3D MODEL OF THE EARTH'S CRUST IN EASTERN CUBA BY GRAVIMETRIC DATA INVERSION

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ABSTRACT

In this research it was obtained a three-dimensional model of the crust through a process of gravity data inversion for the eastern region of Cuba. The data and the model cover a rectangular area of 64 600 km2. The initial model was constrained by surface geology, seismic and drilling data. For that it was used an inversion algorithm that uses gravity data to estimate 3D topographies from main geological units. The model provides quantitative information on the depths and thicknesses of the most important geological formations. The resulting model provides new information about the regional composition of the crust. Alien sequences are observed with different compositions and origin over the basement of Bahamas carbonate platforms. Most of the maximum gravity anomalies are due to the presence of very dense shallow ophiolite sheets. The most remarkable detail is the gravimetric southwest maximum caused by the presence of denser oceanic crust generated in the Cayman Spreading Center.

RESUMEN

En esta investigación se obtuvo un modelo tridimensional de la corteza mediante un proceso de inversión de datos gravimétricos para la región oriental de Cuba. Los datos y el modelo cubren un área rectangular de 64.600 km2. El modelo inicial fue constreñido con la geología de superficie, la información sísmica y de perforación. El modelo nos proporciona información cuantitativa sobre las profundidades y espesores de las formaciones geológicas más importantes. Se utilizó un algoritmo de inversión que utiliza los datos de gravedad para estimar las topografías 3D a partir de las unidades geológicas principales. El modelo resultante da nueva información sobre la composición de la corteza terrestre en la región. En el mismo se observan las secuencias alóctonas de diferente composición y origen sobre el basamento carbonatado de plataformas de Bahamas. La mayoría de los máximos anomalía de la gravedad se debe a la presencia de mantos más densos de ofiolitas poco profundas. Se destaca al suroeste el máximo gravimétrico provocado por la presencia de la corteza oceánica más densa generada en el Centro de Dispersión de Caimán.

INTRODUCTION

Geophysical studies were conducted in the territory of Eastern Cuba aimed for understanding the structure and composition of the crust, for the most part based on the interpretation of deep seismic profiles and potential fields (Shein et al. , 1978 Bovenko et al. 1982; Bush and Shcherbakova et al., 1986; Cuevas et al. 2001; Otero et al. 1998; Arriaza, 1998). Early studies (Shein et al., 1978) determined the existence of three types of crust: Continental, with more than 300 km thickness in the north (Platform of Bahamas and Florida), Oceanic, with 10-15 km thickness located in the sea and in the land territory of eastern Cuba, and intermediate, divided in turn into sub-oceanic and continental with 18 and 30 km thick, respectively, located in the rest of the territory. Regional geophysical tests on geological and geophysical profiles made by Shein in the 80 (Babaev et al., 1989) show that in most cases the base and surface of the crust are flexed. Meanwhile the studies made by Bovenko et al., (1982) show that

The crust of Cuba presents approximately three horizontal layers with complex relief due to tectonic dislocations. They indicate the presence of two layers with abnormal elevations of up to 12-17 km of the mantle in the Cauto-Nipe depression. According to Shein et al., (1978), in the area called miogeosinclinal (carbonated base Bahamas platform) the crystalline basement is "immersed" towards south forming a series of large blocks extending in a southwestern direction to a depth of the basement of 6-2 Km. In 1998 a map of thickness and type crust of Cuba and offshore platform was produced (Otero R. et al. 1998).

Thus the main objective of our research is to obtain the structure of the crust to the east of the island of Cuba in 3D using gravity data inversion. The area of study is 64 600 km ², covering the eastern part of the island of Cuba between the coordinates (100,000, 290,000) m North and (420000, 760000) m East in the coordinate system used in Cuba called "Cuba Sur" and includes areas of the Atlantic Ocean and Caribbean Sea, where the Oriente Fault zone (OFZ) (Fig. 1) is included.

