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Exploration of tectonic structures with GOCE in Africa and across-continents

Carla Braitenberg *

Department of Mathematics and Geosciences, University of Trieste, Trieste, Italy

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ABSTRACT

The gravity anomaly field over the whole Earth obtained by the GOCE satellite is a revolutionary tool to reveal geologic information on a continental scale for the large areas where conventional gravity measurements have yet to be made. It is, however, necessary to isolate the near-surface geologic signal from the contributions of thickness variations in the crust and lithosphere and the isostatic compensation of surface relief. Here Africa is studied with particular emphasis on selected geological features which are expected to appear as density inhomogeneities. These include cratons and fold belts in the Precambrian basement, the overlying sedimentary basins and magmatism, as well as the continental margins. Regression analysis between gravity and topography shows coefficients that are consistently positive for the free air gravity anomaly and negative for the Bouguer gravity anomaly. The error and scatter on the regression are smallest in oceanic areas, where it is a possible tool for identifying changes in crustal type. The regression analysis allows the large gradient in the Bouguer anomaly signal across continental margins to be removed. After subtracting the predicted effect of known topography from the original Bouguer anomaly field, the residual field shows a continent-wide pattern of anomalies that could be attributed to regional geological structures. A few of these are highlighted, such as those representing Karoo magmatism, the Kibalian foldbelt, the Zimbabwe Craton, the Cameroon and Tibesti volcanic deposits, the Benue Trough and the Luangwa Rift. A reconstruction of the pre-break up position of Africa and South America (the plates forming West Gondwana) is made for the residual GOCE gravity field. The reconstruction allows the positive and negative anomalies to be compared across the continental fragments, and so helps identify common geologic units that extend across both the now-separate continents.
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1. Introduction

The satellite GOCE was launched in 2009 (Floberghagen et al., 2011) with the aim to produce an improved global gravity potential Earth field. The mission requirements consisted in a global coverage, with a resolution of 100 km and a precision of gravity of 1 mGal at geoid level. The goals have been successfully met and the observations can be either used in terms of gradient observations along track at satellite height (250 km) or using the Earth Gravity Models (EGM) in terms of spherical harmonic expansion up to degree and order $N = 250$ (e.g. Pail et al., 2011). The EGMs allow to calculate the gravity anomaly at any height above earth surface. The advantage of using the EGM is that the complex geodetic task of averaging all GOCE gradient observations is done by the specialized geodetic team. The slightly varying satellite height and the attitude changes of the satellite measuring frame with respect to a Earth local north oriented fixed frame have been fulfilled optimally by the authors of the EGM. We shall use the geodetic definitions (Hofmann-Wellenhof and Moritz, 2006) for the derivatives of the potential field: gravity anomaly is the analog to free air gravity anomaly used often for terrestrial observations. Bouguer anomaly we call the gravity anomaly corrected for the full effect of a digital terrain model discretized by prisms or tesseroids; it is the analog to the calculation of the classical complete Bouguer correction, which used to be divided into the sum of the Bouguer plate and the terrain correction. We call gravity effect of terrain or the terrain correction the complete effect of the digital terrain model on gravity.

In many parts of the world the GOCE gravity potential field is superior to terrestrial measurements, in terms of resolution and precision. Locally the terrestrial field may be of higher spatial resolution, but coverage is limited to a network of roads, or to specific target areas (aerogravimetry), missing the complete regional field. Further, aerogravity observations are often commissioned by industry and remain undisclosed to the public. It follows that GOCE makes gravity data available also in those areas where terrestrial

* Tel.: ++39 3398290713.
E-mail address: berg@units.it

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gravity surveys have never been done. In Africa important results were obtained from terrestrial gravity surveys (e.g. Hales and Gough, 1957; Collignon, 1968; Louis, 1970; Slettene et al., 1973; Brown and Girdler, 1980; Browne and Fairhead, 1983), but the distribution of the terrestrial data is inhomogeneous, and GOCE gives the opportunity to identify gravity signals over a continent-wide scale with guaranteed equal precision and resolution. The good quality of terrestrial observations is demonstrated in small differences of only a few mGal between the GOCE and terrestrial fields degrading to several tens of mGal where the terrestrial data are insufficient (see e.g. Braitenberg et al., 2011a,b for the Chad basin, Alvarez et al., 2012 for the Andes and Argentina and Bomfim et al., 2013 for the Amazon basin in Brazil). The geologic evolution of Africa is closely linked to the geodynamic evolution of the cratons constituting the continent, leading to the assemblement and break up of Pangaea, Rodinia, and Gondwana. The cratons seem to be near to undeformable crustal or even lithospheric pieces around which deformation in terms of rifting, sedimentation, and mountain range building occurs since Proterozoic (Begg et al., 2009). These processes induce density changes in the rocks, sediments having low density, rifting being often accompanied by magmatism and crustal thinning, and orogenesis by metamorphism, leading to rock densification. Older belts in Africa are the greenstone belts, which formed in the Archean, and include ultramafic and mafic volcanic in the lower levels of the successions, with calc–alcaline and felsic volcanism in the higher levels (Condie, 1981). Another type of Archean belts is the granulite-gneiss belts consisting predominantly (80–85% surface area) of tonalite to granodiorite orthogneiss in high amphibolites or granulite grade (Windley, 1984). The density changes form the link between the gravity field of GOCE and the geological lineaments that can be identified. Hereby with geologic Lineament we intend a linear feature of regional extent observable in a geophysical field that is believed to reflect underlying crustal structure. A practical reason why the lineaments are important to trace is in the frame of mineral exploration, as mineral deposits form in specific geologic conditions and their resources depend strongly on the geodynamic evolution. The Greenstone belts are favorable locations of gold mineral deposits, examples of which are the Kibalian Greenstone Belt and the Greenstone Belt in Zimbabwe, which is discussed further on.

