An integrated analysis of tar sand occurrences in Paraná Basin, Brazil

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Abstract

Tar sandstones occur in the Eastern Border of the Paraná Basin, Brazil. An integrated spatial analysis of these occurrences was performed according to geological features present in the area. Airborne magnetometrics, gravimetric data, field data and remote sensing were applied. Based on these data the structural framework related to the occurrences was interpreted. Besides, based on analysis of regional and field data, a genetic model for the occurrences of tar sandstones in the area was proposed. It was concluded that the best model relates oil generation to the intrusion of Serra Geral sills in the Permian Irati black shales; migration through faults and dike walls and accumulation in Triassic Pirambóia Sandstones trapped by argillaceous layers and basic dikes. The most preeminent structure on the area, the Jacu Structure, is an example of the relationship between geologic structure and geomorphologic development, which helps the understanding the location of the occurrences.

Introduction

In the eastern part of the Paraná Basin, tar sandstones occur at about 15 localities. These mostly occur in sandstones of the Triassic Pirambóia Formation, mainly in its lower portion. The largest occurrence has about 5.700.000 barrels of oil (Thomaz Filho, 1982), derived from the organic-rich source rocks of the Irati Sub-Group (Assistência Formation). The tar sand genesis is related to Irati-Pirambóia Petroleum System (Araújo *et al.,* 2000). The reservoir rocks are fluvial and eolian sandstones of the Pirambóia Formation. Maturation resulted from the anomalous heat of basic igneous intrusions of Jurassic-Cretaceous Serra Geral Formation. Although the tar sandstones have not been dated directly, occurrences are related to basic dikes of the Serra Geral Formation. The majority of the occurrences are located near fault zones or lineaments and there is also a strong relation to structural highs. Many of them are located near or on drainage anomalies and on morphostructural block boundaries.

This paper deals with the mapping of morphostructures, structural discontinuities in rocks, dikes and their spatial relation to the tar sand occurrences.

Airborne magnetometry was used mainly for the detection of regional structures. Magnetometric land survey was applied on detailed areas for the detection of basic rock dikes. Gravity data was applied for the understanding of the Jacu structure framework.

Interpreted geophysical data revealed a close relation between tar sand occurrences and basic rock dikes. Moreover, the gravimetric data helped the understanding of the Jacu structure, which is a conspicuous annular drainage anomaly in the area. So, an important issue is the study of the Jacu structure that is characterized as a morphostructural high and a gravimetric low. The tar sand occurrences are located mainly on the boundaries of the Jacu structure, which indicates a migration pattern.

The morphostructural analyses revealed a direct relation between geomorphology and geology with the spatial distribution of the tar sand occurrences.

Magnetometry

On the study area, the airborne magnetic data were applied to the detection of basic rocks and linear structures, which include faults and geologic block boundaries.

The used database is part of the Botucatu Project (Paulipetro, 1980). The survey was done with line spacing of 2000 m with sampling at every 100 m and flying height of 450 m. The flight direction is N-S. The survey was done in 1980 from June until July.

During the processing of magnetic data it was considered the geographical position of the survey due to the behavior of magnetic anomalies in relation with Earth's magnetic field. Firstly, an important considered issue was the levelling errors on used database. It was tested a microlevelling correction (Geosoft, 2002) and a co-sine filter correction. Both methods are suitable for used database, but the latter was successfully applied and easily implemented. For the enhancement and interpretation of the total magnetic intensity (TMI) data the following methods were applied: reduction to the pole, computation of vertical derivatives, analytic signal and automatic gain control (AGC). The display of the airborne magnetic is a pixel-image type, in which a raster image was created by an image processing system. The grid data presented was obtained in a projected form, using Universal Transverse Mercator Projection (UTM). The data interpolation was done on 500 m grid spacing.

Two main aspects were considered for the interpretation (Figure 1): linear and textural features. The linear features were located between high and low elongated magnetic anomalies observed on the vertical derivative and AGC maps. The textural features were divided into two groups. The first group corresponds to low frequency and medium intensity anomalies related to buried bodies interpreted on the reduced to pole map. The second textural group corresponds to high frequency and high intensity anomalies related to outcropping basic rocks or shallow magnetic bodies; this group was interpreted mainly on the analytic signal map.

Gravity data

Senior author acquired the gravity data. This field survey was developed in the Jacu structure area. It was achieved more than 500 data samples with 1,500 m average distance between samples.

