

Public domain satellite gravity inversion offshore Somalia combining layered-Earth and voxel based modelling

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Introduction

At the end of 2016, Spectrum Geo released two long offset seismic reflection profiles across the Somalian rifted margin, in the Juba Lamu and Obbia basins respectively – part of two larger 2D surveys acquired in 2014 and 2015/16 (Stanca et al., 2016; Figure 1). In frontier areas, potential field data interpretation, in particular public domain satellite-derived gravity, can play a key role in the early stages of exploration by identifying basement structure, sediment thickness, and the continental-oceanic crust transition (COT) or continental-oceanic boundary (COB), and hence indirectly contribute to the understanding of thermal history and the hydrocarbon system. This is particularly relevant over the Somalia margin, where geophysical surveys have been extremely sparse until very recent years.

A high-gradient in the gravity is often used as a marker of the COB along passive margins (see Pawlowski (2008) for a review), expressing laterally contrasting physical properties between the continental and oceanic crusts. However, at magma-poor rifted margins, such as the Somalia margin, the lithosphere undergoes a progressive thinning/stretching process and the transition between unaltered continental crust and oceanic crust becomes gradual (Manatschal, 2004). Crustal hyper-extension, serpentinization, embrittlement, and exhumation of mantle peridotites can precede accretion of true oceanic crust, which in turn can blur the simple transitional model between a dense and highly magnetized oceanic crust and a weakly magnetized and lighter continental crust. Along a magma-poor margin, analysis of potential field data can distinguish the different rifting domains and quantify crustal thinning (Stanton et al., 2016; Cowie et al., 2015). In offshore Kenya and Somalia, the image is further complicated by thick sedimentary cover.

To overcome this complexity, we attempt here to map both the basement structure and the density distribution over the margin through a combined, or hybrid, modelling approach. We adopt a co-operative inversion approach where the results of a conventional layered-earth based structural inversion are fed into a voxel-based inversion to produce a final 3D distribution of density variation over the Obbia basin. This 3D approach is supported by a series of regional 2D gravity models along the

margin. With the exception of shipborne bathymetry, the study was conducted using public domain data, the satellite derived gravity data (Sandwell et al., 2014), and focused on the offshore areas: data onshore were only included to maintain the regional character of the model.

We built on the experience gained from a previous voxel-based inversion of the vertical gravity gradient G_{zz} over a well-known area of the Gulf of Mexico (MacLeod et al., 2016), which showed that a relatively simple inversion scheme of public domain gravity could lead to a realistic 3D model of the subsurface.

Our models reveal partitioned and variable basement architecture and sediment distribution from south to north along the Somalia margin. It also reveals areas of hyper-extended crust and possible exhumed mantle in the Obbia basin, as suggested by Stanca et al. (2016).

This study demonstrates that meaningful results can be drawn from a relatively simple inversion scheme, relying on public domain data. This type of approach is a valuable, low-cost aid for mapping the density of the earth in frontier areas, and to facilitate basin exploration. The approach also has scope for application in better-understood basins.

Data and methodology

The area presented in this study is a large area offshore East Africa, geologically complex and sparsely surveyed, located between $-/+8^{\circ}$ latitude and encompassing the Western Somalian Basin and part of the Northern Somalian basin (Figure 1). While our main objective is to better understand the crustal architecture over the margin, a second objective of our work was to evaluate the added value of a combined inversion scheme. This type of modelling is sometimes referred to as hybrid, and has been mostly applied for sub-salt exploration (Ellis et al., 2015). Conventional gravity 3D inversion for hydrocarbon exploration relies mostly on a layered-earth approach, where the inversion returns discrete interfaces, while assuming a constant density within each layer. It makes for an intuitive modelling process and often suffices to recover the crystalline basement geometry. It is also fast since most available algorithms work in the frequency

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domain. However, assuming a constant density can be misleading in areas of greater complexity.

To map any density variations from the initial regional model (green polygon on Figure 1), we follow up the structural inversion using Geosoft's GM-SYS 3D program with a voxel-based inversion over a smaller area (black polygon on Figure 1), using Geosoft's VOXI Earth Modelling inversion (Geosoft Inc., 2017).

One of the challenges in combining voxel and layered models in a hybrid inversion is that voxel inversions generally produce models which have 'smoothed' transitions between domains whereas layered earth models have discrete transitions. To overcome this inconsistency, a series of constraints can be set up during the voxel inversion to ensure that we honour the layered nature of the physical properties distribution. Finally, a last challenge for the VOXI inversion can be the size of the model as even with high-performance computing, it remains comparatively significantly slower than a frequency domain inversion. The area in the study covers nearly $2.9 \times 10^6 \text{ km}^2$, and we opted for a trade-off between computation time and resolution by running the density inversion over the Obbia basin only, where the seismic data revealed more complexity.