The geologically derived density variations reside in the upper crust, where the gravity signal is mixed to the effect of crustal thickness variations and regional crustal density variations. The isostatic theory (Watts, 2002) predicts that the topographic load be compensated at crustal level, either through lithospheric flexure, producing crustal thickness variations, or through density variations that compensate the topographic load (examples in orogens: Braitenberg et al., 2002, 2003; Wienecke et al., 2007). Provided the wavelengths of topography are big enough (e.g. 100 km), the gravity signal is proportional to the mass variations through the Bouguer plate approximation. In this approximation the gravity anomaly or the Bouguer anomaly field and the topographic load should have a linear relation, estimable by a regression analysis. The regression coefficients represent the completeness of isostatic compensation. The deviation of the observed field from the regression line is characteristic of the geologically induced density variations. The regression analysis has been successfully used in the Alps (Braitenberg et al., 2013) to identify sedimentary deposits and magmatic rocks. Here we calculate the regression over Africa to distinguish geologic domains through the regression result, and to isolate the related gravity signal. The outcome of the study is a geologic gravity field, ready to be used for hydrocarbon and mineral exploration in the aim of tracking large scale geologic lineaments (e.g. faults, rifts, fold belts, sutures) and of defining the depth and geometry of the density inhomogeneities.

2. The GOCE gravity field in relation to topography

The gravity potential field is calculated from the spherical harmonic expansion model GO_CONS_GCF_2_TIM_R4, produced by the Graz University of Technology, Institute for Theoretical and Satellite Geodesy, University of Bonn, Institute of Geodesy and Geoinformation and TU München, Institute of Astronomical and Physical Geodesy. It is based on 26.5 months of data, covering the period 01/11/2009 to 19/06/2012. It is a GOCE-only solution, where no external gravity field information is used, neither as reference model, nor for constraining the solution. The calculations seek for a least squares solution using full normal equations for GPS-satellite to satellite tracking and 4 components of gradiometry (*Vxx*, *Vyy*, *Vzz*, *Vxz*; *z* in radial direction, *x* along orbit, and *y* orthogonal to *x* and *z*) with the time-wise solution (Pail et al., 2011). The data are available through ESA (http://www.esa.int) and at the International Centre for Global Earth Models (ICGEM, http://icgem.gfz-potsdam.de/ICGEM/). The gravity anomaly with a grid spacing of 0.1° is calculated using the software of the EGM2008 synthesis and setting the parameter “isw” = 01, corresponding to “spherically approximated gravity anomaly”. The height of calculation is 4000 m guaranteeing to be above topography and be able to make the topographic reduction with the data points above the topographic masses. The formal error at the full resolution of the GOCE spherical harmonic expansion ($N = 250$) is estimated to be globally 5 mGal (Bomfim et al., 2013). Therefore every gravity variation exceeding the level of 5 mGal is a valid signal and cannot be discriminated as instrumental noise due to the downward continuation process. The GOCE derived gravity field presents an improvement with respect to existing gravity data, as has been shown in studies aimed at the evaluation of the GOCE field (Hirt et al., 2011). Complete topographic reduction was done with standard Bouguer reduction density (2670 kg/m^3 over land, 1630 kg/m^3 over water) in spherical approximation (Forsberg, 1984). The digital terrain model refers to the ETOPO1 (Amante and Eakins, 2009). The regression analysis is tightly connected to the isostatic compensation theory, and is fulfilled considering the equivalent topography instead of the topography, so calculations are transparent to oceanic and continental areas. The equivalent topography is defined as follows:

$$topo\_equiv(x,y) = \begin{cases} topo(x,y) & for\ topo(x,y) \geq 0 \\ topo(x,y) \times \dfrac{\rho_c - \rho_w}{\rho_c} & for\ topo(x,y) < 0 \end{cases} \quad (1)$$

where *topo*(*x*,*y*) is the digital elevation model, *topo_equiv*(*x*,*y*) the equivalent topography, and ρ_c and ρ_w the crustal (2670 kg/m^3) and ocean water (1040 kg/m^3) densities. The topography is reduced in frequency content with a Gaussian filter of 100 km half length (e.g. Bomfim et al., 2013).

