Regional and local anomaly separation in the Almada Basin (Bahia State), using gravity data from the GRACE satellite.

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Abstract

We have detected in the Almada Basin, northeast Brasil, a high correlation between the regional gravity effects produced by the crust-mantle interface obtained from 2D forward modeling and the gravity data from the GRACE satellite. The altitude of the satellite mission of about 500 km works naturally as an upward continuation filter, allowing the use of this kind of data as an independent estimator of the regional component of the gravity field in the Almada Basin.

Introduction

Several crustal sections have been interpreted in the Almada Basin (northeast Brazil) using a 2D gravity forward modeling technique (Talwani *et al.,* 1959). By combining 2D forward modeling and the geologic model interpretation from seismic data, we separate the gravity contributions of the different layers that comprise the model.

The gravity anomaly produced by the interpreted Moho interface using the 2D forward modeling showed close agreement with the Bouguer gravity map from the GRACE satellite. This agreement indicates that the satellite data can be used in estimating the regional gravity anomaly in a sedimentary basin.

The Almada Basin geologic setting

The Almada basin is a narrow basin, located on Brazil's northeastern coast between approximately 14° to 15°S and 38° to 39°14´ W and it is part of the South Atlantic passive margin system. The basin is bounded to the west by a SW-NE trending normal fault system that separate the basin from the nearby São Francisco Craton. The Precambrian high-grade metamorphic rocks of the Craton formed the basin´s basement. To the north and south, the basin is bounded by the basement highs of Itacaré and Olivença, respectively. These highs are the limits that separate Almada from the Camamu and Jequitinhonha Basins (Fig.1).

The stratigraphic record is divided into four main units known as: 1) the pre-rift sequence, 2) the rift sequences, 3) the transitional sequence, and 4) the marine sequences, as has been traditionally interpreted in the Brazilian geological literature (Chang et al., 1992; Mohriak, 2003).

The pre-rift sequence is comprised of fluvio, deltaic and eolian continental sediments that were deposited in a continental sineclesis during the Jurassic to Berriasian times. The rift sequences are mostly composed of pelitic lacustrine deposits and in lesser degree by fluvio, fan delta and lake-turbidite sandstones. In the rift section three sequences from the Berriasian to Early Aptian times have been identified (Gontijo et al., 2007). The rifting process developed half-graben sub-basins from onshore to deep water offshore resulting in a complex tectonic setting (Gordon, 2011).

The post-rift (or transitional) stage, consists of Late Aptian evaporites deposited from the platform to the continent-ocean boundary formed during the Gondwana break up that heralded the opening of the South Atlantic Ocean. The discrete salt deposits exhibit pillows and autochthones diapir structures with maximum thickness in the order of 2,500 meters recognizable in seismic.

The basin evolved later into a marine passive divergent margin during the drift stage. The marine phase comprises three distinct sequences: 1) the Albian–Turonian carbonates deposited in a neritic environment in a shallow and narrow sea; 2) the transgressive marine system, from Cenomanian to Maastritchian, characterized by siliciclastic and marls; 3) the Tertiary regressive system which comprises coarse-grained sandstones, platform carbonates and distal pelitic sedimentary beds (Chang et al., 1992, Gontijo et al., 2007). Structurally, the drift sequences are highly affected by gravitational tectonics such as halokinesis and shale diapirs.

We interpreted four gravity profiles, A-D (see locations in Fig. 1), from the Almada Basin by using the "GMulti" software developed by Silva *et al*. (2007). Our interpretations shows that the crustal sections exhibit: 1) a progressive thinning of the continental crust oceanwards; 2) the development of sedimentary wedges in offshore positions; and 3) a ramp type geometry of the Mohorovicic discontinuity onshore that grows into a rapid mantle rise in the eastern part of the basin (Fig. 2).

Satellite gravity

Two systems of gravity data acquisitions using satellites are currently available, namely, the altimetry satellites and the gravimetric (or accelerometers types) satellites. The altimetric types were the first to be used and were developed during the 1960s for military purposes Altimetric satellites calculate the gravity field from precise measurements made by radar pulses of the distance between the satellite and the sea surface. This method presumes that the sea surface above the level of the ellipsoid is equal to the high of the geoid (Sandwell & Smith, 1997). The GEOSAT mission is an example of an altimetric satellite.

