controls in the formation and evolution of the DSF. While potential methods provide us with more general information on these controls, the seismic method is able to provide information in higher definition of subsurface geological features.

It consists of the interpretation of maps generated from the aeromagnetic data, such as the Map of the Tilt Angle of the Horizontal Total Gradient (TAHG) that allows us to visualize in subsurface the presence of magnetic bodies and their contacts, besides the generation of a quantitative solution in depth. Magnetic maps are frequently used to delineate geologic contacts and border of geological formation. These maps have signals with various amplitudes that originate from different geometric sources, situated at different depths and with different magnetic properties.

2. MAGNETOMETRIC METHOD

The development of the databases involved merging numerous surveys with aeromagnetic data with highly variable specifications and quality [6]. The integrated and corrected anomaly maps were processed and interpreted (Fig. 4). Knowing the magnetic anomaly it was possible to estimate the depth top and bottom, magnetic lineaments, faults, blocks, the lateral extension, the width of the sources. From these results, we can produce a geological interpreting and understanding the tectonic environment. For regional exploration, magnetic measurements were important for example, continental boundaries of terrain were commonly recognized by magnetic contrast in all contact. Such regional interpretations required continental scale for magnetic databases.

The aeromagnetic projects have a spacing of flight lines of 500 m oriented in the N-S direction, with flight height of 100 m, the interval between measurements of the magnetometer of 0.1 s and the spectrometer 1.0 s. The survey was carried out in two different blocks with different flight and tie-line directions, and data acquisition was performed perpendicular to the main structures of the surveyed area [6]. The magnetic data of the study area generated from the pre-processed data, using different combinations of parameters, the cell size of 1/4 of the flight line. Grids of the magnetic anomaly were generated and then a database of each grid generated around the Sergipe-Alagoas Basin defining the study area. The magnetic system used was na optically pumped (cesium vapor) magnetometer that was installed in a stinger extension behind the tail of the aircraft. The output from the magnetometer was sampled at 0.1 s to a resolution of 0.001 nT with a noise envelope less than 0.01 nT.



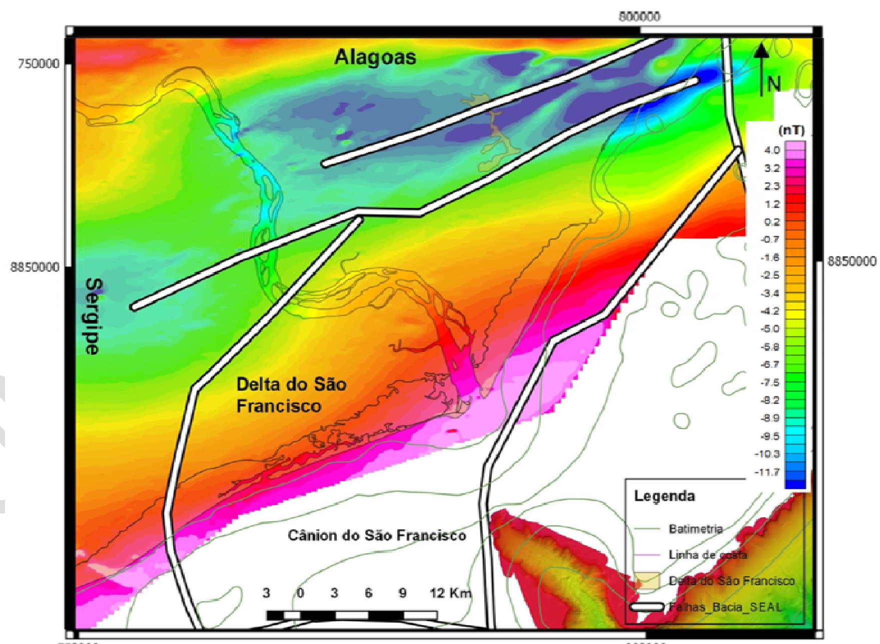


Figure 4: A) TMF map; B) and TMF map reduced to the equator and continued upward with regional / residual subtraction.