The topography is shown in Fig. 1 as shaded relief map. The white outlines mark a few geological entities which have been picked out to illustrate the fact that the GOCE gravity residuals are useful in defining these geological features. This work is considering the gravity field over the entire African continent, with its geologically very diversified and complicated geology. It is impossible to consider all geological units on this scale. We therefore make a selection which shall illustrate some significant gravity signals and links to the geology. The selection has been made with the criteria of defining units rich in natural resources and that presumably generate density anomalies. The density variations are positive in case of metamorphic rocks as Greenstone belts, Fold belts, magmatic rocks, and negative in case of sedimentary sequences. The units have been digitized from the CGMW/UNESCO (1990) Geologic Map of Africa available in 6 sheets. Only the Muglad rift basin has been digitized from Dou et al. (2013). From north to south, and east to west the acronyms of Fig. 1 are listed in the following. AT: Atlas

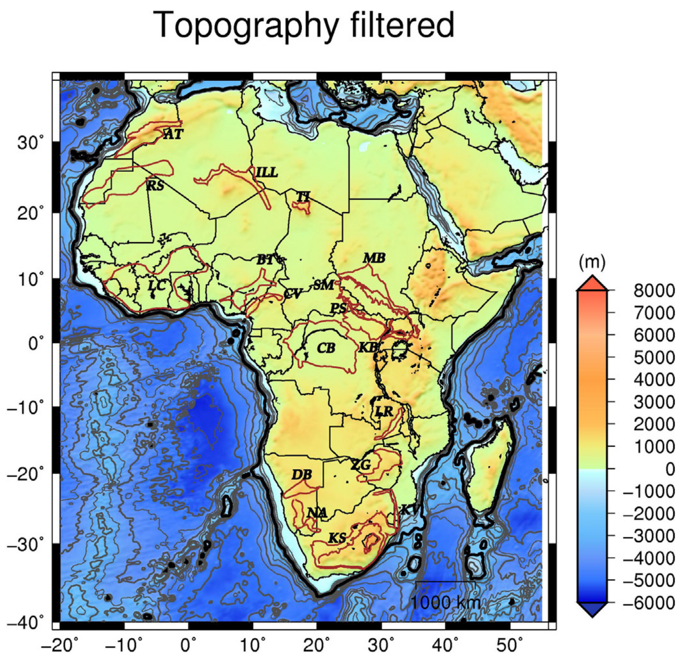

Fig. 1. Topography for the African continent. The Bouguer field correlates strongly with topography, an observation that is used here to reduce the Bouguer field for the ubiquitous effects of isostatic compensation and highlight the signals generated at crustal level. Digital Elevation Model ETOPO1 (Amante and Eakins, 2009). Brown: selected geological features with acronyms (see text for details). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Mountains, contains dense metamorphic rocks. RS: Reguibat shield, makes the northern part of the West African Craton. TIB: Tibesti Volcanic Mountain. ILL: Illizi Arc north of the Hoggar mountains. The digitized outline embraces the Cambrian–Ordovician units of the Arc. LC: Man-Leo Shield, makes the southern part of the Western African Craton. BT: Benue Trough (e.g. Fairhead, 1988), it is an aborted rift basin. CV: Cameroon Volcanic Line. MB: Muglad rift basin (Sudan) with up to 13.7 km thick sediments which formed in three rifting episodes between Early Cretecaeous (140 Ma) to end Oligocene (Mohamed et al., 2001, 2002; Dou et al., 2013). SM: Proterozoic clastic sediments (Schlüter, 2006). PS: Archean metamorphic basement in Southern Sudan (Schlüter, 2006; Civetta et al., 1979). KB: Kibalian belt, a Precambrian metamorphic belt including Greenstone with granitoid intrusions (e.g. Condie, 1981). CB: Congo basin or Cuvette Central, A large sedimentary basin. LR: Luangwa valley, a rift valley from Carboniferous-Jurassic; belongs to the Karoo system of sedimentation. ZG: Zimbabwe Greenstone belt (Condie, 1981; Ranganai, 2012). DB: Damara Metamorphic Belt (e.g. Gray et al., 2008). NA: Nama Group in Namibia, Molasse basin type deposits (e.g. Gray et al., 2008). KV: Lebombo Mountains Karoo Volcanics and Waterberg System Lava. KS: Karoo System deposits. External outline: Dwyka and Ecca series. Middle outline: Beaufort series. Innermost outline marks Drakersberg stage of Karoo System, made of basalt and pyroclasts, overlying the sediments. The two outer lines mark sedimentary rocks as shale, mudstone and limestones.

The gravity anomaly and Bouguer fields for the African continent are shown in Fig. 2.

The gravity anomaly shows small scale features, which are masked in the Bouguer anomaly by the great contribution of the mass variations in response to the topographic load. In terms of eliminating this signal, it is irrelevant whether the compensation occurs at Moho level, below it, or through densification of the crust correlated to topography. In all three compensation mechanisms it