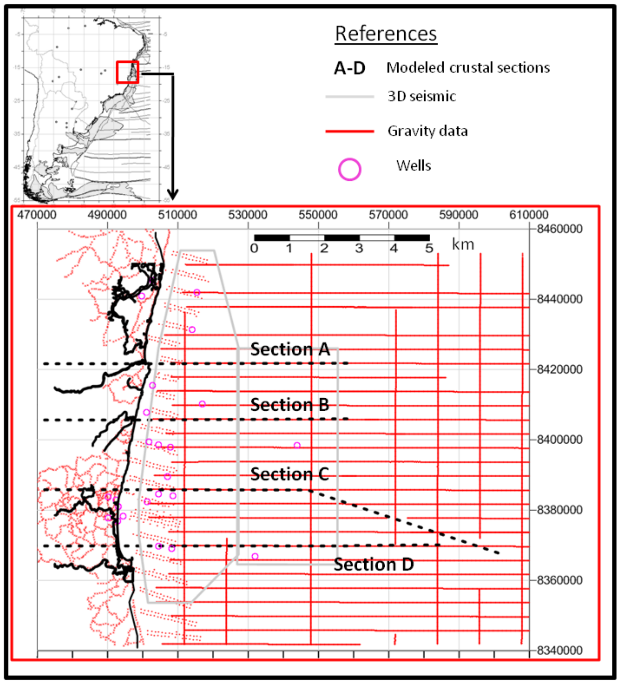

Fig.1- Almada Basin location map. Line segments sections A-D establish the location of the gravity profiles shown, in Figure 2.

The gravimetric satellites use accelerometers that are able to measure the effect of the Earth's gravitational field on the satellite. The CHAMPS, GOCE and GRACE missions are example of gravimetric satellites. The GRACE mission (Gravity Recovery and Climate Experiment) is a joint project of NASA and the German Space Agency. The mission combines two identical spacecrafts flying about 220 km apart in a polar orbit at an altitude of about 500 km. The twin satellites experience differential attractions from the Earth's gravitational field while their absolute positioning is permanently monitored by the GPS constellation and by a microwave ranging system that accurately measures changes in the speed and distance between the spacecraft. The principle used in the regional gravity calculation is based on the effects of this differential attraction. The GRACE gravity data model 02 (GGM02) has been released to the public and it is based on the analysis of 363 days of GRACE in-flight data, spread between April, 2002 and Dec, 2003 (Tapley *et al.*, 2005; GFZ POSDAM, 2006). The Bouguer map, shown in Fig. 3, was generated using the GRACE static gravity data and the bathymetry provided by GEOSAT. The replacement density used was 2.0 g/cm^3, the value found in the density logs for the first sedimentary layer in the wells of the Almada Basin.

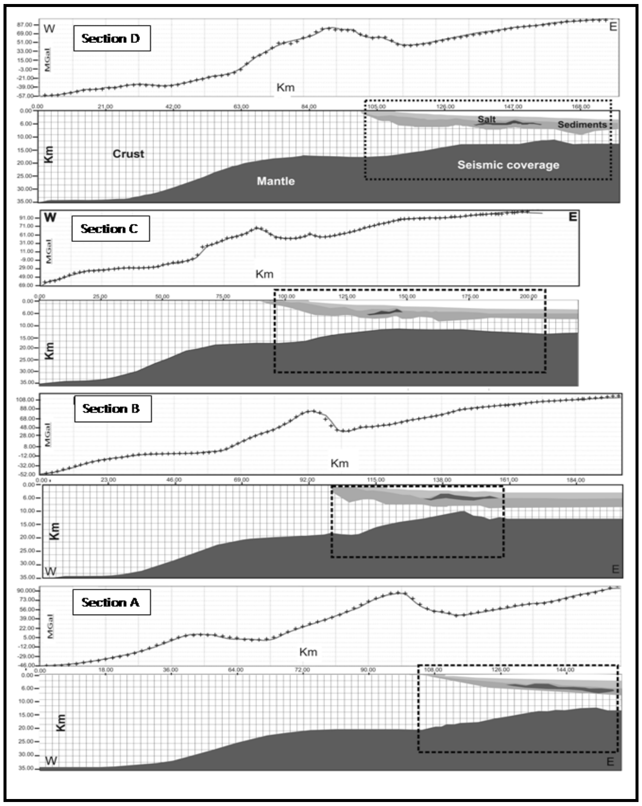

Fig. 2 - 2D forward modeling sections A-D whose location are shown in Fig.1. Observed gravity anomalies (dots in upper panels). The interpreted geologic sections (grayscale polygons in lower panels) and the corresponding fitted gravity anomalies shown in solid lines in upper panels. The dashed rectangles in lower panels represent the areas with seismic control.