The magnetometry data (Figures 4 e 5) used in this work belong to the database of CPRM (Mineral Resources Research Company) and was assigned to this study by the Laboratory of Nuclear Physics and Environment of the Federal University of Bahia. The data includes two aeromagnetic surveys carried out in the region encompassing the Deltaica Plain of the São Francisco River belonging to the projects 1102_ESTADO_DE_SERGIPE and 11_04_PAULO_AFONSO_TEOTÔNIO_VILELA.

In the next processing step, the data were interpolated to a regular grid, using algorithms that maintain data fidelity at the original measurement locations. This step was followed by correction of spurious effects caused by the leveling of the original grids. The fourthorder difference technique was used to track anomalous spikes in the magnetic data and to condition sampling along the flight lines based on the spatial Nyquist frequency. This was performed on the selected interpolated grid, which contained square cells 125 x 125 m. The algorithm was based on linear interpolation along the direction of the flight lines, and on the Akima spline perpendicular to the flight lines. Microleveling and decorrugation techniques were further applied to the data. This procedure resulted several geophysical data products, including thematic maps of both individual variables and composite variables, for use in geologic analysis and interpretation.

Usual linear transformations were applied to the magnetic data to process changes in the amplitude and/or phase related to the set of the data [14]. These transformations are carried out by multiplying the Fourier transform in the data set in the frequency domain. The inverse Fourier transform returns to the space domain and gives the current field to the upper level. This is equivalent to convolving the field in the space domain by an operator (or filter). All transformations of the magnetic field work on this path. For the magnetic data processing, a regional-residual separation process was required to obtain the subject of interest of this study. To do so, an upward continuation was performed, where the estimated depth value used in this process was obtained through radially average power spectrum analysis of the magnetic data.

The aeromagnetic data assigned to this work was in its raw state and its treatment followed a characteristic route: application of the equation reduction filter of the anomalous magnetic field data, power spectrum analysis and regional-residual separation from upwards. The calculation of the field at higher levels is called continuation upwards and proposes the removal of high frequency anomalies relative to low frequency anomalies.

After the Total Magnetic Field (TMF) data was reduced to the Equator, two ascending continuations were applied, one for 100 m and the other for 1000 m, which were defined from the power spectral study of the magnetic signal. The first allowed the removal of low frequencies that are characterized by superficial noises and the second allowed the elimination of deeper frequencies. The grids generated in both processes were subtracted (regional / residual separation) so that the resulting magnetic information is related only to geological features that extend up to approximately 1000 m depth. The gross TMF and TMF maps after the RE and CA steps are shown in Figure 4.

[10] presented an edge detection method that is based on the enhancement of the THG of magnetic anomalies using the Tilt Angle. It is referred to as the tilt angle of the horizontal gradient (TAHG). In this study, efficiency of the TAHG is considered for magnetic data set. The TAHG transform range is from $-\pi/2$ to $+\pi/2$ (Figure 5).

From this, some enhancement methods were used that gave rise to the Analytical Signal Anomaly (ASA), Total Horizontal Gradient (THG), and Total Horizontal Gradient Analytical Signal Slope (TAHG) maps. Both enhancements are best described below.

1) Amplitude of the Signal Analytic (ASA): Asymmetric function in bell format that aims to delimit magnetic bodies and to centralize them above their sources [13]. The ASA map represents magnetic anomalies free of noise and the influence of deep sources.

2) Total Horizontal Gradient (THG): A highlight technique that allows distinguishing the lateral boundaries of anomalous sources through abrupt changes in the

physical properties of lithology. In the THG map the maximum values of the anomalies are located on the edge of the anomalous source.

3) Total Total Horizontal Gradient Analytical Signal Slope (TAHG): TAHG enhances GHT through subsequent application of analytic signal slope [10]. The method centralizes the maximum amplitude at the edges of the magnetic sources and different from the GHT is not related to the depth of the same.

In addition to the corrections and the generation of the enhancement maps that characterize a qualitative data analysis, quantitative solutions were also generated from the SPI method. The SPI method [20] calculates three attributes of the Complex Analytical Signal[16], amplitude, phase and local frequencies, which allow us to calculate the Local Probability Depth, Diving and Contrast parameters of the magnetic sources. Figure 5 shows respectively the ASA, THG, TAHG and SPI solution maps, generated from the data used.