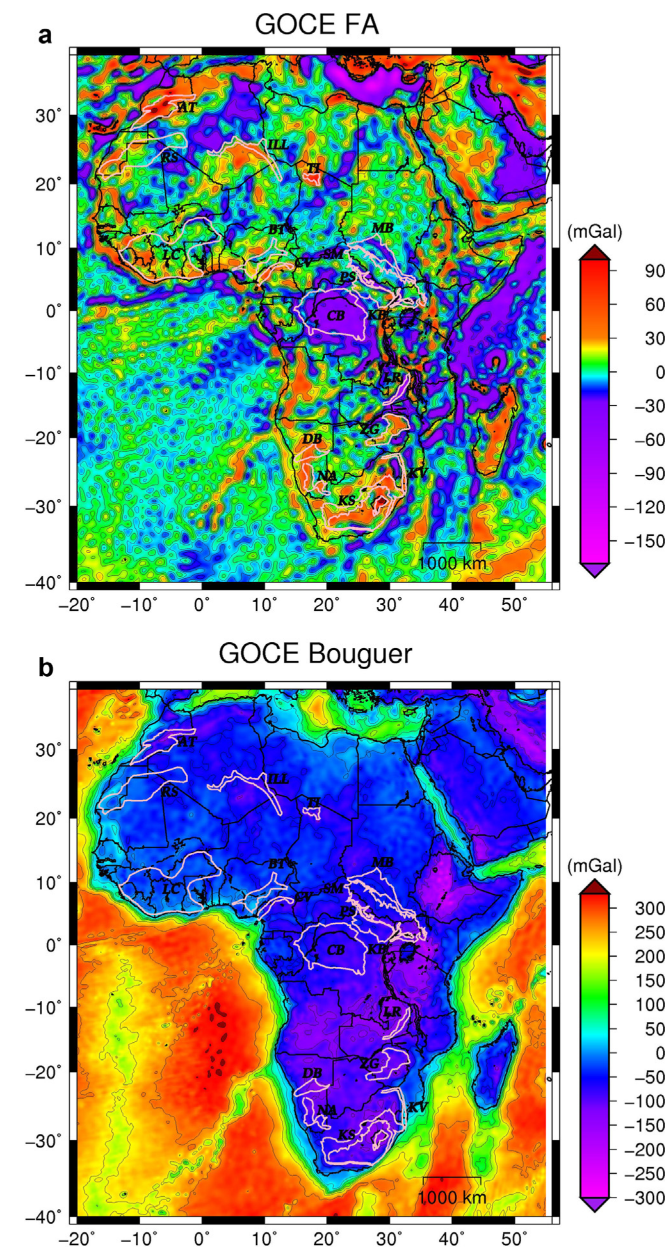

Fig. 2. Gravity potential fields GOCE only TIM-release 4 (released in April 2013, method described in Pail et al., 2011) over the African continent. (A) Gravity anomaly; (B) Bouguer anomaly. The precision and resolution of the field are homogeneous, so that each gravity variation represents a density variation in the subsurface. White: selected geological features with acronyms (see Fig. 1).

is a signal that should be eliminated when the focus relies on upper crustal density inhomogeneities.

3. Regression analysis and isostatic reduction

The regression analysis between gravity and topography is an alternative to the study of the local or regional isostatic compensation models of the African continent. The thin plate flexure model assumes isostatic compensation to be acquired through flexure of the lithosphere, which is approximated in the mathematical formulation as an elastic thin plate overlying an inviscid fluid (c.f. Watts, 2002). Toward increasing wavelengths, and decreasing equivalent elastic thickness, the flexural response tends toward the Airy local isostatic compensation mechanism. Considering the resolution of GOCE of 80 km half-wavelength, we are working in the wavelength

Table 1
Average regression coefficient between equivalent topography and free air and Bouguer gravity fields.

Area	Regression free air				Regression Bouguer anomaly			
	b (mGal/m)	*a* (mGal)	err*b* (mGal/m)	err*a* (mGal)	*b* (mGal/m)	*a* (mGal)	err*b* (mGal/m)	err*a* (mGal)
Entire area	0.0026	4.68	0.000023	0.044	−0.096	3.82	0.000023	0.043

band where the Airy compensation becomes a viable approximation. According to the Airy hypothesis and in the approximation of the Bouguer plate, the expected relation between Bouguer field and equivalent topography is linear, and the linear coefficients are:

$$BG \approx 2\pi G(r-d)(\rho_m-\rho_c) = 2\pi G\,\rho_c\,topo_{equiv} \quad (2)$$

with BG the Bouguer anomaly, G the gravitational constant, r the crustal thickness, d the reference normal crustal thickness, and ρ_m the upper mantle density.

In the same approximation the free air gravity anomaly should be equal to zero, because the topographic effect cancels the crustal thickening effect in the Bouguer plate approximation. In reality it is found that there is a small positive correlation between free air values and topography.

The global availability of the GOCE data presents a new opportunity to calculate the regression line between Bouguer and equivalent topography over the entire African continent. We consider an average regression as well as the variation of the regression for overlapping smaller windows. A homogeneous regression coefficient would correspond to a uniform isostatic compensation mechanism and absence of superficial density inhomogeneities. In case of a sedimentary basin with flat topography, the Bouguer field is increasingly negative toward the center of the basin. Therefore the presence of the basin can be identified by the deviation of the gravity signal from the average regression line. Considering local windows of analysis for the regression, an area with a local density anomaly will have the effect of a scarce correlation between gravity and topography and an anomalous linear coefficient. We can therefore use the linear coefficient to distinguish subsurface density inhomogeneities and changes in the style of isostatic compensation. Moreover, subtracting the average regression relation, the residual gravity is obtained, with enhanced signal from local density variations. The two results, the residual gravity anomalies and the linear coefficients are both a means to distinguish different crustal units of the African continent.

