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A Grip on Geological Units with GOCE

Carla Braitenberg

Abstract

The scope of this work is to show the observations of satellite GOCE in mapping geological units in a key area for mineral exploration, which is also a key location for understanding the formation of the America and Africa continents from the former western Gondwana. The observations of the satellite GOCE have allowed to achieve a qualitative leap ahead in today's global gravity. The new global field has an improved resolution of 80 km with precision of 5 mGal; this resolution is sufficient to study crustal thickness variations and the upper crustal structure. Geological macrostructures generating density variations are mapped for the first time by a global satellite derived field in continental areas, which opens a new series of applications in geophysical exploration. The study area is located in and around the Congo craton, which is a part of Africa poorly covered in ground gravity surveys, so that GOCE data are essential there. The GOCE gravity field is reduced by the effect of topography, of the isostatic crustal thickness and by sediments, obtaining the field representative of the geologic lineaments. The foldbelts surrounding the Congo craton are identified well through the field, generating signals near to 50 mGal. Compared to the existing geologic map, along the Kibalien belt, a narrow belt with increased density is distinguished, about 125 km wide, and 800 km long, that must be representative of a major compressive or magmatic geologic event that generated these rocks. The distinction of separate geologic units characterized by density variation is useful for identifying the areas where focused future geophysical and geologic mapping will be effective in the exploration of new mineral resources.

Keywords

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1 Introduction

Density is an important parameter that allows to classify rock types, due to the characteristic densities in the transition from unconsolidated sediments, compact sedimentary rocks, volcanic, metamorphic and mantle rocks (e.g. Brocher 2005). Investigations using remote sensing with multispectral images are useful only for exposed rocks, and are less efficient in identifying different rock types in areas with thick vegetation, limiting applicability for terrestrial investigations as in the sub-Saharian range (e.g. van der Meer et al. 2012). For the first time with satellite GOCE (Floberghagen et al. 2011), resolution and precision have crossed the line that divided deep Earth investigations from the studies with direct impact in exploration of natural resources. The boost in resolution and precision of the gravity field was obtained with the space-borne observation of the full gradient tensor at low satellite height (250 km) (Rummel et al. 2011). AQ1 After downward continuation of the observations to ground

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level the precision at 80 km wavelength is comparable to that of an aero gravimetric campaign (measurements accuracy near to 4 mGal), with the great bonus of having a global access to the observations (Braitenberg et al. 2010). In fact the gravity anomaly error up to degrees 180, 200, and 250 derived from the cumulative error curves of the third generation GOCE only model TIM (Pail et al. 2011) spherical harmonic expansion is 0.8 mGal, 1.5 mGal and 5.1 mGal respectively (Bomfim et al. 2013). This does not imply that the aerogravimetric campaign cannot have greater spatial resolution, but it shows that at the long-wavelength end of the aero-gravimetric measurements the two observations are of similar precision. The precision of the GOCE observation is best represented in the degree-error curve of the spherical harmonic expansion, which we can translate into the resolution of the crustal body to be studied. Assuming that overlying density heterogeneities have been correctly reduced, and assuming that the density contrast at Moho level were known exactly, the Moho and basement theoretically can be recovered at a level of 0.1 km uncertainty, sufficient to successfully map the depth variations (Braitenberg et al. 2010; Reguzzoni and Sampietro 2012). These uncertainties consider only the error on the gravity data, and are valid under the assumption that the density contrasts at the boundary are known, and that the overlying density inhomogeneities have been stripped off the observations correctly prior inversion. For the Tibetan plateau and Himalayan range the GOCE data proved useful for defining the Moho seamlessly from the lowlands of India, through the Himalayas to the Tarim basin (Sampietro et al. 2014). New findings from GOCE data are most likely to occur where the GOCE gravity field improvement is the greatest, particularly over parts of Asia, Africa, South America and Antarctica (Hirt et al. 2011, 2012), as has been shown in detail for the Andes (Alvarez et al. 2012). In Europe the improvements are most likely to be restricted to high mountains (like Alps) and across the coastal areas, where the transition from terrestrial measurements to satellite altimetric observations occurs. The precision of the altimetric gravity data decreases towards the coast, approximately starting from a distance of 25 km from the coast, due to the footprint of the altimetric signal and due to the dynamic topography of ocean currents in shallow waters (Hwang et al. 2002).