We used the Free-Air satellite derived gravity anomaly (FAA; Sandwell et al., 2014; 2 mgal accuracy), and work with G_z rather than the vertical derivative G_{zz} , as we did in the Gulf of Mexico, since we want to image density variations within the sediment and the upper crust.

We first built an initial 3D regional density volume from global crustal models, and used published refraction data to constrain sediment densities. The initial Moho depth is from the Crust 1.0 model (Laske et al., 2013). For the initial sediment thickness, we used the recent NOAA global sediment thickness map (Whittaker et al., 2013). Shipborne bathymetry data were provided by Spectrum Geo over the seismic survey area (H. Kearns, personal communication), and completed with the Sandwell bathymetry offshore (Sandwell and Smith, 1997), and the SRTM data onshore. When using satellite gravity, such a modelling approach is enhanced if the bathymetry measurements are independent from the gravity, and the final model is more reliable where there are bathymetric soundings.

From the three DSDP holes in the area (DSDP 234, 235 and 241; Figure 1), only DSDP 235, located east of Chain Ridge, reached acoustic basement and recovered basalts with a density of 2.9 gcm^{-3} .

In the 2D and 3D starting models, the densities of the basement rocks are assumed constant: 3.3 gcm^{-3} for the mantle, 2.9 gcm^{-3} for the lower continental and oceanic crust, 2.7 gcm^{-3} for the upper continental crust and 2.75 gcm^{-3} for the upper oceanic crust. For the sediments, we derived densities from refraction data located in the south west corner of our model, offshore Kenya (Makris et al., 2012), using a Nafe-Drake density depth function to convert from V_p to densities.

In parallel, we also built a series of long regional gravity 2D models from south to north along the margin. Two of the models over the Juba Lamu and Obbia basins integrate Spectrum Geo published seismic data, and help in calibrating our regional 3D model. A starting top lower crust surface was created by

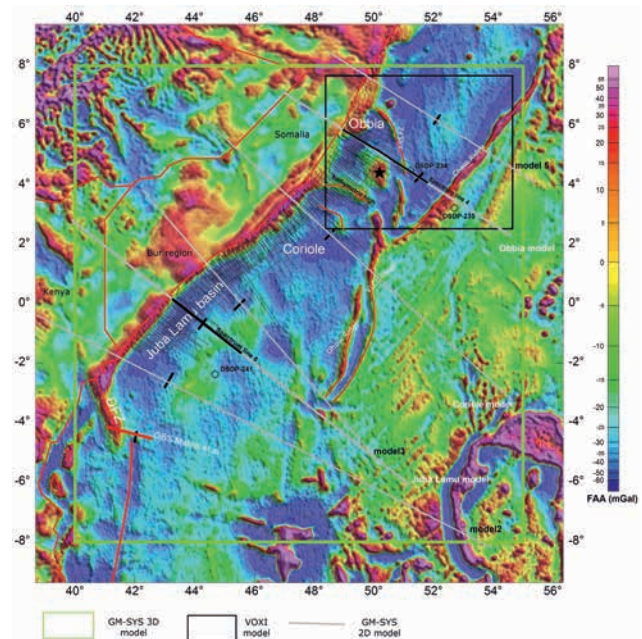


Figure 1 Map showing the satellite derived Free Air gravity anomaly G_z (shaded with calculated G_{zz}). The green polygon indicates the extent of the layered-Earth 3D model (GM-SYS 3D model), the grey lines show the location of the layered-Earth 2D gravity models (the COB/COT location on each model is indicated by a thick black line). The black polygon shows the extent of the VOXI density inversion. In the south, the red EW line shows the OBS profile used for velocity-density conversion (Makris et al., 2012). Red lineaments indicate basement ridges and fracture zones (Davie Fracture Zone (DFZ), Very Large Crude Carrier (VLCC), Dhow Ridge and Chain Ridge). Spectrum survey tracks indicated by thin black lines. The black star indicates possible exhumed mantle (Stanca et al., 2016).

extrapolating the 2D models and using half the thickness of the crystalline crust in areas distant from the model. The Moho, top lower crust and top basement surfaces were then successively inverted within GM-SYS 3D to fit the observed FAA. This layered-Earth model is imported as a density volume into VOXI to calculate a residual G_z anomaly (bathymetry-lower crust-Moho reduced), which is in turn inverted with a set of constraints to recover a 3D distribution of density variations. The full workflow is summarized below.