Gravimetric and residual maps were produced. The minimum curvature algorithm was considered for data interpolation. The cell size used was about half of the average distance between samples.

For the interpretation of gravimetric data the following aspects were taken into account: gravimetric highs (positive residuals), gravimetric lows (negative residuals), gravimetric alignments and inflection of the discontinuities on the gravimetric relief.

The interpretation (Figure 2) was performed in a GIS using the gravimetric and residual data interactively.

The total field map (Bouguer) is considered as result of the cumulative gravimetric responses of the various materials in the crust, including the basement and the sedimentary package with the basic rocks. For the Jacu structure area, the 2nd order residual was considered as the most suitable for minimizing the regional gravimetric field. In this sense, the residual map illustrates the responses from the basin geology (sedimentary package with basic rocks).

In a general view, Jacu structure is a low gravimetric area. The area has an elliptical shape with NW axis bounded by a series of gravimetric highs. The majority of tar sand occurrences is on gravimetric inflection areas, between gravimetric highs and lows. The gravimetric highs are interpreted as indicative of buried high-density bodies and structural highs as well. On the southwestern portion there are several outcrops of the Angatuba Sill and the Sobar Structural High. The Angatuba Sill is a Jurassic-Cretaceous basic rock intrusion. The Sobar High is a structural high of Permian sediments (Teresina Formation) in a Triassic-Jurassic terrain (Pirambóia Formation). On the eastern portion, the gravimetric highs correspond to the Permian outcropping area.

The Jacu structure is clearly observed on the 2nd order residual map, there is a correspondence between interpreted lineaments and the gradients of the residual gravimetric map. On the same way, the Sobar and Angatuba structures correspond to high residual gravimetric responses. It is important to observe that the intrusions are located on the borders of the Jacu structure. It is concluded that Jacu structure is not derived from one large intrusion but it is the product of the major structures outside the Jacu structure, which are in a NE-NW configuration. So, the geomorphologic development in an area of NW-NE trend crossing lineaments generated the Jacu annular drainage anomaly.

Morphostructural analysis of the drainage network

The morphostructural interpretation was based on the identification of drainage anomalies. This method allows delineation of geological terrain flexures. The drainage anomalies correspond to geometric modifications of the regional drainage pattern.

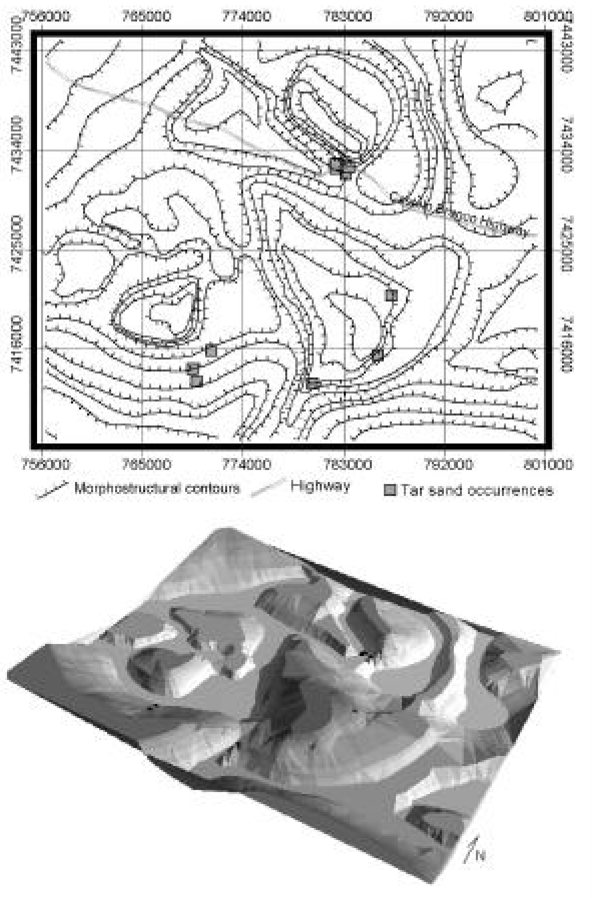

Figure 3 - Morphostructural diagram and tar sand occurrence sites

For the study area, the morphostructural map represents mainly the recent geological events. However, it is possible to recognize basement, Permian and Jurassic-Cretaceous features due to several reactivations of older structures.