3. RESULTS AND DISCUSSION

Then analysis of all products generated with the magnetic data was performed and the maps chosen for joint interpretation were: TMF reduced to the equator and continued upwards, TAHG and map with SPI in-depth solution. In the TMF map (Figure 6) it was possible to individualize the main magnetic regions of the study area:

1) Region of very low magnetic amplitudes; F.
2) Region of low magnetic amplitudes;
3) Region of intermediate magnetic amplitudes; D.
4) Region of high magnetic amplitudes: C.
5) Regions of very high magnetic amplitudes: A, B.

With respect to the TMF map and its magnetic regions, it is possible to observe that there is a tendency in the increase of the magnetic field when approaching the coastline, expected factor since the sea behaves like a great conductor and influences positively in the values from Camp. The regions E and F characterized as zones of low and very low magnetic field, respectively, may be associated to existing depocentres within the Sergipe-Alagoas basin, since a large column of sedimentary material would increase the distance to the basement of the basin and present smaller values of magnetic field.

The TAHG map (Figure 7) was interpreted and the main magnetic lineaments of the study area were duly marked. The joint analysis of this interpretation with the map of the SPI solution (Figure 8) allowed us to individualize the bodies and their respective depths.

Another important feature observed in the map interpreted TAHG is the preferred direction of the magnetic lineaments. These, in turn, have preferential directions NE-SW and E-W, in addition to some NW-SE perpendicular structures. These directions coincide with the tracing of the main flaws that constitute the structural framework of the Sergipe-Alagoas basin.

Based on depth information obtained in the SPI solution map, it is possible to verify that the interpreted magnetic lineaments, which in turn may correspond to contact regions or faults, on the TAHG map are at a maximum depth of about 1200 m, which leads us to suggest that the faults in the structural framework of the SE-AL basin, which are deeper, have an extension to shallower regions.