Modelling sequence:

- We upward continue G_z to 1 km above Mean Sea Level.
- We built 2D gravity models, using seismic when available. A top lower crust horizon is added to each of these models.
- We built a layer-based 3D density model of the subsurface, including seafloor, top basement, top lower crust and Moho, using Geosoft GM-SYS 3D. We used a density-depth function derived from the Makris et al. (2012) model for the sediments. This allows a rapid calculation of the model's gravity anomaly in the frequency domain.
- We successively invert the Moho, top lower crust and top basement horizons to fit the long wavelength of the FAA. The final model is exported as density volume.
- We calculate a residual gravity anomaly, corrected from the bathymetry, lower crust and Moho contributions and invert it in VOXI to recover a volume of density variations.
- We add these variations to the starting density model to obtain a final density model over the area.

2D gravity modelling

We carried out six long regional gravity models along the margin. We present three models from south to north (Figures 2-4). For the Juba Lamu and Obbia basins, we integrated the two time-migrated, 15 s TWT seismic sections published by Stanca et al. (2016). Although the reflection profiles are shorter than our models, which extend beyond the margin itself, they provide valuable ties for the model main horizons.

Stanca et al. (2016) describes a change in crustal architecture from south to north, with the continental-oceanic transition progressing farther seaward, which is confirmed by our models.

In Juba Lamu (Figure 2), the geophysical signature of the COB is unambiguous. The lateral changes in seismic character and gravity anomaly allow for clear identification of the oceanic crust. The FAA displays a steep gradient approximately 180 km from the present coastline, which is modelled by a relatively rapid transition from a stretched continental crust to a 7-9 km thick oceanic crust and a contrast of 0.5 gcm^{-3} in density within the upper crust. Version 2 of the World Digital Magnetic Anomaly Map (WDMAM; Lesur et al., 2016) and extinct ridges identified by Phethean et al. (2016) over this portion of the Western Somali basin support the location of the COB.

The proximal margin over the Juba Lamu basin displays a low gravity, and the 2D models required the addition of diapiric structures, with a density of 2.2 gcm^{-3} to fit the observed anomaly. Interpreted initially as Jurassic salt diapirs by Coffin and Rabinowitz (1987), more recent interpretation of modern seismic data suggests that these structures are more likely to be gravitational shale diapirs (H. Kearns, personal communication). The density in our model is consistent with measured densities for shale diapirs, reported between $2.1\text{-}2.3 \text{ gcm}^{-3}$ (Graue, 2000).

Farther north in the Coriole basin (Figure 3), although the transition between continental and oceanic crust remains easily

identifiable in our model. We locate the COB 215 km from the actual coastline, suggesting a wider zone of transitional/stretched continental crust and enhanced thinning of the continental crust. The signature of the COB is partly attenuated by a thicker sedimentary cover, $\sim 4.9 \text{ km}$ thick.

In the Obbia basin (Figure 4 a,b), bounded in the North by the Auxiliary Rescue and Salvage Fracture Zone (ARS FZ), and separated from the Coriole basin in the south by a pronounced bathymetric high at 4°N , both Spectrum Geo seismic and the gravity models suggest that we enter a different and more complex rift domain. Here, the necking zone is wider (120 km), followed by hyper-extended crust and possibly exhumed mantle (Stanca et al., 2016; Figure 4a,b). The COB is not readily apparent. Farther seaward along the profile (Figure 4a), i.e. beyond the hyper-extended crust domain, the interpretation is farther complicated by an area of uplifted basement (Figure 4b) exhibiting late or post-rift tectonic activity, and characterized by a gravity high and a magnetic high (based on WDMAM map).

Stanca et al. (2016) discussed alternative gravity models and interpretations for the Obbia basin. In one model, a zone of stretched crust, is followed by exhumed mantle (with a density of 3.2 gcm^{-3}) juxtaposing oceanic crust east of the ARS FZ, i.e. east of the basement high. In a second model, the high is interpreted as a volcanic high with a uniform density of 2.9 gcm^{-3} . Mantle exhumation is accompanied by serpentinization of peridotites. Densities are strongly negatively correlated with the degree of serpentinization and highly variable, going from 3.3 gcm^{-3} for 0% serpentinization, down to 2.5 gcm^{-3} for 100% (Miller and Christensen, 1997). Hence, without further constraint, a range of densities is possible to model serpentinized mantle. Our simplest model (Figure 4a,b) suggests that a hyper-extended upper/lower crust ($<3 \text{ km}$ thick) with unchanged $2.7/2.9 \text{ gcm}^{-3}$ densities fits the observed FAA adequately. Substituting this two-layer