Here an area is considered where terrestrial observations are scarce due to difficult terrain, making the new GOCE-derived field the best gravity-field today available. This area is located in and around the Congo craton, and straddles different countries as Cameroon, Central African Republic, South Sudan, Uganda, Tanzania, Democratic Republic of Congo, Republic of Congo, Gabon and Equatorial Guinea. The area is of general interest, being in a key position of the continent Gondwana, from which the South American and African continents were formed (De Wit et al. 2008a). The Congo craton is an old crustal nucleus with a deep lithospheric root, which constitutes an indeformable unit, against which the surrounding crustal units are deformed (e.g. Begg et al. 2009). We use the GOCE satellite to deliver some new data that help to unscramble these deformations, which cover 2 Ga years of Earth history, and have produced important mineral deposits as gold, platinum and iron. We demonstrate that the Bouguer field derived from the GOCE observations perfectly correlate to known geologic units. We then demonstrate that the GOCE observations differentiate the geologic structures, identifying the margins of the high density units formed by metamorphic addensations of rocks. The results have direct applicability in mineral exploration and show that the GOCE observations constitute an innovative tool for mineral exploration in remote areas.

2 The Area of Study and the GOCE Gravity Observations

2.1 The Geologic Macro-units and Expected Density Variations

North Central Africa (Fig. 1) has greatly benefited from the GOCE observations (see difference map between GOCE and EGM2008 (Pavlis et al. 2012) in Braitenberg et al. 2011b) and is geologically extremely important, due to great oil deposits onshore (Chad, Congo basins) and offshore (Niger delta, Congo craton oceanic margin), due to the high volcanic risk (Cameroon Volcanic Line) and due to its key position in understanding the evolution of West-Gondwana and the opening of the Atlantic (De Wit et al. 2008b). The map in Fig. 2 shows the main geologic units according to CGMW/UNESCO (1990), to which we refer for the detailed color coding of the units; as in Fig. 1 we have added country borders; the colored lines mark the outlines of selected geologic units that due to their rock constitution are generally expected to be accompanied by density variations and that we shall analyze in terms of the gravity field. The exact nomenclature of the numbered units according to the geologic map or according to Kadima et al. (2011) is given in Table 1. In general terms, the younger sediment units have lower density, the palaeozoic sediments have average density, as they have been mostly compacted, and therefore have a density that corresponds to the density of the rock grains, due to expected low porosity. Metamorphic units and magmatic units containing basalts have increased density, and granites have average density.