Figure 3 shows the morphostructural DEM for the entire study area with the main tar sand occurrences plotted. The study area comprises mainly N-NE regional directions. The Jacu structure region is characterized by an annular morphostructure. This annular morphostructure is composed of minor blocks with relative higher and lower positioning. It is bounded by a series of morphostructural highs. This configuration is recognized in gravimetric and magnetometric maps. Its genesis is interpreted as related to intrusions (dikes and sills) of the Serra Geral Formation. It is important to consider the conditional geological factors responsible for this spatial distribution of basic rock intrusions: interaction of basement weakness areas and Jurassic tectonic.

The tar sand occurrences are located mainly on intermediate portions, i.e. between high and low morphostructures. These high slope portions are interpreted as boundary areas of tectonic blocks, which are defined by faults and dikes that were installed over weak areas. So, these discontinuities were considered as paths for hydrocarbon migration.

Results

The stratigraphic positioning of the occurrences leads on to the consideration of the tar sandstones as exhumed reservoirs. The hydrocarbon possibly migrated into the sandstones under burial conditions. Due to the direct relation between dikes and tar sandstones, probably there was a horizontal migration of the hydrocarbon in the Triassic Pirambóia Sandstones. These dikes acted like vertical barriers.

The explanation of the migration and accumulation processes is related to the presence of basic rock dikes, fault trends and stratigraphical positioning. The primary migration occurred due to the intense fracturing of the Irati black shales (Araújo *et al.* 2000). The secondary migration is related to the tectonic block boundaries: more precisely faults and dikes. These discontinuities are interpreted on magnetic and gravimetric data.

The Serra Geral magmatism is related to the generation (Simoneit *et al.* 1978), migration and accumulation. Considering an interval of 10 to 12 Ma for the Cretaceous magmatism (Stewart *et al.* 1996) it is possible to consider Serra Geral as responsible for the entire process of the tar sand genesis. Diabase sills from the beginning of the magmatism caused anomalous heating of the organic rich beds of the Irati Group. The beginning of the magmatism reactivated older lineaments, which fractured the black shales providing primary migration. The reactivated faults and the new faults formed paths for secondary migration (Figure 4). This model considers a close time frame between generation and migration processes. The entire process is almost contemporaneous from the generation to the accumulation. Finally, the hydrocarbon accumulation on the dike walls and under argillaceous layers occurred later when the basic rocks were already crystallized.

The Irati-Pirambóia petroleum system is Permian according to the source rock. It is important to consider not only the Mesozoic reactivation but also the Permian tectonic events as related to the tar sand genesis. The Cabo-La Ventana Orogeny caused the reactivation of basement structures and the development of new fractures over basin sediments. This event caused a fracture network on the source rock, allowing primary migration. Moreover, with the beginning of Mesozoic reactivation, these older weakness terrains worked as avenues to hydrocarbon migration. It was not found any occurrence on the Jurassic Botucatu Sandstones, so it is considered that the main migration paths were developed until the Late Triassic, including Permian tectonic structures. Although, it is still considered that the main migration engine is the Jurassic-Cretaceous magmatism.

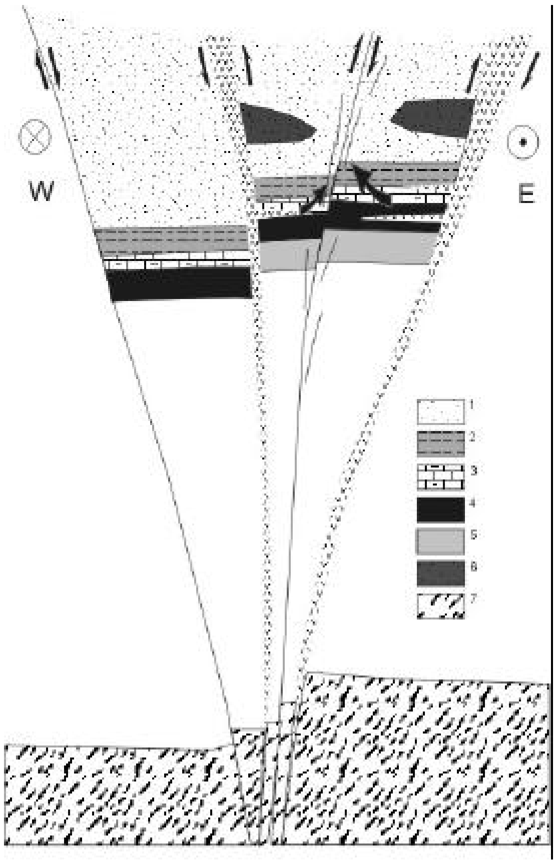

Figure 4 - Schematic model of hydrocarbon migration and accumulation. (1) Pirambóia Formation; (2)Teresina Formation; (3) Irati Calcareous; (4) Irati Black Shales; (5) Tatuí Formation; (6) Tar sandstones; (7) Crystalline Basement.