We run the above regression between the Bouguer field and the equivalent topography, and between the gravity anomaly and the equivalent topography. Average regression coefficients are reported in Table 1.

The regression is run twice: the second run is made on the data values that are within 1 standard deviation from the regression line, in order to eliminate outliers. The regression is positive for free air anomaly and negative for the Bouguer anomaly. The regression coefficient of free air anomaly is about one thirtieth of the one of the Bouguer anomaly. The maps of the residual gravity fields are shown in Fig. 3.

The residual fields reflect density inhomogeneities which are uncorrelated to topography and therefore to the isostatic root. The regression is more effective for the Bouguer values, due to the higher regression coefficient. The two residual fields are consistent among each other, evidencing the same density inhomogeneities. They are also very similar to the free air anomaly, with the difference that the geologic signal is more focused. An example is seen comparing the sequence of NNE–SSW trending gravity highs in Angola (Long. 15°, Lat. −10°), which form one continuous high in Fig. 2a, and several distinct gravity highs in Fig. 3a. The variation of the regression coefficient is obtained by calculating the regression on sliding windows of 2° by 2°, with 75% overlap. In Fig. 4a the map of the regression coefficients for the Bouguer field is shown.

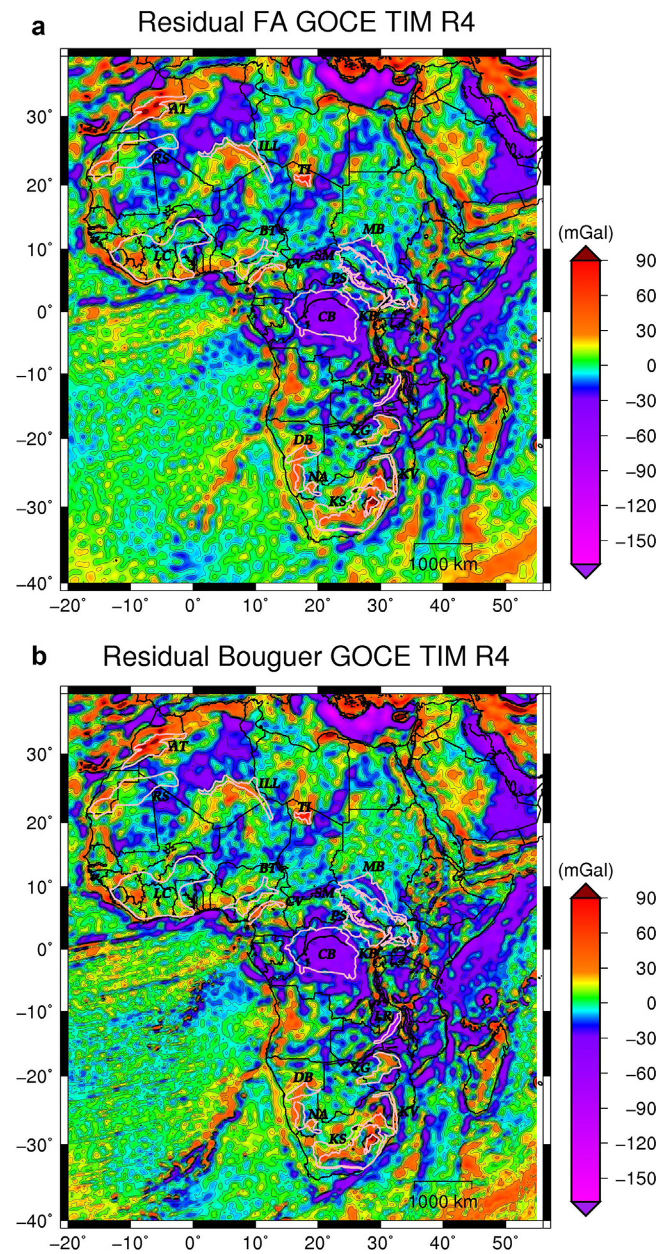

Fig. 3. The residual gravity after the field correlated to topography has been removed. (A) Residual of the free air gravity anomaly; (B) residual of the Bouguer anomaly. White: selected geological features with acronyms (see Fig. 1).

These coefficients are more reliable than the ones obtained for the free air field, due to their greater amplitude; the standard error of the coefficients is shown in Fig. 4b.

The scatterplots and the regression lines for each window are seen in video 1, a video which unites all windows. In the video, at the top of the frame the central position of the window and the regression coefficient with error are written. Each graph shows