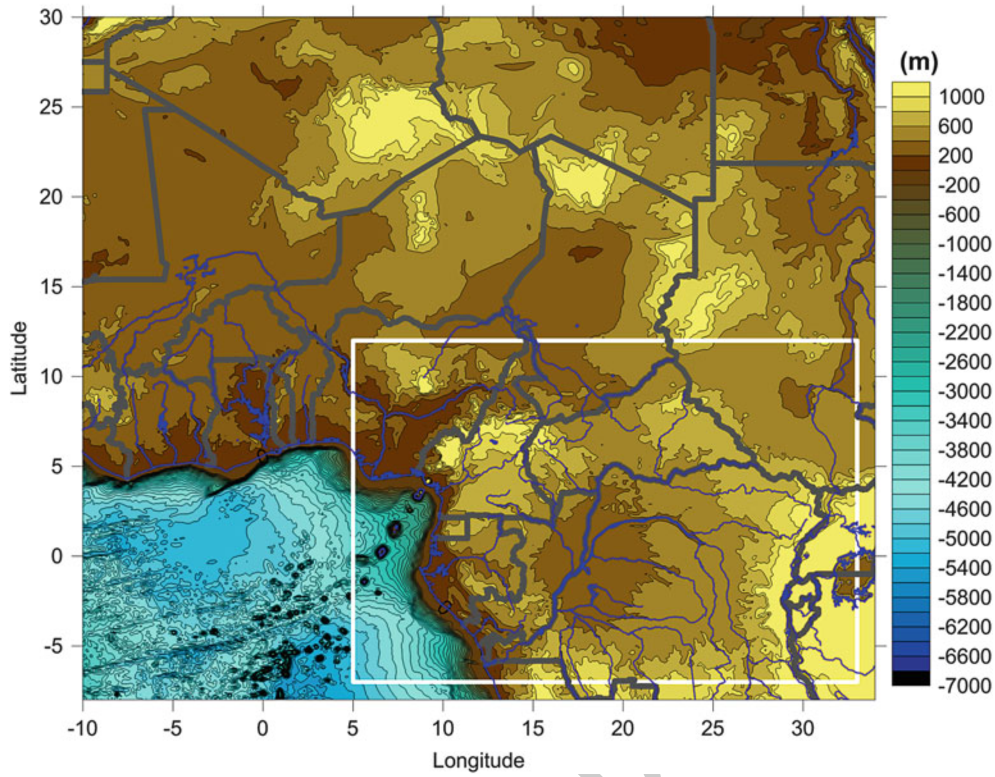

Fig. 1 Topography of Central North Africa. The *white square* shows the detailed study area centered on the Congo basin

2.2 The Reductions of the GOCE Gravity Field

We calculate the GOCE gravity values at 4,000 m height according to the Gravity Global model of 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/). We used the file go_cons_gcf_2_tim_r3.gfc and calculated the gravity anomaly with a grid spacing of 0.2° using the software of the EGM2008 synthesis and setting the parameter "isw" = 01, corresponding to "spherically approximated gravity anomaly". The choice of 4,000 m was taken in order to be above topography and be able to make the topographic reduction with the data points above the topographic masses. All reductions were made considering this 4,000 m height. As mentioned above, the formal error at the full resolution of the GOCE spherical harmonic expansion (N = 250) is estimated to be globally 5.1 mGal (Bomfim et al. 2013). 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). We correct the observations for the effect of topography with standard Bouguer reduction density (2,670 kg/m^3 over land, 1,630 kg/m^3 over water) in spherical approximation. The digital terrain model refers to the ETOPO1 (Amante and Eakins 2009). It is further necessary to reduce the observations for the effect of crustal thickness variations in order to enhance the signal that is generated by the density variations that accompany the different geologic macro-units and are expected to be at upper crustal levels. A crustal thickness model from seismology is unavailable for the entire area, so we estimate the gravity effect of a flexural isostatic model by calculating the flexural isostatic thickening and a standard density contrast at the base of the crust. Different couples of effective elastic thickness and density contrast for the forward calculation of the gravity field are considered. In Table 2 the extreme values, the root mean square and the average values for the reduced fields are shown. The extreme values and root mean square values are greatly reduced after applying the isostatic reduction. It is seen that the reduction with a density of 500 kg/m^3 is more effective than the one with 300 kg/m^3, and that the reduction does not greatly depend on the choice of the effective elastic thickness. As expected the isostatic correction reduces the Bouguer variations, e.g. the greatest amplitudes due to topographic relief as continent-ocean transition and high elevation (Cameroon Volcanic Line, unit 12). The effect of sediments in the basins is another obvious negative gravity signal, due to the negative density contrast of sediments with respect to a reference standard crustal column. We reduce this contribution with the most up to date sediment thickness model having been