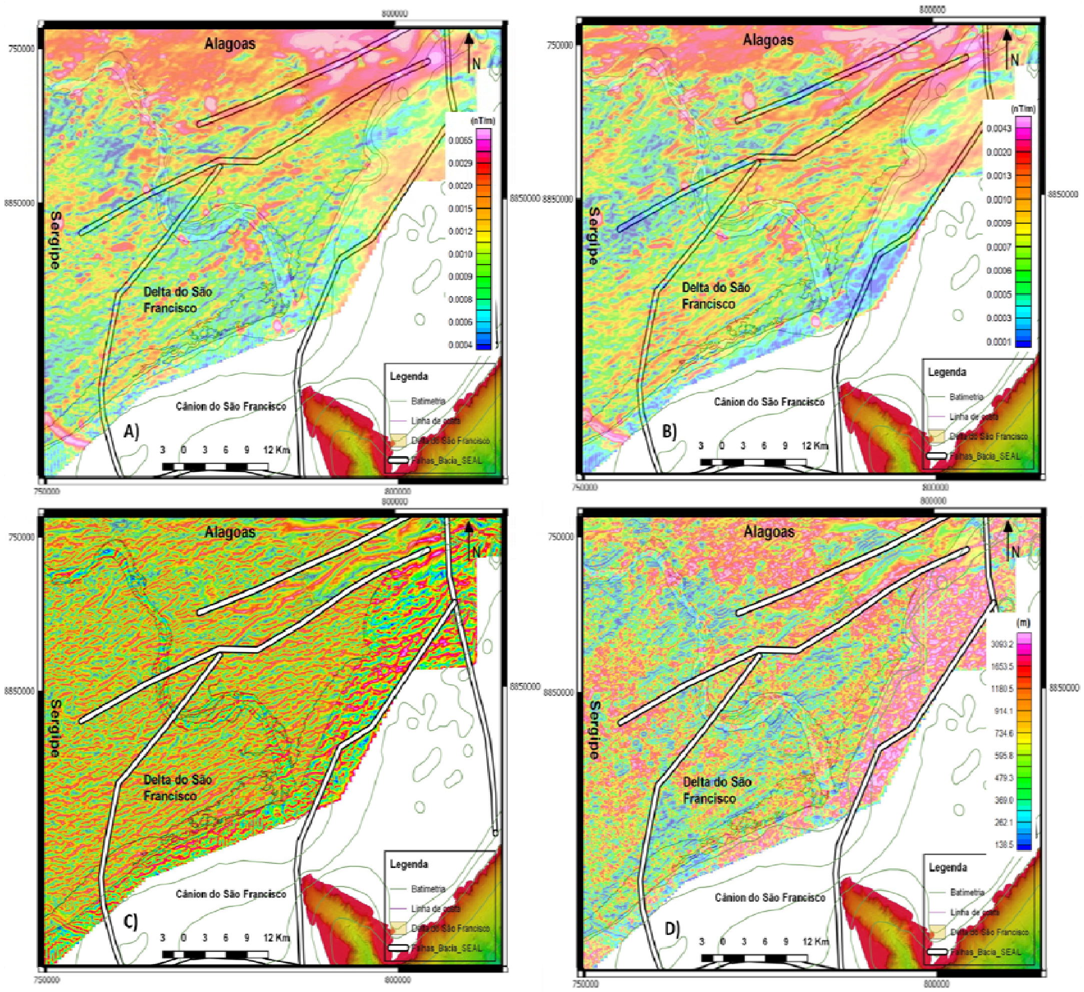


Figure 5: A) ASA map; B) Map of THG; C) TAHG Map; D) Map of SPI.

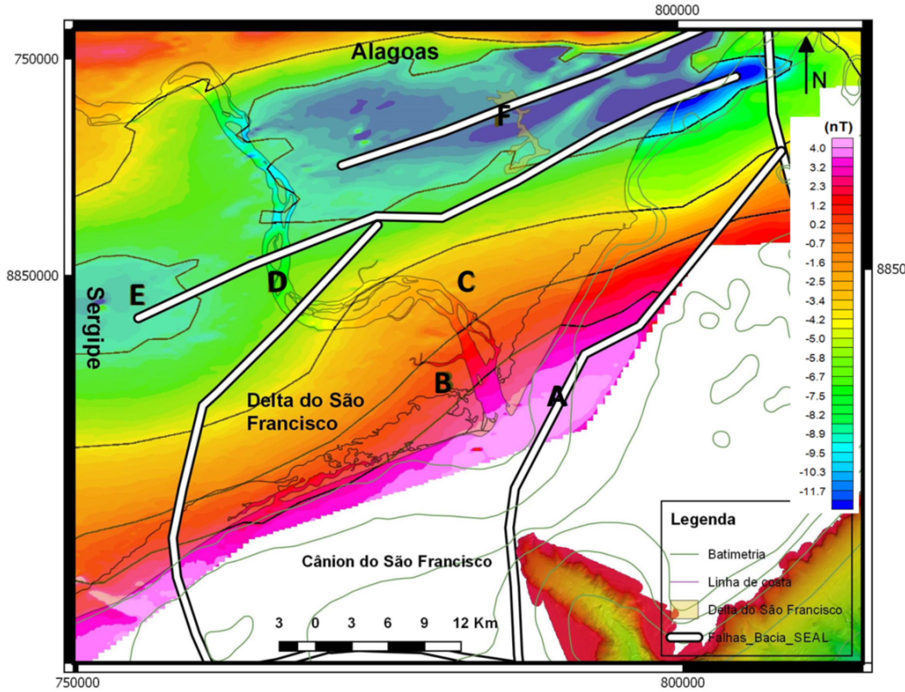


Figure 6: Map of TMF reduced to the equator and continued upward with its main individualized magnetic regions.