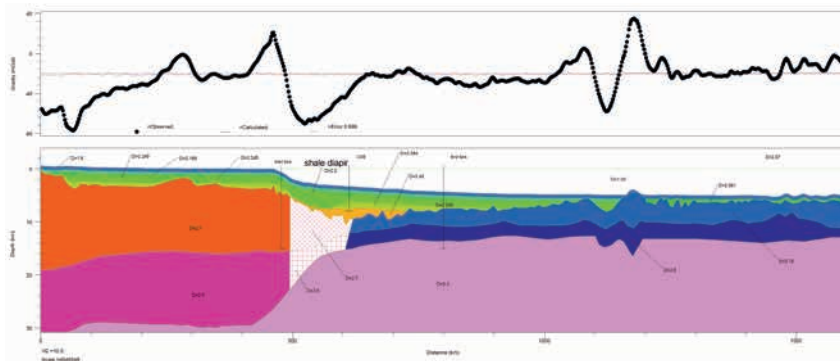
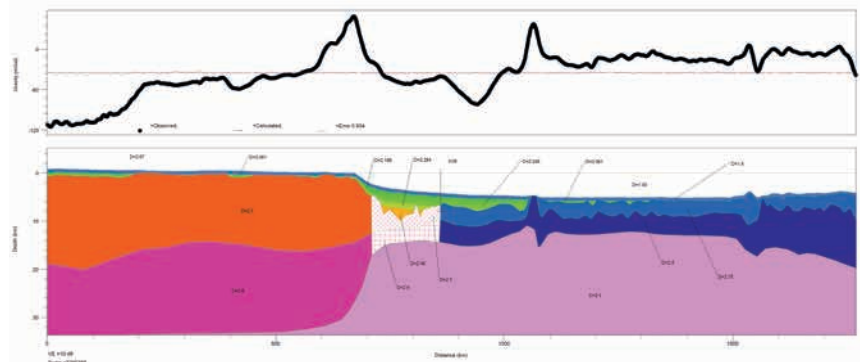


Figure 2 Juba Lamu gravity model (see location on Figure 1). Vertical lines indicate the start and end points of the Spectrum Geo seismic along the profile. The interpreted COB is also indicated by a thin vertical line. Transitional/stretched continental crust is indicated by hatch patterns blocks in the model.

Figure 3 Coriole basin gravity model (see location on Figure 1). Transitional/stretched continental crust is indicated by hatch patterns blocks in the model.



model by a single layer of stretched crust at 2.9 gcm^{-3} also provides an acceptable fit. However, introducing an exhumed mantle at 3.2 gcm^{-3} largely overestimated the FAA (by more than 30 mgal) and is not viable. Most recent interpretations of magma-poor passive margins argue in favour of the presence of exhumed serpentinized mantle, and Cowie et al. (2015) have found on the Iberian-Newfoundland margin that the extremely thinned crust ($<3 \text{ km}$) suggests the presence of an exhumed mantle. Serpentinization has also been suggested to vary rapidly with depth, with the first 2 km being more highly serpentinized. Although speculative, a hyperextended crust, followed by exhumed mantle at $2.7/2.9 \text{ gcm}^{-3}$ seems to be a plausible interpretation of both the seismic and gravity data. Farther oceanward the nature of the basement high remains to be constrained: again a simple two-layer model with $2.75/2.9 \text{ gcm}^{-3}$ densities suffices to fit the observed FAA. But signs of late/post rift tectonic activity could argue in favour of a tectonic high formed of exhumed mantle with a higher serpentinization rate in

the upper first few kilometres, and consequently lower density than for the serpentinized mantle described earlier in the northwest of the basin. The adjacent long reflection line located north of the model, where tilted continental blocks are present, could support this hypothesis (Mohamed Gouiza, personal communication). In all scenarios, oceanic crust is not present closer than 350 km from the actual coastline (Figure 4a).

Layered-earth-based gravity modelling and structural inversion

The initial regional density model (Figure 1) integrates an initial COB derived from Coffin and Rabinowitz (1987), significantly modified in the north based on the 2D gravity models and the magnetic data (EMAG2 v3, Meyer et al., 2017). We chose a 0.5 gcm^{-3} density contrast between the upper continental and oceanic crusts. For the sediments, we extrapolate the 1D density-depth function derived from the Makris et al. (2012) refraction line.