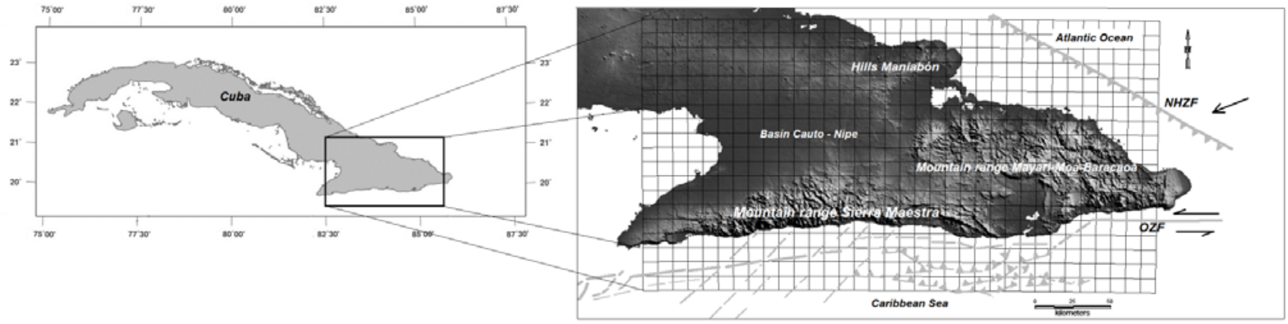

Figure 1. The study area is located at southeastern Cuba island. The area was divided in a regular grid of 646 prisms of 10 km x 10 km at surface. One grid represents one geological unit. Nine grids are located stratified. Green represents the area elevations. Density contrast is kept constant for every unit.

METHOD DESCRIPTION

Gravity data consists of a rectangular mesh of 340 km East direction and 190 km North direction, with interpolated data every 3 km. This design is optimal because we are looking for low spatial frequency structures. This produces at least nine observations over every 10 km x 10 km prism. Data was collected and processed by *Instituto de Geología y Paleontología de Cuba (IGP)* and represents the complete Bouguer anomaly (Blakely, 1996), using 2.3 gr/cm^3 for the earth crust density (Fig 2).

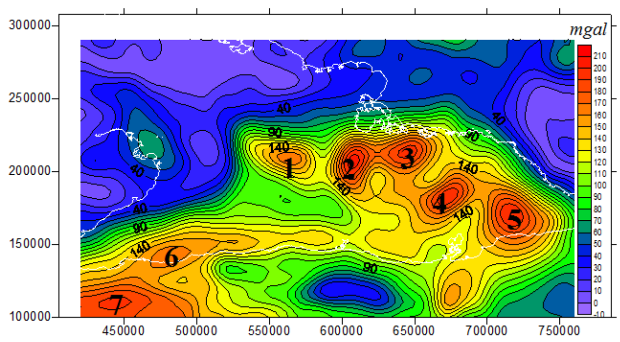

Figure 2. Complete Bouguer anomaly map for Southeastern Cuba island. Gravity anomaly highs are named; 1 Levingstone, 2 La Guira, 3 Piloto, 4 El Salvador, 5 La Perrera, 6 Eje Magmático Sur, 7 New oceanic crust coming

from the Cayman dispersion center. Capital letters and lines indicate the six 2D cross-sections made to the 3D density model.

To derive the 3D density model from the complete Bouguer gravity anomaly the software developed by *Gallardo et al.* [2005] was used. The top and bottom depths for multiple rectangular prisms were determined using inequality or equality constraints for those depths. We assume that the ground consists of geological units with irregular bottom and top topography in contact with other units. We simulate every unit with a conglomerate of rectangular prisms as shown in Figures1. The whole 3D model is constituted of separate geological units or set of prisms with different density contrasts.

The inversion process moves the top and bottom depth for every single prism at every geological unit. Restrictions are imposed to not allow overlapping or spaces between prisms. The quadratic norm of the differences is minimized between data ($\boldsymbol{g}_o$) and model response ($\boldsymbol{g}_r$) plus a smoothing term (equation 1).

$$F(\boldsymbol{m}) = \|\boldsymbol{g}_o - \boldsymbol{g}_r\|^2 + \beta\|\boldsymbol{Dm}\|^2, \quad (1)$$

subject to

$$\boldsymbol{m}_{low} \leq \boldsymbol{m} \leq \boldsymbol{m}_{upper},$$

Where ***m*** is the unknown vector containing the depths from every prism. Matrix ***D*** is the horizontal (*x, y*) first derivatives of the depths. This term minimizes the top depths differences between adjacent prisms. Term β magnifies or dismisses this term. When it is zero the model shows very rough top topography for every unit; when large, every topography unit looks very smooth, except where the data (first term in equation 1) requires larger jumps. This can happen where geological faults are located. We used smooth three-dimensional models, considering that the simplest model is more probable (Occam's razor rule). Depth determination is quoted by means of quadratic programming (*Gill et al*., 1986), using inequalities or equalities. This allows introduction of surface geology, wells and seismic data as constraints.