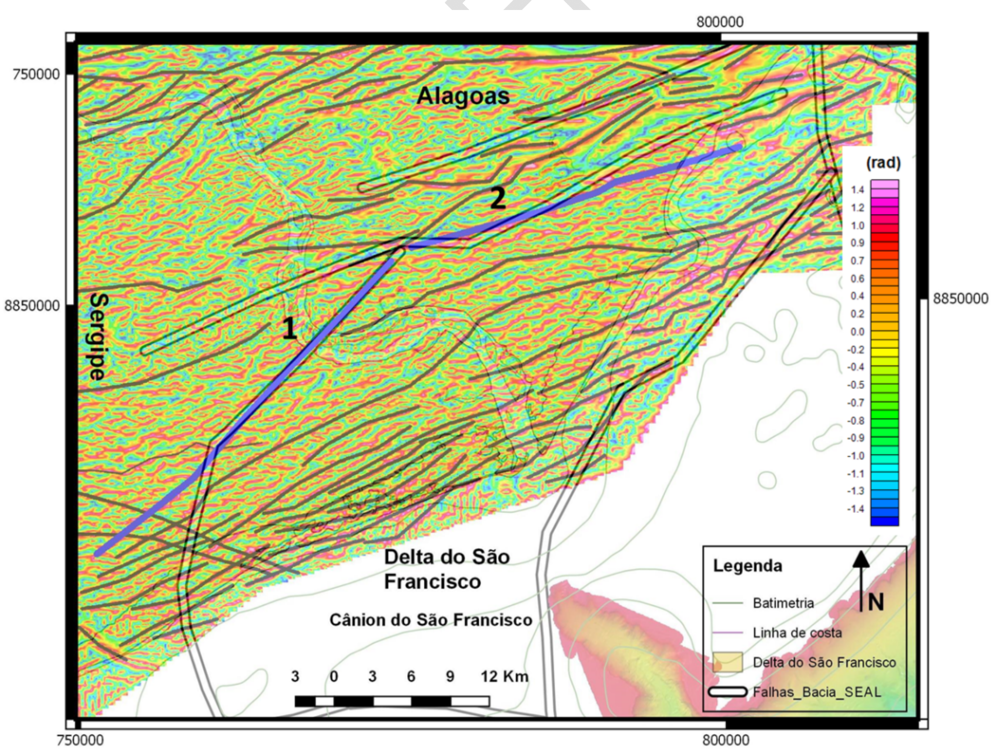


Figure 7: Interpreted TAHG map. The lines marked in black represent the marked magnetic lineaments and the blue lines the deltaic plain with the Barreiras Formation.