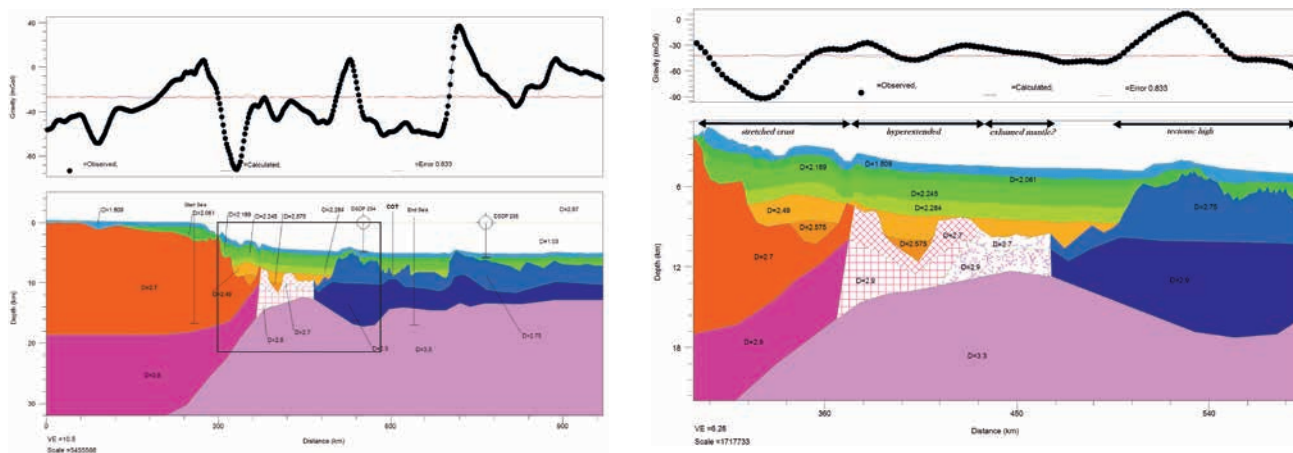


Figure 4 a) Obbia gravity model. The start and end points of the corresponding seismic profile are indicated by thin vertical lines. The black polygon shows the zoomed area in Figure 4b. Interpreted COT is indicated by a black vertical line. b) Zoom of the gravity model of the rifted margin in Obbia Basin, Figure 4a.

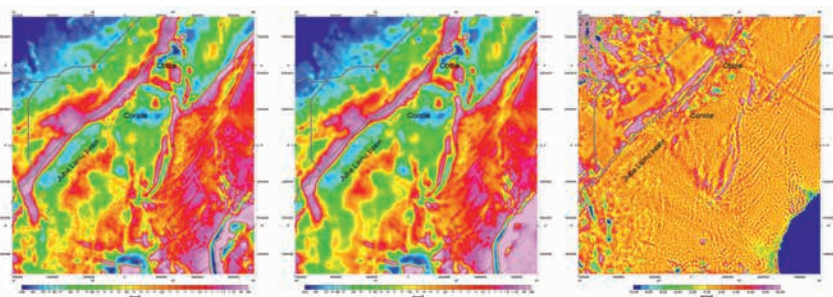


Figure 5 From left to right: observed Bouguer-FAA, calculated anomaly, and error map in mGal. The observed and calculated grids are displayed with the same colour scale using histogram equalization. The error grid is displayed with a linear distribution.

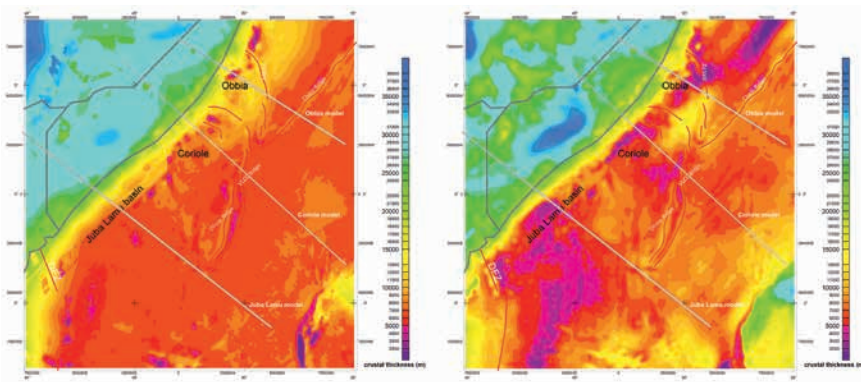


Figure 6 crustal thickness map before (left) and after inversion (right), displayed using a linear scale. Grey lines show the location of the 2D models.