The genetic model for the tar sand occurrences of the area has the following characteristics:

- ?? Anomalous heating of the source rock due to the intrusion of basic rock sills;
- ?? Migration through older zones of weakness and discontinuities generated during the earlier stages of the Mesozoic reactivation; there is a strong tectonic contribution due to the development of structural highs allowing the hydrocarbon migration from the center of these structures to their borders. The tar sandstones are always on the border of a structural high. Moreover, the source rock is closer to the reservoir rock in these structures and there are faults acting like block boundaries and migration paths.
- ?? Accumulation on the bottom of Pirambóia Formation under argillaceous beds and on dike walls;

The migration process occurred at earlier stages of the Mesozoic reactivation, the NE fault trend was the most important for the migration and accumulation.

Conclusions

The gravimetric and magnetometric surveys helped the definition of the tectonic framework on the area. So, Jacu area is characterized as a low gravimetric region with thick sedimentary package bounded by volcanic intrusions. This results in a well-defined annular drainage anomaly. The morphostructural method employed allowed the mapping of the main tectonic blocks and their boundaries. It also allowed the analysis of the Jacu structure, which is a geomorphologic feature, related to the NW and NE crossing trends.

Spatial distribution of the tar sand occurrences on the study area is directly related to the conditional geological elements. These conditional elements are recognized on the geomorphologic features of the area. The genesis of the tar sand occurrences is directly related to the stratigraphic and structural conditions but the denudation process is also considered fundamental to the spatial positioning of the outcropping occurrences.

On a general view, the main elements of the stratigraphic factor are related to the structural contour map: the occurrences are located on flanks of structural highs. Major occurrences are located few meters from the Teresina-Pirambóia contact, which is an important stratigraphic parameter. On the outcrops, the presence of the argillaceous beds in the bottom of Pirambóia Formation act like a horizontal barrier for hydrocarbon migration. Besides, the horizontal migration followed the bedding of the Pirambóia Sandstones (eolian cross-bedding).

The structural factor is related to the lineaments: the occurrences are located near the major structural lineaments, especially those of NE trend and strong magnetic response. These discontinuities act like paths for oil migration. The fault generation is related to the older weakness zones including basement structures, Permian tectonic events and the Mesozoic reactivation.

The key element in the study area is the presence of basic rock dikes on the tar sand outcrops. Moreover, the occurrences are associated with areas of high magnetic responses. This magnetic signature is interpreted as the presence of igneous intrusive bodies of basic rock composition. The magmatism acted as on the generation, migration and accumulation stages.

Acknowledgments

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References

Araújo L.M., Triguis J.A., Cerqueira J.R., Freitas L.C. da S., 2000, The atypical Permian Petroleum System of the Paraná Basin, Brazil. In M.R. Mello & B.J. Katz (eds.) *Petroleum systems of South Atlantic margins*. AAPG Memoir **73**:377-402.

Geosoft, 2002, Geosoft Technical Note:Microlevelling using Bi-directional gridding; www.geosoft .com

Paulipetro, 1980, Projeto Botucatu-Levantamento Aeromagnetométrico, Interpretação Qualitativa Preliminar, PAULIPETRO-Consórcio CESP/IPT Relatório GEF-SMP-RT-05/80, 1 vol., 14 f.

Simoneit B.R.T., Brenner S., Peters K.E., Kaplan I.R., 1978, Thermal alteration of Cretaceous black shale by basaltic intrusions in the eastern Atlantic. *Nature*, **273**:501-504.

Stewart K., Turner S., Kelley S., Hawkesworth C., Kirstein L., Mantovani M., 1996, 3-D, ^{40}Ar-^{39}Ar geochronology in the Paraná continental flood basalt province. *Earth and Planetary Science Letters*, **143**:95-109.