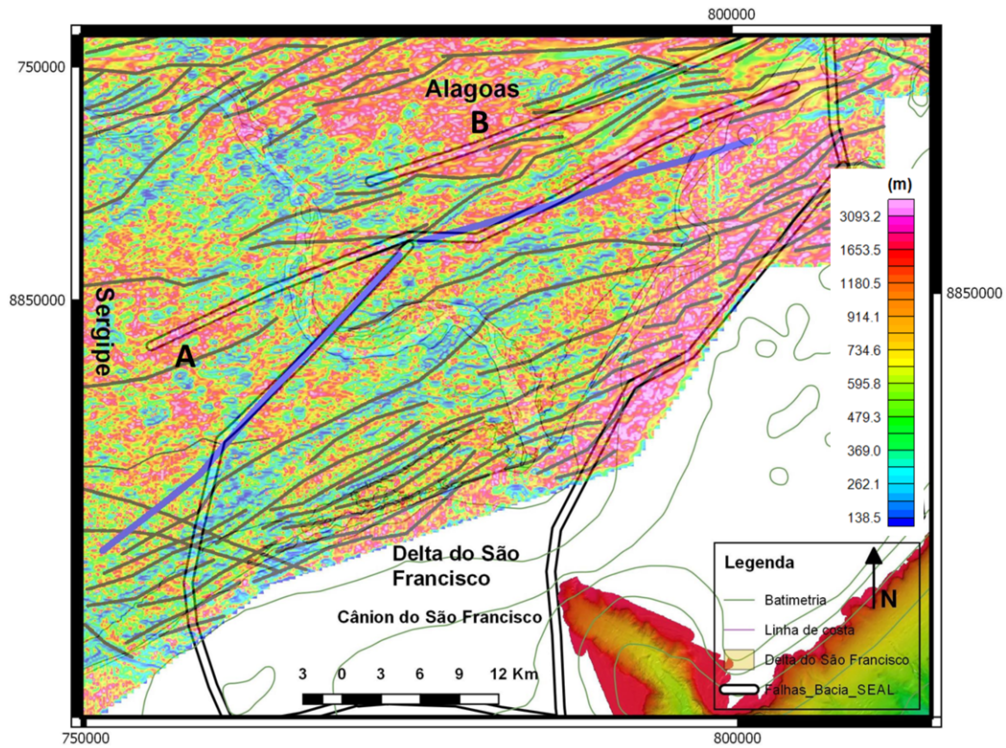


Figure 8: SPI solution map. The lines marked in black represent the marked magnetic lineaments and the blue lines the deltaic plain with the Barreiras Formation.

On the magnetic information obtained in this work, we have the maps of TAHG (Figure 20) and the SPI depth solution (Figure 21) superimposed on the study area. It was previously highlighted the existence of a preferential direction of the magnetic lineaments found in the region, they are parallel or subparallel to important flaws that delimit the structural framework of the SE-AL basin. Note that the magnetic lineages on the DSF are very shallow when observing the depth values of the region on the SPI map, which suggests that they may be the expression of coastal strands in the delta plain.

Another important point to note is the marking of the magnetic lines that delimit the San Francisco low on the TAHG map (area 1 and 2 on the map). The blue lineages on the map (Figures 21 and 22) were interpreted as the region of rectilinear cliffs belonging to the Barreiras Formation and are the internal boundaries of the deltaic plain with formation. Note that these cliffs accompany the tracing of lineages belonging to the SE-AL basin, which, according to Ponte (1969), shows a direct influence of the basin structuring on the formation of the DSF. Another important aspect to be noticed is the regions A and B, of the SPI solution map, which present higher values of depth and continue to reinforce the idea of the presence of depocentres of the basin.

It was possible to identify, from the joint analysis of all the information generated and pre-existing, the presence of a set of faults that directly affect the sedimentation in the region. However, previous knowledge of the geology of the area leads us to believe that the observed faults would not be related to a possible reactivation of tectonic character, but to processes that involve material overload and consequent gravitational collapse of the region being studied.

4. CONCLUSION

The present work presents the results of a joint analysis of magnetic data and previous geological and geophysical information of the area comprising the DSF and its environment. There has been an attempt to understand the structural controls that affect the origin and evolution of the delta, whether these controls are associated with a new tectonic present in the region and whether the structuring of the SE-AL basin also exerts some influence. The treatment and interpretation of the aeromagnetic data provided us with a design of the magnetic framework of the region, where it was possible to show the main lineaments in the area. It was also possible through the magnetic die to mark the inner boundary of the delta plain. Thus, the greatest contribution of this method was to the information on the geological aspect of the area, which together with the Bouguer anomaly map of the region provided us with more precision, the expression of coastal strands present in the delta sedimentation, the marking of possible depocentres of the basin and the limits of the delta. It was not possible to identify in this work the presence of a more recent and active tectonic in the region, so the origin of the failures that exert a structural control in the area can be associated with mass gravitational collapses driven by the overload of material deposited in the region.

REFERENCES

1. ARMSTRONG C., MOHRIG D., HESS T., GEORGE T., STRAUB K. M., 2014. Influence of growth faults on coastal fluvial systems: Examples from the late Miocene to Recent Mississippi River Delta, Sedimentary Geology 301, 120–132.

2. BITTENCOURT, A.C.S.P.; DOMINGUEZ, J.M.L.; FONTES, L.C.S.; SOUSA, D.L.; SILVA, I.R.; SILVA, F.R., 2007. Wave refraction, river damming, and episodes of severe shoreline erosion: the São Francisco river mouth, northeastern Brazil. Journal of Coastal Research. 23 (4), p. 930-938.

3. BHATTACHARYA, J.P.; GIOSAN, L., 2003. Wave-influenced deltas: geomorphological implications for facies reconstruction. Sedimentology. 50, p.187-210.