We expanded from the simplest model (Occam's razor) with only seven units to nine units (Table 1) for the inversion process. We considered only those units that exhibit a density change, plus the gravity response of the sea, and the Mantle response which was subtracted when corrected by theoretical ellipsoid (Blakely, 1996).Twenty iterations were performed to arrive at the final model.

Table I. Listed are the nine geological units used to obtain the 3D density model. We worked with the shown density contrasts in gr/cm^3**.** Densities were obtained by direct sampling on the surface. Those densities have a variance range due to heterogeneities inside the geological unit. In the inversion process we adjusted the density contrasts along those ranges. The inversion is not completely automatic because we had to try different density contrasts, much like fine adjustments. Geological units were established from the geological models proposed recently (Iturralde-Vinent 1998, 2002; Cobiella, 2005. Sommer et al, 2011).

	Units	Density (g/cm³)	Density Contrast
1	Sea	1.03	-1.27
2	Neogene-Cuaternary deposits	2.25	-0.05
3	Paleogene Volcanic Arc	2.29	-0.01
4	Ophiolite 1 (Maffic Mayarí -Sagua - Baracoa)	3.05	0.75
5	Cretaceous Volcanic Arc (Tunas - Holguín y Sagua- Baracoa)	2.95	0.65
6	Ophiolite 2 (Ophiolite Melange North Holguín)	3	0.7
7	Bahamas Platform	2.2	-0.1
8	Oceanic crust	3.15	0.85

9	Mantle	3.3	0

RESULTS AND DISCUSSIONS

The obtained 3D model (Fig. 3b) reproduced the named gravity highs (from 140 to 214 mGal) observed, and also the Cauto-Nipe basin gravity low at the NW with values from 0 to 10 mGal, it is important to show the model response. Model response has a 6% data misfit. Resemblance is very good.

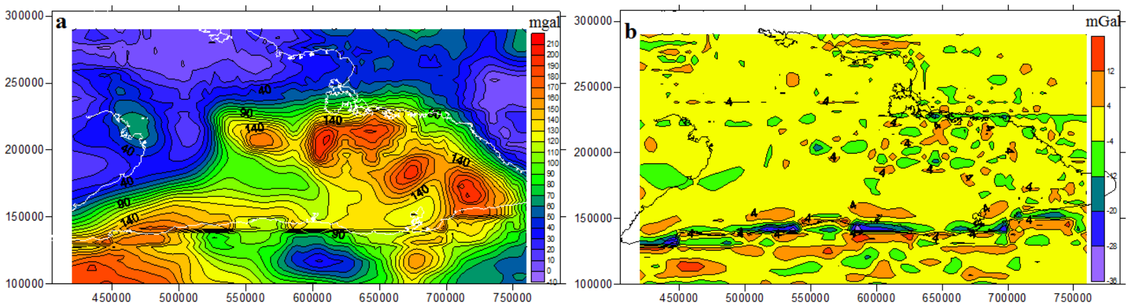

Figure 3. (a) 3D density model response. (b) Differences between data and response in mGal. RMS misfit is 6%. Average misfit ranges (-4, +4) mGal. The differences map has a minimum and maximum of -4 to 4 mGal and shows almost a random behavior. The main differences concentrate at the south border of the Island because the 10 km x10 km prisms do not fit exactly the steep coastline (Fig 1). There is a surface excess or deficiency of mass producing a misfit. Excluding that border misfit, general misfit must be lower than 6%.