Thomaz Filho A., 1982, Ocorrência de arenito betuminoso em Anhembi (SP) - cubagem e condicionamento geológico. In: SBG, Congr. Bras.Geol., 37, Salvador, *Anais,* **5**:2344-2348.

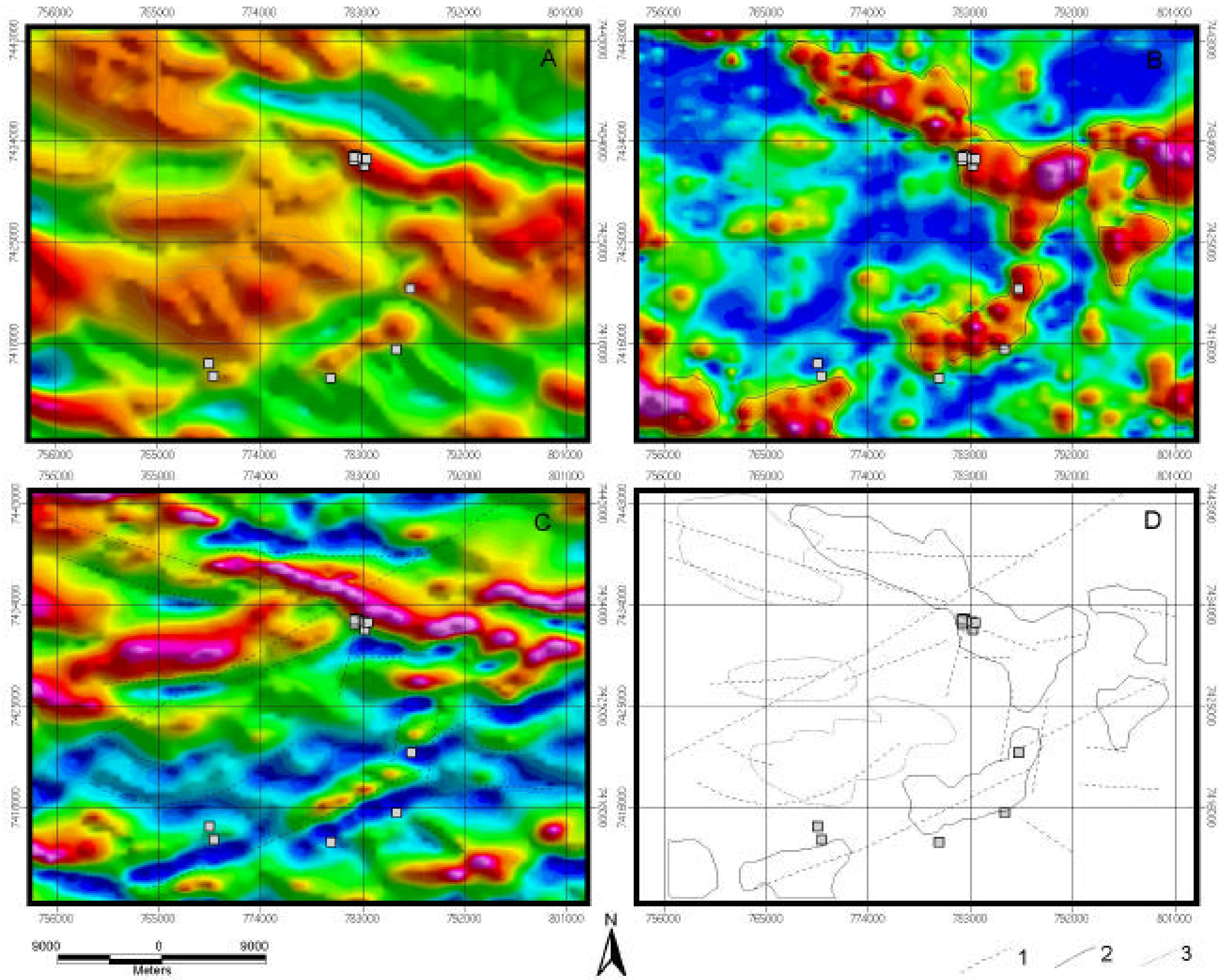

Figure 1 - Interpretation on airborne magnetic data. All maps are presented as pseudo-colors (red high – blue low) and gradient enhancement using sun-angle routine with azimuth from northeast. (A, upper left) TMI reduced to pole; (B, upper right) Analytic signal of the TMI; (C, bottom left) TMI 1 vertical derivative with automatic gain control; (D, bottom right) interpretation of airborne magnetic data: (1) Magnetic lineaments; (2) Edges of shallow magnetic bodies; (3) Buried magnetic bodies.