2D gravity forward modeling

The Almada Basin has an extensive data base that includes 2D and 3D seismic, gravity-magnetic shipborne surveys, and 28 wells drilled to date. The large 3D survey, acquired with long cables (6 km) and lengthy recording times (9.2 seconds), resulted in good seismic images of the rift deep structure. Four dip lines from the 3D and 2D seismic data set were chosen for the 2D gravity forward modeling and were integrated with the seismic analysis to corroborate the geological model (Fig. 2). The geological sections modeled by gravity data were constrained by the seismic interpretation, well log densities, published maps and lithostratigraphic reports from the Brazilian Geological Survey (CPRM).

The 2D gravity forward modeling requires the building of 2D homogeneous source with polygonal cross-section (Talwani *et al.,* 1959; Talwani, 1965). Here, we used the "GMulti" software (SILVA *et al*, 2007) to apply the gravity forward modeling in interpreting the gravity data from Almada Basin. The observed gravity field is produced by a superposition of overlapping gravity effects of many geologic sources. Usually, in a sedimentary basin these sources are the mantle, crust, sediments and water layer. By using the 2D gravity forward modeling we constructed a geologic model composed by these geologic sources that produce an acceptable anomaly fit. Afterwards, we can isolate the gravity contribution of each source (grayscale polygons in Fig. 2) produced by our interpretation.

Local and regional anomaly separation

"A gravity map is almost never a simple picture of a single isolated disturbance, but practically always is the combination that goes from sharp shallow anomalies to very broad anomalies of regional origin" (Nettleton, 1971).

A key initial step in the gravity interpretation is the separation between the "regional" and "local" component of the gravity field but the definition of "regional" will depend on the scale of the geologic problem (Blakely, 1996).

Usually, in the component separation of the gravity field, the interpreter assumes:

1) Regional and residual components are characterized, respectively, by low and high-wavenumber spectral contents.
2) Regional anomalies are produced by a single deep-seated source while the residual are generated by shallow and small-sized sources. Both confined to narrow depth intervals and separated by a great depth interval.

Hence, shallow sources are expected to produce residual gravity anomalies with high-wavenumber spectral content. On the contrary, deep-seated sources are going to exhibit smooth variations of the regional gravity response with low-wavenumber spectral content (Nettleton, 1971; Blakely, 1996).

The regional-residual separation procedure consists in separating the "regional" component from "residual" component of the gravity data. According to Nettleton (1976), regional-residual techniques in the analysis of potential field data may be grouped into graphical, spectral, and polynomial fitting methods. In the graphical method the interpreter imposes an intuitive degree of smoothness on the regional gravity response.

Among the traditional regional-residual separation methods applied to gravity anomalies, the spectral and the polynomial-fitting methods are most frequently used to date (Silva Dias *et al.,* 2007). In the polynomial fitting methods a polynomial surface is fitted to the observed gravity data and the interpreter assumes that the regional gravity anomaly can be modeled correctly by this fitted polynomial surface. In this case, the smoothness of the regional gravity anomaly is controlled by the polynomial order (Agocs, 1951; Simpson, 1954).

In the spectral method the regional-residual separation is performed by filtering the observed gravity anomaly with a suitable low-pass filter resulting in a smooth regional gravity map characterized by low-wavenumber spectral content.

An important feature in the spectral methods is that they presume that the regional and residual anomalies present non-overlapping spectra, so a judicious cutoff wave number may be used to separate the anomalies (Silva Dias *et al.,* 2007). However, the non-overlap of the regional and residual spectra is uncommon; hence, a complete regional-residual separation is not always possible and non-desired effects such as signal distortion (partial elimination of the spectral content) and incomplete removal of noise are always present (Beltrão *et al*., 1991).

The upward continuation filter has been used as a spectral technique for regional-residual separation, which consists in transforming the potential field measured on one surface to the field that would be measured on a higher surface farther from all sources.

This method tends to accentuate gravity anomalies caused by deep sources while minimizing anomalies produced by shallow sources (Blakely, 1996).