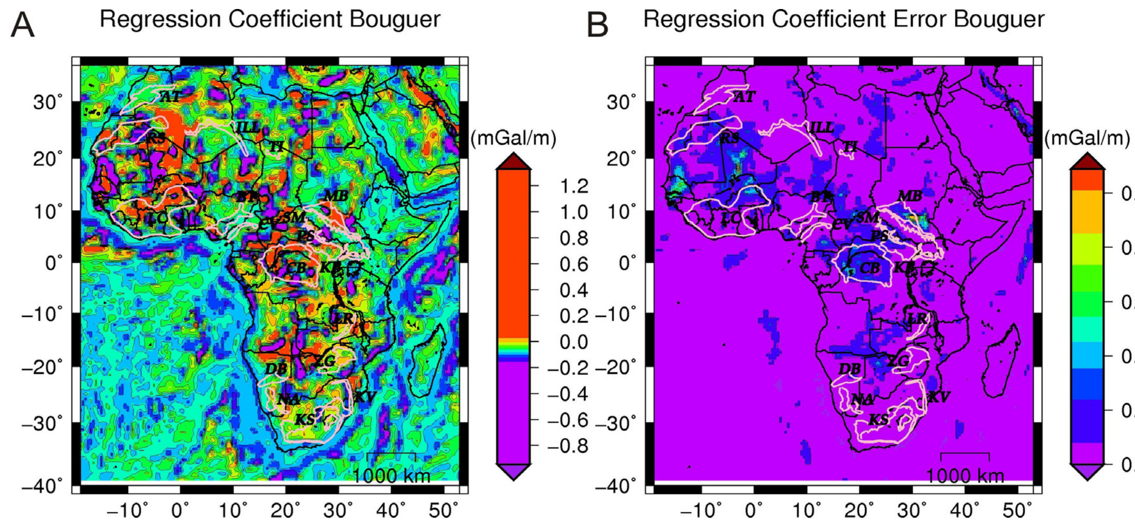

Fig. 4. Regression coefficient between Bouguer field and equivalent topography. (A) Regression coefficient. (B) Error on regression coefficient. White: selected geological features with acronyms (see Fig. 1).

the scatterplots of Bouguer and equivalent topography and the regression line. Over many windows, especially in oceanic area, the regression is linear, in some windows the values can be very scattered when a local anomaly is encountered.

The final goal of our study is to obtain the geologic GOCE field, which is the one shown in Fig. 3a and b, obtained with the non-parametric method. Comparing the residual Bouguer field of Fig. 3b with the original field (Fig. 2b), it is seen that the amplitude of the residual Bouguer has been greatly reduced, and highlights the geologic signal; the amplitude of the free air anomaly (Fig. 3a compared to Fig. 2a) has only minor change.

4. Discussion

The regression analysis of gravity and equivalent topography is a non-parametric method to extract the geologic signal from the GOCE observations. The regression has smaller scatter and greater stability in case of the Bouguer field with respect to the free air anomaly. The error of the coefficient is smallest and homogeneous over the ocean, in comparison to continental areas. Over the ocean the coefficient is a geophysically reliable parameter, signalizing changes in crustal structure. The interpretation of the coefficient is an open question. A systematically more negative value covers a ribbon bordering the African continent. The ribbon is from 2° to 10° wide, with largest values along the Atlantic coast southwards of the equator. The ribbon seems to mark the transition to oceanic crust. Over the continent the local coefficient has greater variability, due to the presence of crustal density inhomogeneities. Positive correlation coefficients for Bouguer over an orogen signalize strongly increased density due to metamorphism, and are analogous to the Nettleton method used to determine the density for the topographic correction of gravity measurements. The great majority of the coefficient values is negative, validating the fact that the coefficient is a means to globally describe the anticorrelation between Bouguer values and topography.

The residual Bouguer field is greatly reduced in amplitude, and highlights smaller scale density variations that correlate to the geodynamic products as fold belts or rifting, sedimentation and magmatism. The margins of the Man-Leo craton (LC) and the Reguibat shield (RS) are partly lined with a gravity signal. It is not necessarily a positive signal, as would be expected for a metamorphic foldbelt, but can be also negative. Positive gravity signals are found for the Tibesti (TI), the Cameroon Volcanic line (CV), the Illizi arc north of Hoggar (ILI), the Damara belt (DB). The Kibalian (KB) and Zimbabwe (ZG) Greenstone belts generate a clear positive linear signal. The Karoo magmatic Drakensberg deposit in Lesotho generates a well defined positive signal (KS). Same is the case for the Karoo Volcanic (KV) sequence of the Lebombo Mountains along the eastern border of the South African Republic. The Karoo forms an arc lining the South African coast inland (KS), continuing Northwestwards along the Nama sequence (NA) up to the Damara belt (DB). Clear negative signals are found for the Congo basin (CB), the Benue Trough (BT) and the Luangwa Rift valley (LR). An example of the inference of geologic units which are partly concealed is given in Sudan and at the Sudan-DRC (Democratic Republic of Congo) border. In Sudan the Muglad rift basin (MB) generates a linear negative gravity signal of near to −30 mGal amplitude. The negative signal is expected for a rift basin with a thick sequence of sediments and scarce magmatism (Mohamed et al., 2001). The parallel linear gravity low which is found westwards, in DRC and CAR (Central Africa Republic) along the Sudan-CAR-DRC-border has comparable amplitude and size, but must have different origin, as no rift basin is known matching it. It rather correlates with the presence of Proterozoic clastic sediments (PS) (Schlüter, 2006), which are located between the Archean basement gneisses and intrusives in DRC (KB) and the Archean metamorphic basement in Southern Sudan (SM) (Schlüter, 2006; Civetta et al., 1979). The gravity low resembles the outline of the Proterozoic sediments, though covering an enlarged area and extending into the basement. If the Proterozoic sediments were responsible for the gravity low, they extend over a greater area than the one mapped on the general geologic map available today.