The most recent hypothesis about the Southeastern Cuba Island states that Earth crust structure consists of a folded basement overriding Bahamas platform. The folded basement is constituted of ophiolites thin sheets intercalated over and under the Cretaceous Volcanic Arc (CVA). At the Southeast of our study area, the Paleogene Volcanic Arc (PVA) rocks are predominant and lay over the ophiolites flakes and CVA package (Iturralde-Vinent 1998; Iturralde-Vinent et al. 2002; Sommer et al. 2011). The geophysical model obtained validates the concepts used in the geological models mentioned above and provides new quantitative elements on the thickness and composition of the crust in the studied region. Cross-section AA’ (Fig.4) shows clearly how this platform penetrates the mantle in a kind of slab with an approximate thickness of 10 to 12 km, dipping southward. It begins with a low angle at North, where it almost outcrops, increasing the angle southward to 45º below the Cauto-Nipe basin. West shows a rebound or vertical uplift of the Bahamas platform. It seems that the PVA is distributed more at the West of this part of the island. Iturralde-Vinent (1998), Cobiella (2005), García-Casco et al. (2008) and Sommer et al. (2011) have suggested this slab before, but this is the first geophysical evidence. The Bahamas platform density is very close to 2.3 g/cm^3, meaning that density contrast is almost zero. The shallow presence of Bahamas platform at NW (~2 km) justifies the low gravity values. At the SW corner of the study area, the model needed a high density body (cross-section AA'; Fig. 4) in order to fit the gravity high (number 6 at Fig. 2). Chang (2003) has suggested a pluton below the CVA rocks.

Southward in the Cuba Island, the Oriente fault is present (Fig.1). The fault signals the change from continental to oceanic crust. Even southward of cross-section AA' (Fig. 4), the 3D model cuts this fault. The high gravity anomaly requires a denser body which could be oceanic crust. This new oceanic crust has been shifted from West to East by the Caiman trench. The gravity anomaly decreases southward. The 3D model justifies this with the less dense Gonave continental microplate (Calais et al. 2002; Calais et al. 2006).

Cross-section BB', at the center cuts an ophiolite body of 4 km thick. This high density body causes the Levingstone high gravity anomaly (number 1 at Fig. 3). Levingstone had been interpreted as caused by an ultrabasic mantle intrusion (Otero et al. 1998). We sought to understand the origin of such gravity anomaly highs (Fig. 3). We made two additional cross-sections over the 3D density model. Cross-section EE' (Fig. 8B) crossed Levingstone, La Guira and Piloto gravity highs (number 1, 2 and 3 at Fig. 3). Figure 8A shows a great correspondence between the ophiolites bodies and the gravity anomaly highs. This is explained because the density contrast is +0.75 gr/cm^3 (Table 1) and also because those bodies are shallower producing three high frequency features over the gravity anomaly. Cross-section CC' passes over the El Salvador gravity high (number 4 at Fig. 3). Despite the smoothing at Figure 8, it is clear that ophiolites at km 80 are producing the gravity high.