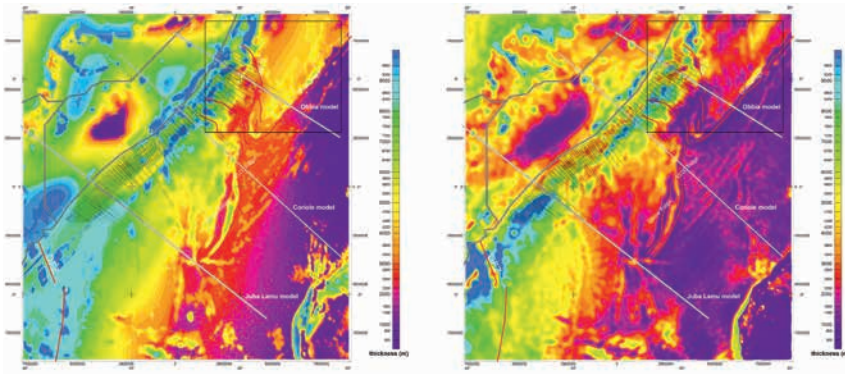


Figure 7 Sediment isochore maps before (left) and after inversion (right) displayed with a linear distribution. Cold colours indicate thick sediments while hot colours show thin sediments. Spectrum Geo survey shown in black. Black polygon shows the Obbia area for VOXI inversion.

Once this initial model is compiled, we then run successive structural inversions within GM-SYS 3D. We start with the deepest interface, the Moho, and then the top lower crust and then the top crystalline basement, with the aim of fitting the longer wavelengths of the observed G_z . We use the Bouguer onshore-Free-Air offshore of the Sandwell v23 satellite derived gravity with a 2.67 gm^{-3} Bouguer reduction density.

Since the voxel inversion intends to recover density variation within the sediments and the upper crust, we residualize the observed FAA from deeper contributions and produce a reasonable starting density model for the inversion. After the structural inversion, 95% of the error between the observed and calculated G_z ranges between $\pm 8 \text{ mgal}$ (Figure 5), with a standard deviation of 11 mgal. The misfit increases in areas where we had fewer constraints: onshore Africa and Seychelles, as well as in the southwest corner of the grid, with little effect on the offshore model.

The crustal thickness and sediment isochore maps after inversion (Figures 6 and 7) highlight the partitioning of the margin into three distinct areas from north to south, which encompass the Juba Lamu, Coriole and Obbia basins and the heterogeneous sediment distribution along the margin, with thicker sediment cover in the Juba Lamu basin. In the Obbia basin, the isochore map after inversion shows significant thinning on the eastern, deep part of the basin, located beyond the seismic survey (Figure 7), where a gravity high is observed.

The most notable change in crustal thickness in our model occurs in the north of the margin, north of the VLCC ridge and over the Obbia basin. The combination of the NOAA data and Crust 1.0 Moho indicates a large area of stretched continental crust east of the ARS FZ and oceanic crust between the ARS FZ and the Chain Ridge. Our model proposes an area of highly thinned crust east of the ARS FZ in the Obbia basin ($< 5 \text{ km}$ thick). This thinned crust also extends north of the ARS FZ.

Voxel-based gravity inversion over the Obbia basin

Once the regional Moho, top lower crust and top basement surfaces are adjusted, we then export a voxelized density model from GM-SYS 3D for a smaller area covering the Obbia basin. We worked with a mesh of $2000 \text{ m} \times 2000 \text{ m}$ horizontally and 100 m vertically (Figure 8), rapidly increasing downward at the depth of $\sim 5400 \text{ m}$ (deepest bathymetric point) ending up with a model that contains 23 million cells. In VOXI, the bathymetry is accurately represented by using a Cartesian Cut Cell method

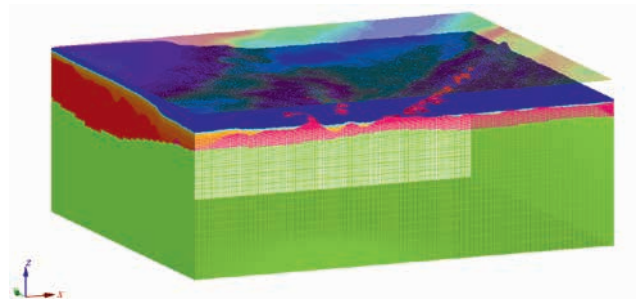


Figure 8 Orthographic view of VOXI mesh and starting model showing density distribution within the sediments and the upper crust. Vertical cell size increases downward. Density is set to zero below the top lower crust (green volume). The overlay grid shows the residual G_z .