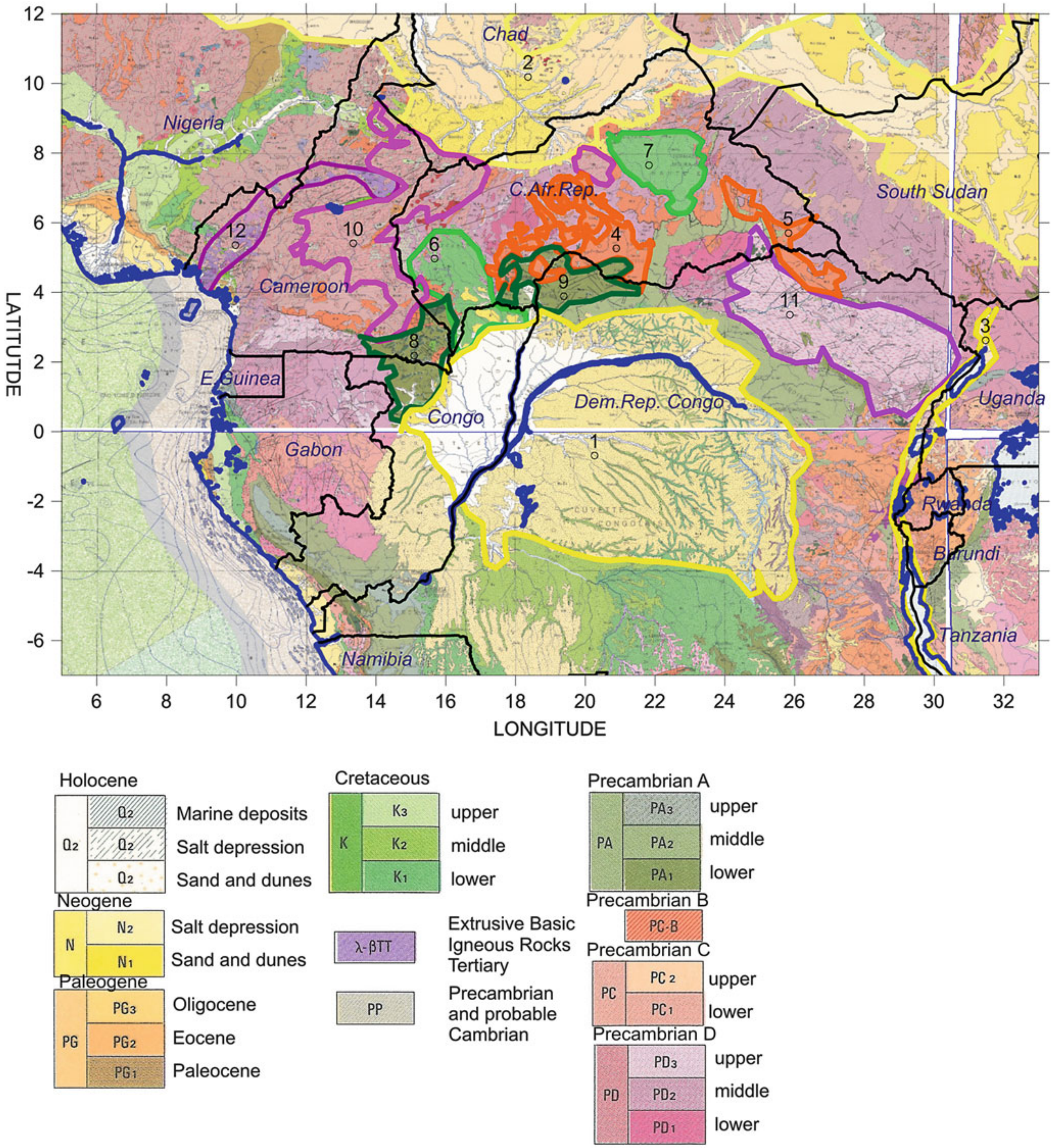

Fig. 2 Geologic map for the area centered on the Congo basin. The numbers refer to geologic units defined in Table 1. *Yellow lines* mark Tertiary sediments, *orange* mark Palaeozoic sediments, *green* mark Cretaceous rocks, *pink* to *purple* Precambrian units affected by metamorphism and magmatism, *dark violet* mark the Cameroon line, with Extrusive Tertiary Igneous rocks