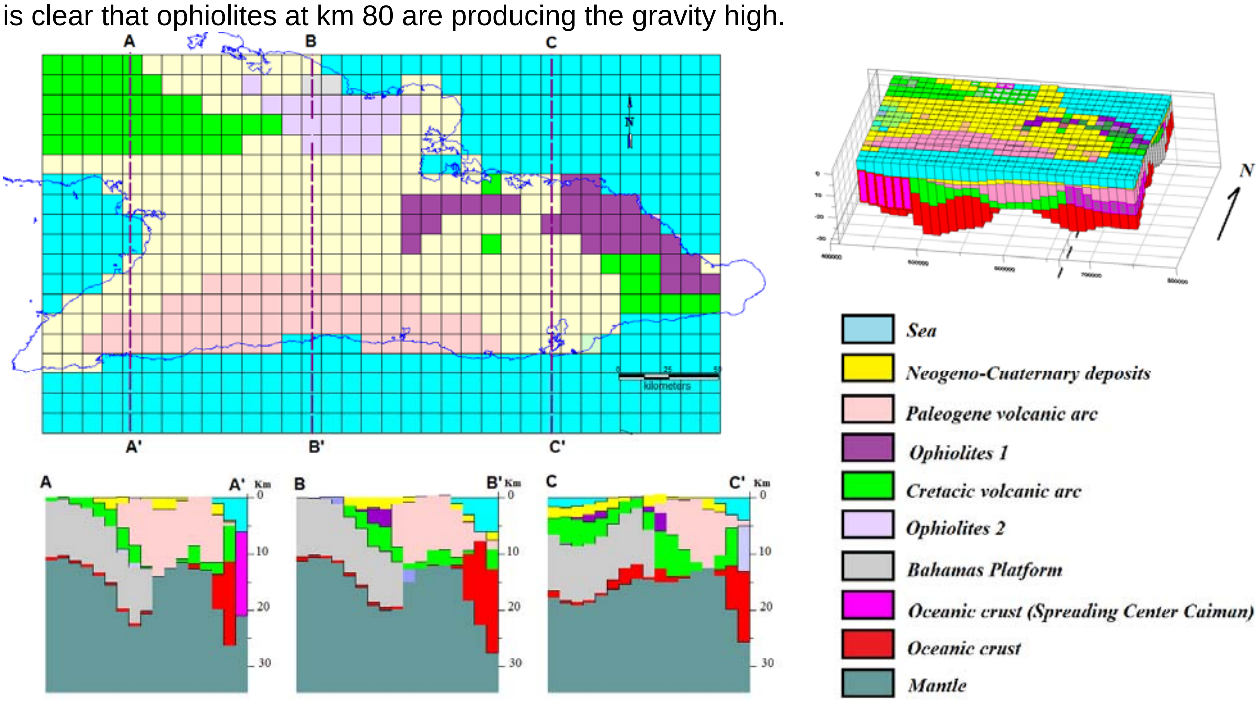

Figure 4. (A) Surface geology as introduced in the 3D model as constraints. Dotted lines indicate the 2D cross-sections over the 3D model. Red lines represent the main faults known at the area. (B) Four two-dimensional cross-sections of the 3D density model only are shown.

The Eastern island has a more complex geology, including the Mayarí-Moa-Baracoa ophiolitic massif. Iturralde-Vinent (1998), Cobiella (2005) and Sommer et al. (2011) suggest that the evolution of this area is different. Cross-section CC' (Fig. 8B) shows that the Bahamas carbonate basement raised up, forming a horst bellow the Mayarí-Moa-Baracoa massif. Here, the Earth crust thickness is 15 km.

The Southern corner of cross-section CC' (Fig. 8B) reached the deformed Santiago de Cuba belt, formed by the rising of the ancient ocean crust. Tectonically this was due to a transpressive process produced by the oblique contact between the Caribbean plate and Gonave microplate. It is important to emphasize that here the Gonave microplate is constituted by the CVA and ophiolites over the ancient oceanic crust that have been migrating from the Yucatan basin and is displaced by the Oriente fault to the present position. Similar crust composition is observed at La Española Island (Case et al. 1990) where ophiolites and CVA outcrop.

A limitation of this research is that we used 10 km x 10 km prisms area, therefore, we cannot resolve high spatial frequencies. Nonetheless, the gravity anomaly is very smooth (Fig. 3). There is not high frequency information in such a gravity anomaly. Another limitation is that we could not differentiate the

Cuban metamorphic complex from the Cretaceous volcanic arc because densities are similar and between sedimentary volcanogenic sedimentary sequences and Paleogene age. These limitations are due to the need to take a single conceptual model starting in a region with significant differences in the composition of the shell and the units are not the same patterned structure or origin position in the entire area.

CONCLUSIONS

The gravity response from the 3D density model obtained reproduces very well the general shape of the data, particularly the gravity lows at Cauto basin (NW of the map), with values between 0 and 10 mGal. It also fits the named gravity maximums. We determined that those maximums are caused by the presence of shallow ophiolite sheets mainly.The Earth crust thickness ranges from 10 to 15 km south of the area, raising to 20 km where Mayarí-Moa-Baracoa massif is located and also where Bahamas platform dips with a high angle inside the Mantle. This numerical information obtained from the 3D model is in good agreement with the previous qualitative geological models. The density model further shows the complex 3D topographies of the Bahamas platform, the Cretaceous volcanic arc, the Paleogene volcanic arc, and the ophiolites sheets, and how they intrude each other. The 3D density model shows good gravity agreement (gravity maximum) due the presence of the new oceanic crust from the Gonave microplate (SE of the area) caused by the pull of the Caiman dispersion center. The general location of the ophiolites sheets and the Cretaceous volcanic arc overriding the Bahamas platform provide evidence for a collision tectonic process rather than a subduction between the ancient Caribbean plate and the Bahamas platform (present North-American plate).

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