(Ellis and McLeod, 2013). This allows us to calculate a precise terrain model using a density contrast of 0.77 gm^{-3} between the youngest sediments and the water. Because we aim to recover density variations from our starting model, within the sediments and the upper crust, we first calculate the contribution of the bathymetry, mantle and lower crust, and subtract them from the observed FAA. This residual anomaly is VOXI's input (standard deviation of 5 mGal).

VOXI allows constrained inversions, both spatially and in terms of physical property range. This means that available geological and geophysical data, such as a density-depth function inferred from wells, or seismically constrained basement depth, can be easily integrated to guide the inversion through a series of constraints. For the inversion over Obbia, we apply several constraints to take into account the inherent characteristics of the physical property distribution within the study area:

1. Starting model and parameter reference models: both are set as our initial density model for the sediment and the upper crust, and to a null density from the top lower crust downward since we have removed the contribution of deeper layers (Figure 8).
2. Density upper and lower bounds: we expect densities to vary within a realistic range, so we bound the densities between $1.8\text{--}2.7 \text{ gm}^{-3}$ in the sediments and $2.6\text{--}2.9 \text{ gm}^{-3}$ in the upper crust.
3. We introduce a differential gradient weighting between the NS/EW gradients and the vertical gradient, set to 10 and 0.1 respectively.
4. We apply two passes of the iterative reweighting process (IRI; Ellis, 2012) that emphasizes positive and/or negative properties.

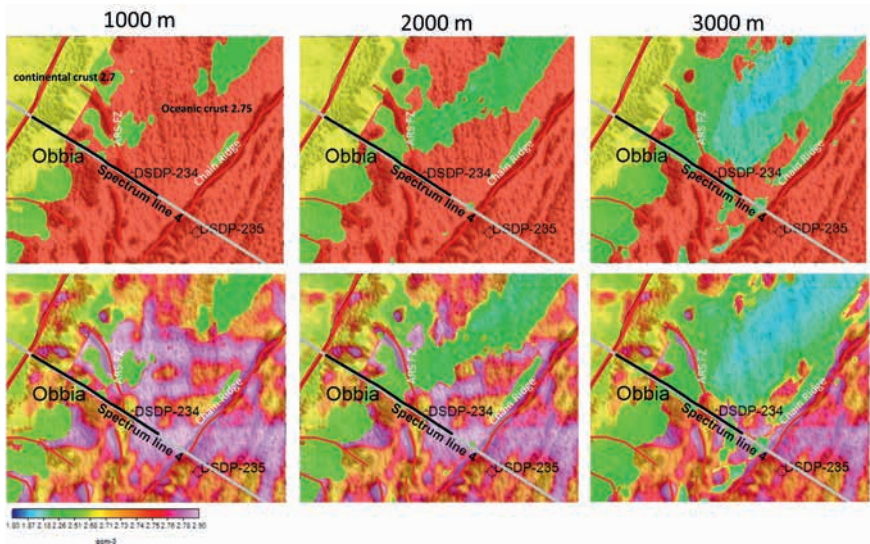
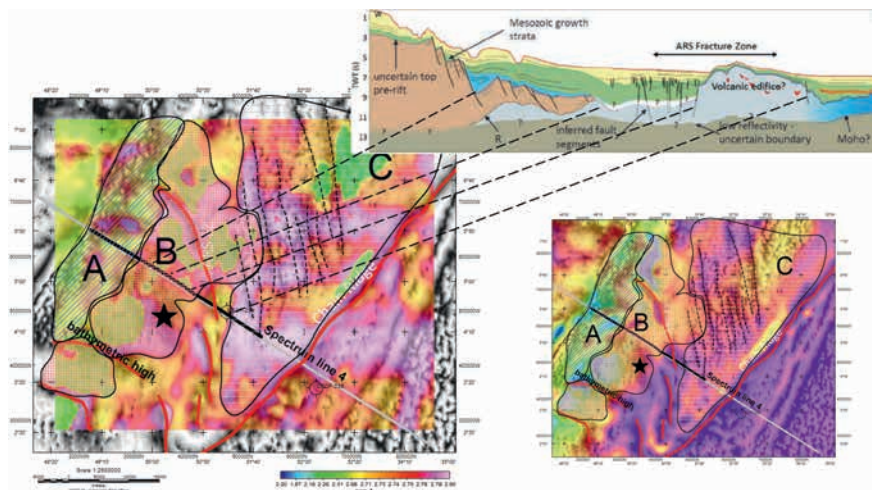


Figure 9 Density slices at 1000 m intervals upward from the top lower crust before (top) and after VOXI inversion (bottom). All grids are displayed with the same colour scale. The grey line indicates the 2D gravity model while the black line shows the extent of Spectrum Geo seismic data. The density is shaded with the calculated first vertical derivative G_{zz} .