compiled by TOTAL for the Commission for the Geologic Map of the World (Frizon de Lamotte and Raulin 2010), from which sediments are available in terms of sediment thickness isopachs. We adopt a linear first order variation of density with depth characterized by top density 2,250 kg/m^3 and bottom density 2,670 kg/m^3 at 8,000 km depth (e.g. Allen and Allen 2005). The top density corresponds to sand, the bottom density to granite, and the bottom depth is found to be a limit at which generally sediments are compacted so as to have closed liquid-filled pores and have acquired the grain density.

AQ2 **Table 1** Selected geological units expected to generate variations in the bulk density

AQ3

Number of unit	Selected uniton geologic map in Fig. 2. Units and ages refer to UNESCO geologic map (CGMW/UNESCO 1987)	
1	Congo basin sediments. Pliocene-Pleistocene coverage of sands and dunes	t3.1
2	Chad sediments. Pleistocene coverage of sands and dunes	t3.2
3	Sediments of east African rift	t3.3
4	Oubangui-Bambari—Precambrian-B (1,300–1,600 Ma) alternates	t3.4
5	Haut Mbomou—Precambrian-B (1,300–1,600 Ma)	t3.5
6	Lower Cretaceous sediments Muabere'	t3.6
7	Lower Cretaceous sediments Formation Moukka Ouadda	t3.7
8	Sembe–Ouasso basin, West Precambrian A	t3.8
9	Liki-Bembe basin, Bangui, Precambrian A	t3.9
10	Ouham Pende Metamorphic rocks of undetermined age, syntectonic granites, Precambrian or Palaeozoic	t3.10
11	Kibalian basement comprising greenstone belt, with Syntectonic granites, some amphibolite outcrops. North East Congo block. Upper Precambrian	t3.11
12	Cameroon volcanic line, Tertiary extrusive igneous rocks	t3.12

The numbers refer to Fig. 2

AQ4 **Table 2** Statistical parameters of the gravity anomaly, Bouguer values, gravity effect of sediments, and residual Bouguer after reduction for sediments and crustal thickness

	Min (mGal)	Max (mGal)	Mean (mGal)	Root mean square (mGal)	
GOCE gravity anomaly	−62.3	89.2	−0.4	18.14	t6.1
GOCE Bouguer anomaly (BG)	−179.6	320.3	−5.9	105.8	t6.2
BG corrected isostasy; Te = 05 km, rho = 500 kg/m^3	−120.9	61.0	−26.2	25.0	t6.3
BG corrected isostasy; Te = 15 km, rho = 500 kg/m^3	−137.5	59.8	−26.2	24.7	t6.4
BG corrected isostasy; Te = 20 km, rho = 500 kg/m^3	−143.5	59.0	−26.2	24.6	t6.5
BG corrected isostasy; Te = 05 km, rho = 300 kg/m^3	−111.4	128.3	−18.1	44.0	t6.6
BG corrected isostasy; Te = 15 km, rho = 300 kg/m^3	−111.5	129.0	−18.1	44.1	t6.7
BG corrected isostasy; Te = 20 km, rho = 300 kg/m^3	−111.3	128.6	−18.1	44.2	t6.8
BG corrected sediments only	−145.4	348.8	20.7	105.1	t6.9
BG corrected isostasy and sediments; Te = 05 km, rho = 500 kg/m^3	−67.3	82.1	0.33	16.1	t6.10
BG corrected isostasy and sediments; Te = 15 km, rho = 500 kg/m^3	−88.1	79.1	0.33	16.3	t6.11
BG corrected isostasy and sediments; Te = 20 km, rho = 500 kg/m^3	−94.0	76.9	0.34	16.5	t6.12
BG corrected isostasy and sediments; Te = 05 km, rho = 300 kg/m^3	−78.3	140.6	8.5	40.8	t6.13
BG corrected isostasy and sediments; Te = 15 km, rho = 300 kg/m^3	−82.3	143.3	8.5	41.0	t6.14
BG corrected isostasy and sediments; Te = 20 km, rho = 300 kg/m^3	−83.0	146.1	8.5	41.2	t6.15