4. BHATTACHARYA, J. P.; WALKER, R. G., 1992. Deltas. In: WALKER, R. G.; JAMES, N. P. (eds.): Facies Models - Response to sea level change. Toronto. Geological Association of Canada, p. 157-178.

5. CARMINATI, E., MARTINELLI, G., and SEVERI, P., 2003, Influence of glacial cycles and tectonics on natural subsidence in the Po Plain (Northern Italy): Insights from 14C ages: Geochemistry, Geophysics, Geosystems, v. 4, p. 1082.

6. CPRM , 2008. Projeto Aerogeofísico Borda Leste do Planalto da Borborema, CPRM (Programa Geologia do Brasil).

7. DOMINGUEZ, J.M.L., 1990. Delta dominados por ondas: críticas às idéias atuais com referência particular ao modelo de Coleman & Wright. Revista Brasileira de Geociências, 20 (1-4), p. 352-361.

8. DOMINGUEZ, J.M.L., 1996. The São Francisco strandplain: a paradigm for wave-dominated deltas. Geological Society Special Publication 117: 217-231.

9. DOMINGUEZ, J.M.L.; BITTENCOURT, A.C.S.P; MARTIN, L., 1981. O papel da deriva litorânea de sedimentos arenosos na construção das planícies costeiras associadas às desembocaduras dos rios São Francisco (SE-AL), Jequitinhonha (BA), Doce (ES) e Paraíba do Sul (RJ). Revista Brasileira de Geociências. 13(2). 1983. p. 98-105.

10. FERREIRA, F. J. F.; de SOUZA, J.; de BARROS, A.; BONGIOLO, S.; de CASTRO, L. G. e ROMEIRO, M. A. T., 2010. Realce do gradiente horizontal total de anomalias magnéticas usando a inclinação do sinal analítico. parte i-aplicação a dados sintéticos, In:IV Simpósio Brasileiro de Geofísica.

11. GUIMARÃES, J.K., 2010. Evolução do delta do rio São Francisco – estratigrafia do Quaternário e relações morfodinâmicas. Tese (Doutorado em Geologia) - Universidade Federal da Bahia. Instituto de Geociências. Orientador: José Maria Landim Dominguez. 2010. 127p.

12. GOODBRED, S.L., Jr., KUEHL, S.A., STECKLER, M.S., and SARKER, M.H., 2003. Controls on facies distribution and stratigraphic preservation in theGanges-Brahmaputra delta sequence: Sedimentary Geology, v. 155, p. 301–316.

13. GUNN, P.J., 1997. Quantitative methods for interpreting aeromagnetic data: a subjective review. Journal of Australian Geology & Geophysics, v.17, n.2, p.105-113.

14. Hood, P.J. and Teskey, D.J., 1989. Aeromagnetic gradiometer program of the Geological Survey of Canada. Geophysics, 54 (8), 1012–1022.

15. LIMA, C.U., BEZERRA, H.R., NOGUEIRA, C. C., RUBSON, P., SOUZA, O.L., 2014, Quaternary fault control on the coastal sedimentation and morphology of the São Francisco coastal plain, Brazil. Tectonophysics , 633, 98-114.

16. NABIGHIAN, M. N.,1972. The analytic signal of two-dimensional magnetic bodies with polygonal cross-section: Its properties and use for automated anomaly interpretation, Geophysics,37(1):507§517.

17. SÁNCHEZ-ARCILLA, A.; JIMENÉZ, J.A.; VALDEMORO, H.I., 1998. The Ebro delta: morphodynamics and vulnerability. Journal of Coastal Research 14 (3): 754–772.

18. SOUZA-LIMA, W. Litoestratigrafia e evolução tectono-sedimentar da bacia de Sergipe-Alagoas, introdução. Fundação Paleontológica Phoenix. Aracaju. Ano 8. n. 89. 2006.

19. STANLEY D.J., 1988, Subsidence in the northeastern Nile delta: Rapid rates, possible causes, and consequences: Science, v. 240, p. 497–500.

20. THURSTON, J. B. e Smith, R. S., 1997. Automatic conversion of magnetic data to depth, dip, and susceptibility contrast using the spi (tm) method, Geophysics,62(3):807.