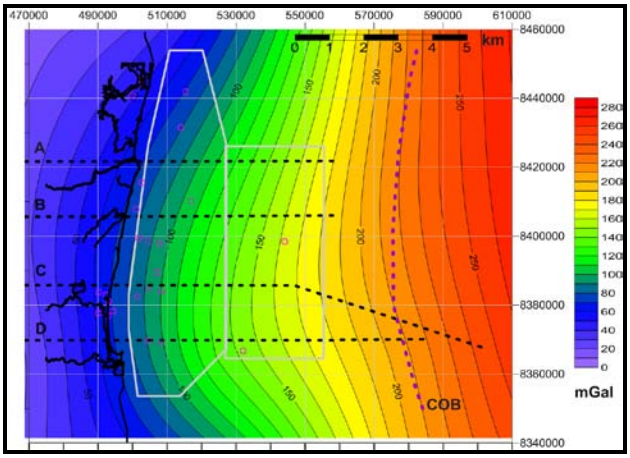

Fig. 3 – Bouguer gravity map from GRACE satellite. The COB dash line represents the ocean-crust boundary.

The upward continuation technique always attenuates gravity anomalies with high-wavenumber spectral content, resulting in a smooth gravity map than the original one. For this reason, this technique has been used as a basis for regional-residual separation (Nettleton, 1971).

In this study the principle of the upward continuation is used to separate the regional from residual gravity signatures. Because the GRACE satellite gravity data are measured at satellite altitude of about 500 km, these data work naturally as an upward-continuated data.

The relationship between the 2D gravity forward modeling and the GRACE gravity transformation

Figure 4 shows the relationship between the 2D gravity forward modeling and the GRACE gravity. We plotted the gravity effect produced by the mantle layer interpreted from our 2D forward modeling along the sections A to D (Fig. 2) versus the Bouguer Grace gravity data. Both values are crossplotted for the same geographical locations (x and y coordinates) and show a strong correlation (r2=0.97265) fitting a cubic-degree polynomial curve (dashed red line in Fig. 4). This function is used to transform the Bouguer GRACE gravity map (Fig. 3) into the estimated gravity contribution from the mantle layer of Fig. 5.

Example

In the Almada Basin a regional and residual separation was performed to enhance the gravity response of the sedimentary sections. The seismic isopach map in Fig. 6 reflects the evolution of the rift, transitional and drifts sequences, showing their maximum development in the central part of the basin.

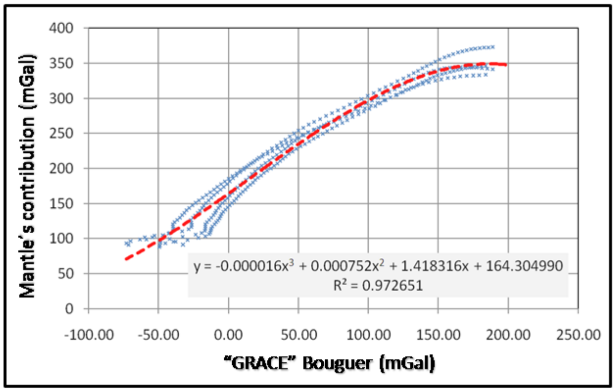

Fig. 4 – Crossplot at crustal sections A-D. The fitted gravity anomalies produced by the interpreted crust-mantle interfaces (shown in Fig. 2) versus the GRACE satellite gravity anomalies . The best adjust is defined by a cubic polynomial function (dashed red line) with a regression coefficient of 0.97265.

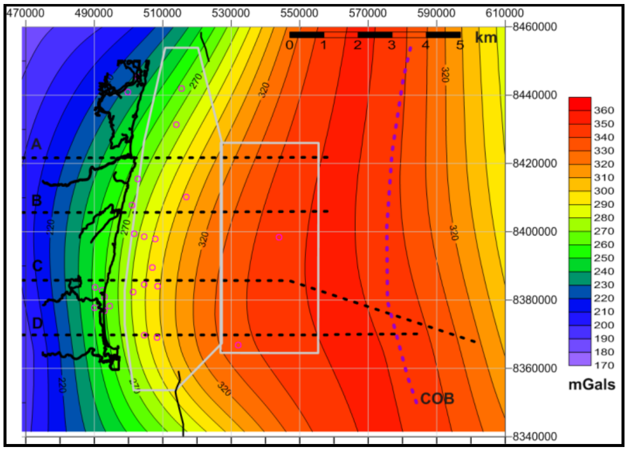

Fig. 5 – Estimated regional gravity map produced by crust-mantle interface over the Almada Basin by using the GRACE satellite gravity data and the fitted cubic-degree polynomial function (Fig. 4)

The rift sequences evolved from west to east along a series of depocenters formed by five NNE-SSW striking half-graben subbasins. The transitional and drift sequences wedges exhibit their thicker deposits in the mid-basin.