Geographical window Longitude (−10°,32°), Latitude (−6°,30°). BG = Bouguer anomaly, Te = elastic thickness of the flexure model, rho = density contrast at isostatic Moho

The adequateness of this reduction is again evident when we consider the amplitude variation and the root mean square of the Bouguer values (Table 2). Here it is seen how the starting amplitude of the Bouguer values is reduced successfully after correcting for isostatic crustal thickness and then for sediments. The gravity anomaly, Bouguer field, the Bouguer field reduced for the gravity effect of the isostatic Moho (Te = 15 km and density contrast rho = 500 kg/m^3), and the final Bouguer residual reduced for the isostatic Moho and the sediments are mapped in Fig. 3a–d. We cannot exclude in principle that the residual Bouguer field is still affected by gravity signals generated at Moho level, but we find that the isostatic Moho is effective in reducing the long-wavelength and high-amplitude part of the Bouguer field, allowing the smaller scale features to be visible. The residual field may still contain some gravity from the Moho, but nonetheless the scope of enhancing the signal generated at shallower crustal levels is successfully accomplished.

2.3 Analysis of the Residual GOCE Gravity Field

The Bouguer gravity residual (Fig. 3d) represents the signal produced by the crustal density inhomogeneities of the basement underlying the sediments. The basement has undergone volcanic activity, orogenetic formations, and metamorphism, documenting events that presumably have affected also the