Figure 10 Schematic interpretation into crustal domains A,B,C. The main map on the left displays modelled densities as a slice 1000 m above the lower crust surface, overlaid on the grid of the tilt derivative of G_z (grey colour scale). Basement ridges and bathymetric highs are outlined in red. The black star shows possible exhumed mantle. NW-SE dashed lines correspond to lineaments picked on the tilt derivative. Top right: Spectrum Geo TWT seismic line, as modelled in Figure 4a (from Stanca et al., 2016). Bottom right: sediment isochore map overlaid on G_z tilt derivative (the sediment isochore grid is displayed with same colour scale than used on Figure 7).



The inversion algorithm then seeks to minimize the misfit between the response of the starting model and the input residual anomaly, and returns a 3D volume of density variations. To interpret the final model, we can extract horizontal slices parallel to a reference surface at regular intervals. In Figure 9, we compare density slices between the starting and final models taken from the top of the lower crust upward at 1000 m intervals.

Discussion

Based on the joint analysis of the gravity anomalies, density inversion results, along with the crustal thickness, sediment isochore and 2D gravity models, we sketch three different domains, A, B and C, corresponding to three distinct crustal domains within the study area (Figure 10).

Domain A corresponds to the proximal margin, a north-south corridor, approximately 120 km wide, and is associated with the necking zone. Here our 3D starting density model has been left fairly untouched by the VOXI inversion (Figure 9) and the range of densities is in good agreement with the 2D model.

Domain B encompasses the distal margin and is the most complex area. Combining density slices and crustal thickness below 5km, we outline an area of hyperextended crust, coherent with the section identified by Stanca et al. (2016), and our 2D model along

Spectrum Geo line (Obbia model, Figure 4a). The area shows several pockets of density reaching 2.9 gcm^{-3} . Some of these can be interpreted as exhumed mantle, and this is likely to be the case in the area of gravity high marked by a star on Figure 10. Without any further structural constraint on its nature, we left out the tectonic high identified on Spectrum Geo profile (Figure 4a) located at the intersection of the ARS FZ and the seismic profile.

Domain C is a SW-NE trending V-shaped oceanward domain, located in deep water (~ 5 km deep), starting in the northeast of the area, bounded by Chain Ridge to the east, and dying against the ARS FZ to the south. This area is characterized by a thick sediment cover and thin crust. The calculated first vertical derivative of the FAA, G_{zz} , and the Tilt derivative also reveal a series of distinctive lineaments, oriented at 10° NW, and display a distinct corrugated or grainy texture, gradually disappearing toward the south. Neither the EMAG2 v3 data nor the latest version of the WDMAM magnetic grids give enough clues of the nature of the magnetic anomaly, and no clear magnetic stripes are present on the west side of Chain Ridge. At the southern tip of this area we had identified potential oceanic crust along both the seismic and 2D model (i.e. southeast of the tectonic high). The crust there is adjacent to unambiguous oceanic crust on the opposite side of Chain Ridge. Both the calculated densities in the upper crust leaning toward 2.9 gcm^{-3} ,

and the crustal thickness could suggest an affinity with oceanic crust. However, without unequivocal recorded oceanic magnetic anomalies, we can only speculate on its nature.

Conclusions

The combination of 2D and constrained-combined 3D modelling has revealed rifted domains along the Somalian margin defined by distinct basement architectures and density distribution. In the north of the margin over the Obbia basin and in the area beyond in the Northern Somalian basin, the density model indicates more complexity than farther south, and potential extensive areas of hyperextended crust. The model argues in favour of Cochran's (1988) early suggestion that the area west of the ARS FZ and north of 4°N may be extended continental crust, although we would extend this domain north of the ARS FZ. The model has also confirmed an oceanward progression of oceanic accretion, lying at ~180 km from the coastline in the Juba Lamu basin, 215 km in Coriole and ~350 km in Obbia.

Today's high performance computing makes possible large-scale regional satellite gravity inversion and this study reveals how public domain data inversion can provide a realistic density model of the subsurface and help us to understand frontier domains. Though these approaches are particularly interesting in frontier basins with little or no seismic coverage, we argue that there is perhaps even an application for better-understood basins where existing seismic data and wells are used to build more rigorous constraints into the inversion.

Acknowledgments

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