The Bouguer map of Fig. 7 clearly shows the existence of the westernmost subbasins (1st, 2nd and 3rd subbasins), while the easternmost depocenters (4th and 5th subbasins) show a weak gravity responses , probably due to the rapid mantle rise (Fig. 7).

The composite map of Fig. 8 allows to observe this comparison. In Fig 8, the observed gravity map shown in Fig. 7 is overlaid by the seismic sedimentary thickness map shown in Fig. 6. We can note the mild expresion that the eastern depocenters have in the gravity map.

In the regional-residual separation process, the residual map results from the subtraction of the water, crust and mantle layers (the regional component) from the observed Bouguer map. This residual map presumably shows the gravity contribution of the sedimentary section.

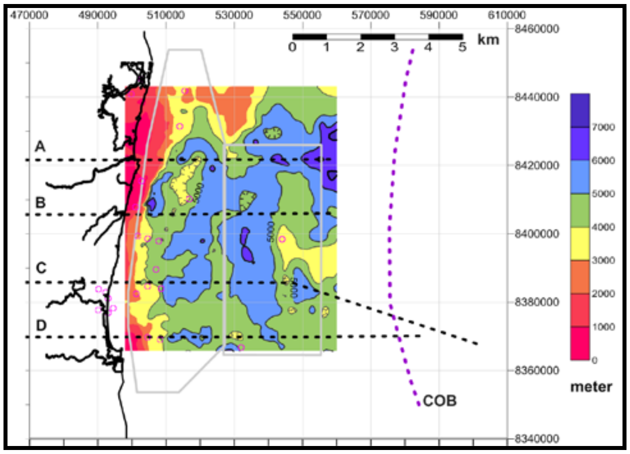

Fig. 6 – Isopach map of the sedimentary section in the Almada Basin obtained from our 3D seismic interpretation. The maximum sedimentary thickness is located in the central part of the basin.

In the Almada Basin, to obtain the residual map, the following corrections were applied:

1) The mantle contribution (Fig. 5) has been estimated from the GRACE satellite gravity data using the cubic-degree polynomial function (dashed red line in Fig 4).

2) The vertical component of the gravity field produced by the volume of the seawater layer (Fig. 9) was calculated according to Martins (2009) and Martins et al. (2010) using the vertical attraction of rectangular prisms method.

3) The gravity contribution of the continental crust was estimated as a polynomial regression of order 1 of the residual map (Fig. 10). This assumption is based on the observation that Eastern Brazilian Basins exhibits a progressive thinning oceanwards of the continental crust as a result of the margin evolution (Fig. 2).

Afterwards, the gravity effects of the mantle, water and continental crust layers were subtracted from the original observation map (Fig. 7) to estimate the residual gravity map (Fig. 11). This residual gravity map, is presumably due to the Almada's sedimentary pack. Figure 11 shows a more complete picture of the Almada Basin's framework and it is in agreement with the results obtained from the seismic analysis.

Conclusions and future works

The GRACE satellite gravity data can be used as an estimator of the regional component of the gravity field because they work as upward-continuated data. The relationship found in this study, between the modeled mantle contribution and the satellite data, only apply to the Almada Basin. But this methodology is under testing in other Eastern Brazilian basins aiming at understanding the relationship in others sedimentary settings.

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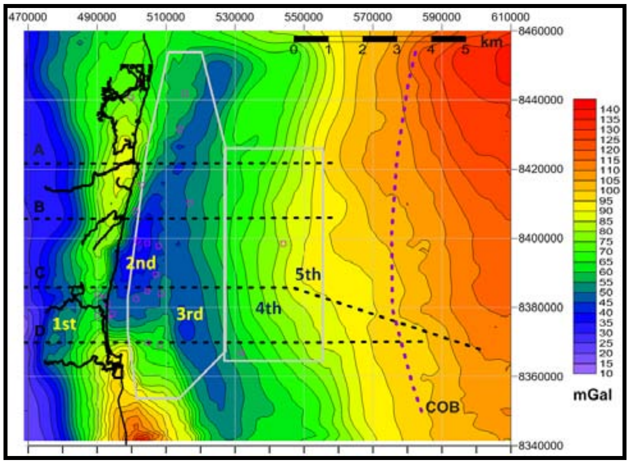

Fig. 7 – Bouguer anomaly map (shipborne) from the Almada Basin with five known structural lows assigned as 1st, 2nd, 3rd, 4th and 5th sub-basins.