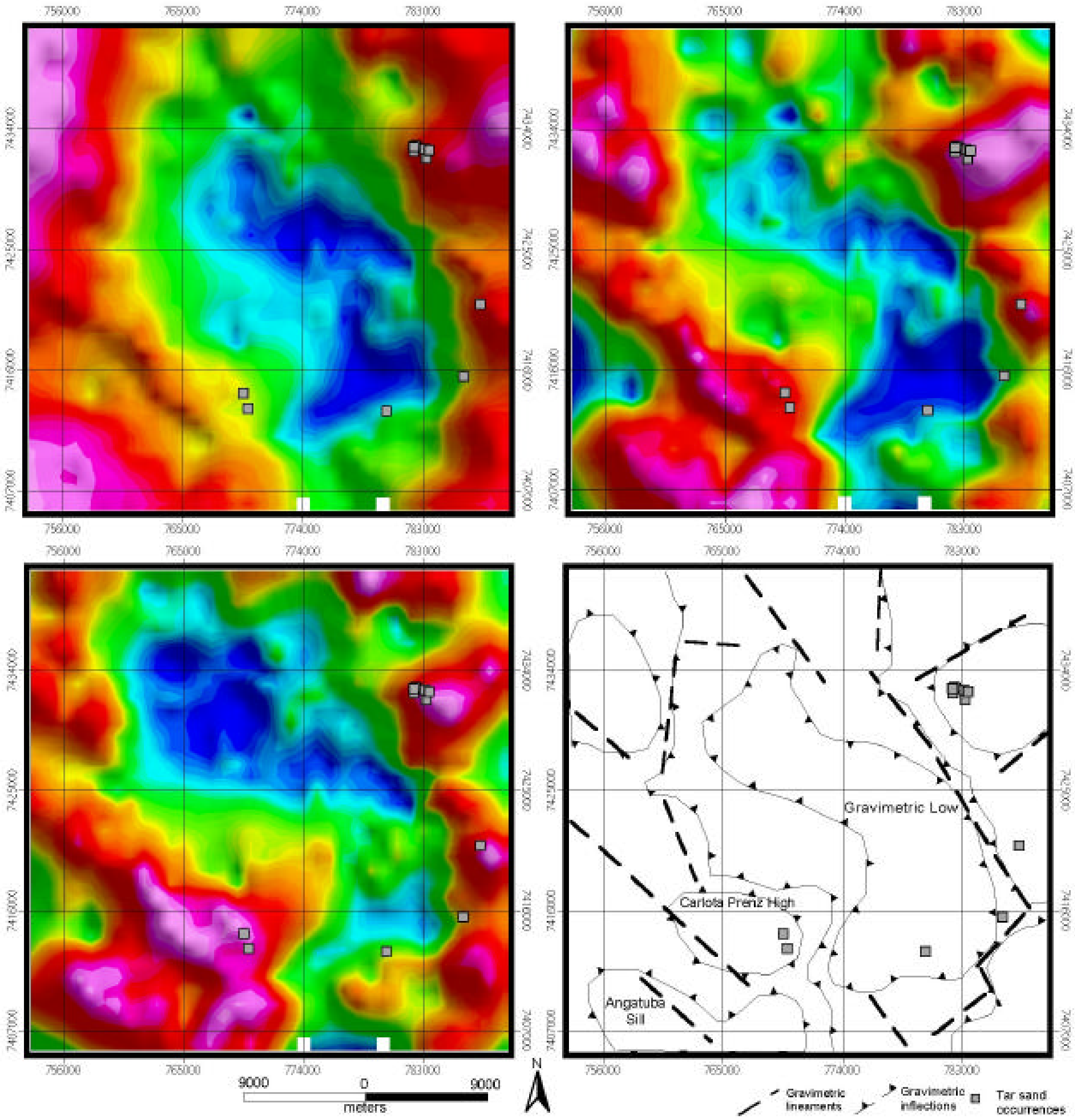

Figure 2 - Gravimetric images and interpretation on Jacu structure area. (A) Total field; (B) 1st residual; (C) 2nd residual; (D) Interpretation.