To illustrate the results in greater detail, Fig. 5 shows the geological map (Wiles, 1971) and the residual Bouguer field for Zimbabwe, together with the location of gold mines (GSC, 2013). The green units in the geologic map (Fig. 5a) are the outcropping Greenstones; the gold findings are associated to the Greenstones, and are therefore located along or at the green patches of Fig. 5. The outcropping units could well be only a percentage of the complete Greenstone belt, the remainder being possibly concealed below the surface. The gravity field shows an extensive regional gravity high, which correlates with the Greenstone outcrops, and is generated by the entire Greenstone belt. The gold mines are found to match the gravity high or its border. This demonstrates the link between the gravity high and the regional Greenstone belt, revealing its dimension and orientation, also where it is concealed. If more detailed investigations of the subsurface were planned, the GOCE

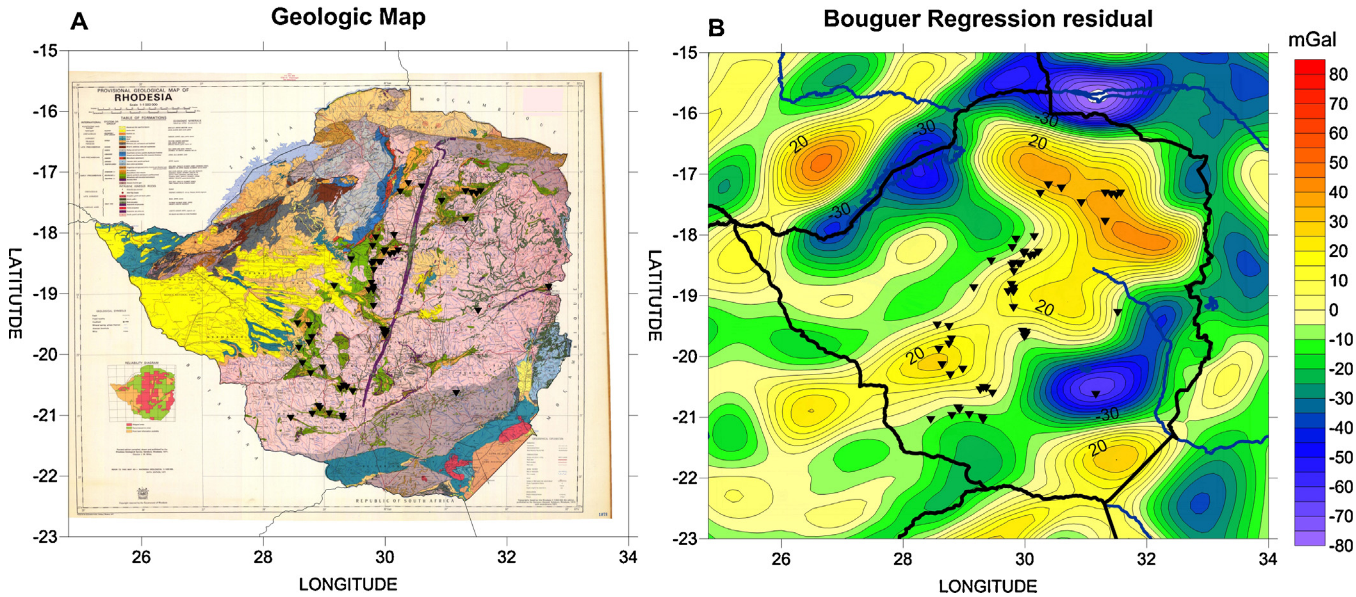

Fig. 5. Detail of Bouguer gravity residuals for the country of Zimbabwe (or Rhodesia). (A) Geological map (Wiles, 1971), (B) Bouguer gravity residual; triangles: gold deposit (GSC, 2013). White: selected geological features with acronyms (see Fig. 1).

gravity high could be used as a guideline in defining the extent and directionality of the units of greater interest to mining exploration.

Considering the reduction of the Bouguer field, the isostatic flexure model gives similar results in terms of reducing the gravity signal for crustal thickness variations, as has been done in Braitenberg (2013) for the Congo basin area. The isostatic flexure model has the disadvantage that it depends on the flexure parameters that must be fixed by the user. The flexure model implies crustal thickness variations being responsible of the isostatic compensation, and does not consider a compensation of density variations at crustal or mantle levels. This makes the regression analysis more flexible, as the latter reduces both crustal thickness and density variations.

The global availability of the gravity field, allows the anomalies to be traced across continents with the aim of determining a common origin, tied to the pre-break-up history. In our case of the African continent, we must apply the rotations that lead to the reconstruction of western Gondwana. The reconstruction is ambiguous, and depends on the specific author (e.g. Doucouré et al., 2000; Torsvik et al., 2008). Here I have chosen one particular reconstruction which has made the rotation poles and the continent outlines both digitally available (Torsvik et al., 2008). Details on rotation poles and continental outlines are documented in the reference publication. These digital data are necessary for extracting today's gravity values and rotating them to the reconstructed position. This particular reconstruction (Torsvik et al., 2009) leaves a gap between the coastlines of Africa and South America, having though a tight fit along the Southern Coast of Western Africa. According to the authors, the reconstruction reflects the paleomagnetic database. The discussion on the quality of the reconstruction must be done elsewhere, as it is far from the topic of the present paper. Notwithstanding, the major focus here is to show that the GOCE observations allow this composite field to be represented for