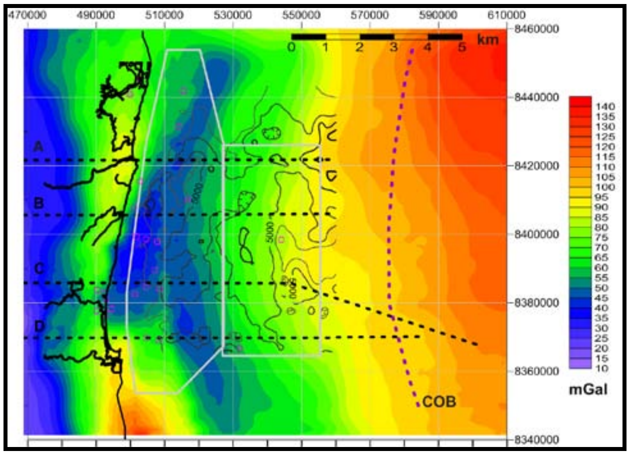

Fig. 8 –Bouguer anomaly map (in color scale) overlaying by the seismic sedimentary thickness map (contour lines). Note the weak gravity responses in the easternmost depocenters.

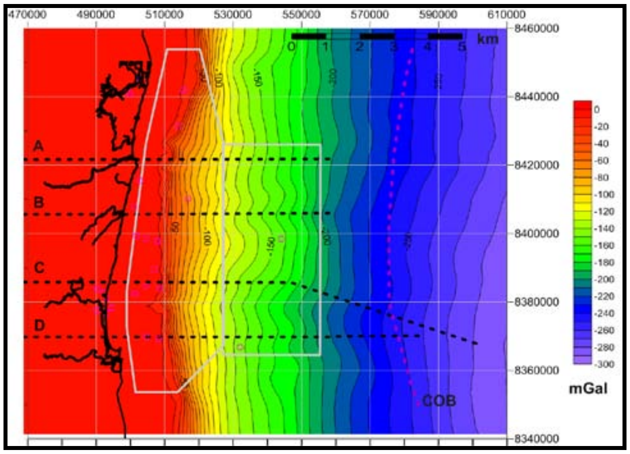

Fig. 9 – Gravity effect produced by the seawater layer. After Martins (2009) and Martins et al. (2010).

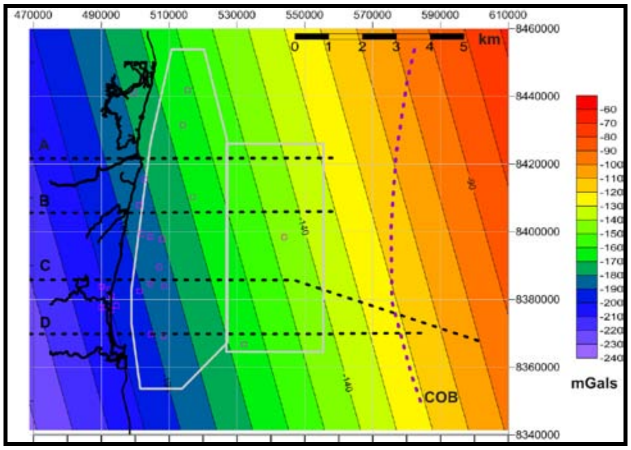

Fig. 10 – The contribution of the crust is assumed as a polynomial regression of order 1 of the residual map.

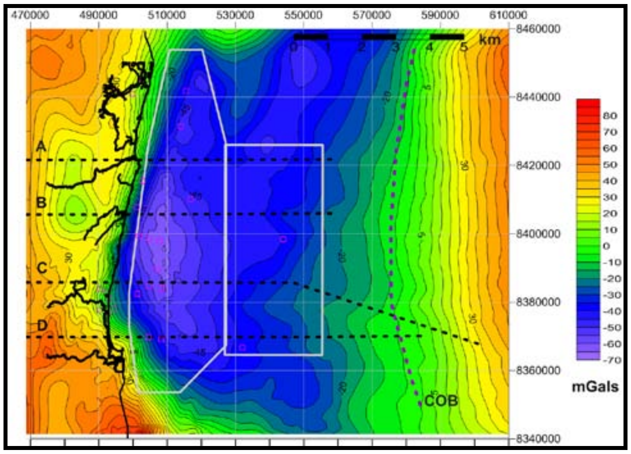

Fig. 11 – Estimated residual gravity map over the Almada Basin. Note the more complete configuration of the basin, especially in the eastern part.

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