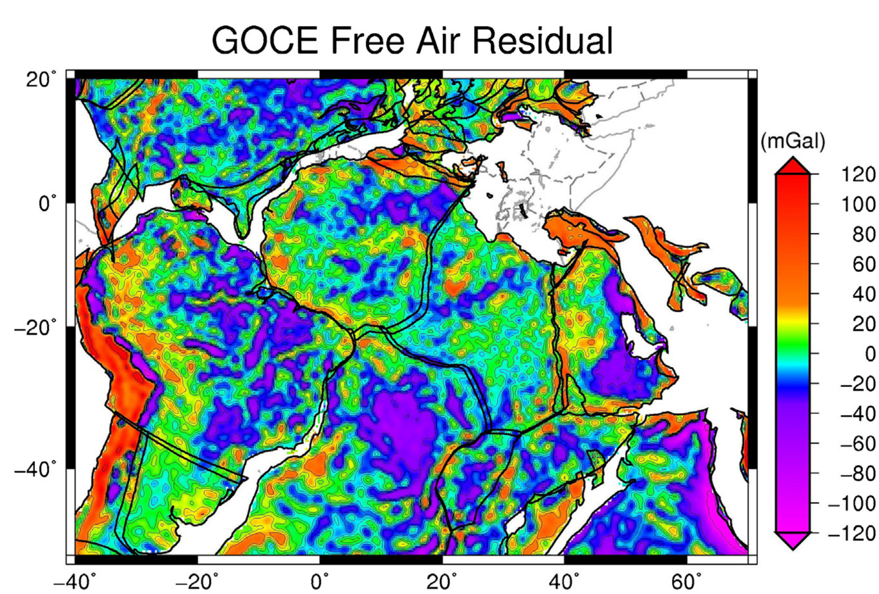

Fig. 6. Residual gravity from regression analysis on free air anomaly for Western Gondwana. The correlation of anomalies across the continents highlights the mineral-bearing foldbelts which formed before the opening of the Atlantic. Details in text.

the first time at a homogeneous resolution, as it is global and has no bias from one to the other continent. The reconstructed field shown in Fig. 6 reflects today's crust, which has an altered density column due to the processes that occurred successively to the Africa–South America separation through erosion, sedimentation and magmatic emplacement. The correlation of the field between continents is masked by the events which occurred after rifting. If we succeed to clean the field from the more recent events, we will be able to support cross-continental geologic correlation efforts (e.g. Pankhurst et al., 2008) also at deeper crustal levels, concealed to direct geologic observation. As an example we focus on the Borborema Province in Brazil which connects geologically to West Central Africa (e.g. Van Schmus et al., 2008; de Wit et al., 2008). The Sergipano domain in Brazil and the Yaounde' domain in Camerun geologically represent stacked nappes of tectono-stratigraphic units which were thrust during the Brasiliano-Pan African cycle onto the San Francisco and Congo cratons, respectively (Oliveira et al., 2006; Toteu et al., 2006). Both can be traced as a gravity low. To the north, the adjacent Pernambuco-Alagoas and the Adamawa-Yade' domains partly give a gravity high. The Tertiary volcanism of the Cameroon Volcanic Line generates a linear NE-SW oriented gravity high which must be distinguished from the above signal. This example shows that the new field of GOCE allows study the continuation of the geologic units through the gravity field, but that the effects of the later geologic events which are uncorrelated on the two continents must be reduced.

5. Conclusions

The GOCE derived gravity field is an important data set, useful in the search of natural resources as hydrocarbons and minerals. The data are globally available, crossing national borders, are independent from topographic changes and continent–ocean transitions. This, together with the homogeneous precision of the GOCE field, guarantees global reliability of the results. Here a gravity map is offered, that reflects geological boundaries and which has been freed from the disturbing signal of deep crustal origin to a great extent. A selection of geologic units and lineaments are well evidenced by the gravity field. The usefulness in exploration consists in identifying a signal that matches a known natural resource. The continuation of this line increases the chance to encounter analogous favorable productive geologic environs. The margins of cratons have been the location of crustal shortening, subduction and rifting, producing the metamorphic and magmatic rocks that are essential for mineral production and the sedimentary basins that can develop to hydrocarbon reservoirs. The residual gravity field that is presented here allows for the first time a cross-plate mapping of all the geologic lineaments linked to density variations. The gravity field can be used in a second step for defining the geometry and depth of the density units, an essential information for the geodynamic evolution. The regression between Bouguer and equivalent topography is a means to characterize crustal type, as it reflects the isostatic compensation mechanism. The continental margins of Africa result to change the type of continent–ocean transition, with a broad transition (more than 8° width) along the southwestern margin, and a width of only 3° at the western central Africa coast. This observation leads to a wider stretched crust in the southern west, with respect to the northern and eastern margins.

The global availability of the field allows the geologic units to be traced across the continents, or equivalently across the protocontinent as Gondwana, as is demonstrated by the composite South-America and Africa map that evidences the link between several of the positive gravity anomalies identifying foldbelts that were common to both continents. The cross-continent link can be done for the first time due to the great improvement brought by satellite GOCE.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jag.2014.01.013.

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