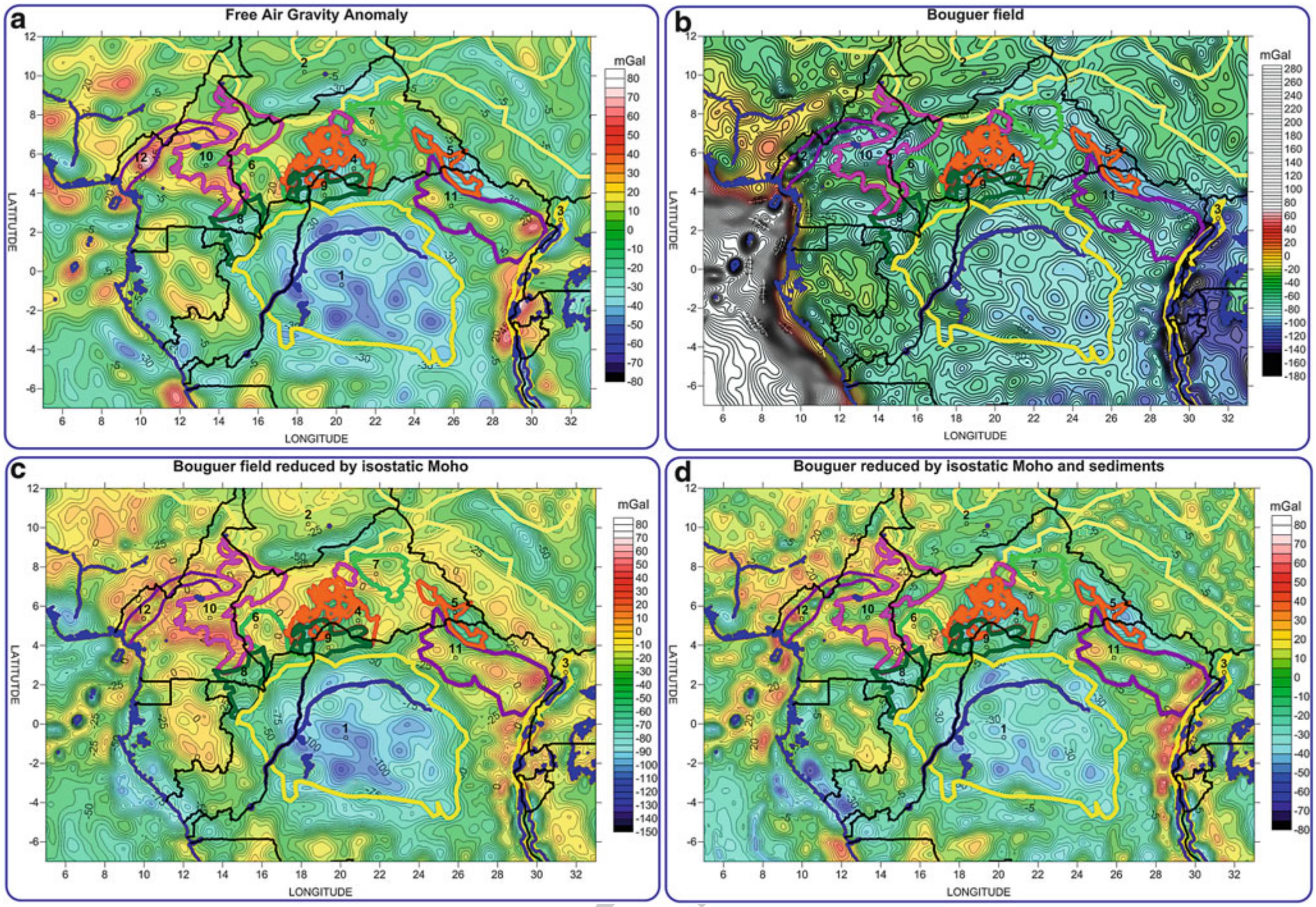

Fig. 3 The GOCE gravity fields: (**a**) gravity anomaly; (**b**) Bouguer field; (**c**) Bouguer field reduced for the gravity effect of the isostatic Moho (Te = 15 km and density contrast rho = 500 kg/m^3); (**d**) final Bouguer residual reduced for the isostatic Moho and the sediments

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crust, not only geologic units (for a general overview De Wit et al. 2008b). Exposed volcanic activity is the product of magmatic processes that reached the surface, but which are always accompanied by intrusions and underplating, increasing the density of the lower crust, and implying a thin lithosphere in order to allow the melting process to be initiated.

The residual GOCE values can be matched to several of the geologic units we marked in Fig. 2. We quantify this relation by calculating histograms of the gravity values pertaining to an identified geologic unit. The reduction of the Bouguer values for sediments and isostatic crustal thickness is well illustrated in the histograms over the Chad basin before reduction and after the first and second reduction stage (Fig. 4a). The Bouguer values are strongly negative, are a bit reduced by correction for the crustal thickness variations, and are scattered around zero after correcting for the sedimentary cover. This shows that the underlying basement has local anomalies, with varying positive and negative density contrast, the long range systematic signal having been reduced. The histogram for the free air gravity anomaly is also shown for comparison, and is slightly more negative than the Bouguer values reduced for crustal thickness and sediments effect. The histograms of the Bouguer residuals for the other selected geologic domains are shown in Fig. 4b. The negative values are found for the Pleistocene dunes and sediments that cover the Congo basin (unit 1), the nappes of the Oubanguides fold belt in the northern margin of the Congo craton (unit 4), and the Precambrian units Haut Mbomou of Precambrian age, presumably also nappes of a fold belt. Positive values are found for the 2.5 Ga metamorphic range bordering the craton, as the Kibalian range (11) and the Ouham Pende (10) domains, where the geologic map documents presence of dense rocks as amphibolites and magmatic products. The most positive residual values are found in the Kibalian range (11), along a lineament which does not have a counterpart on the geologic map, and therefore is of great interest. It is a major discontinuity that is missing on the geologic map and surely marks an important geologic metamorphic or magmatic event that produced increased rock density, generally related to a collisional boundary.

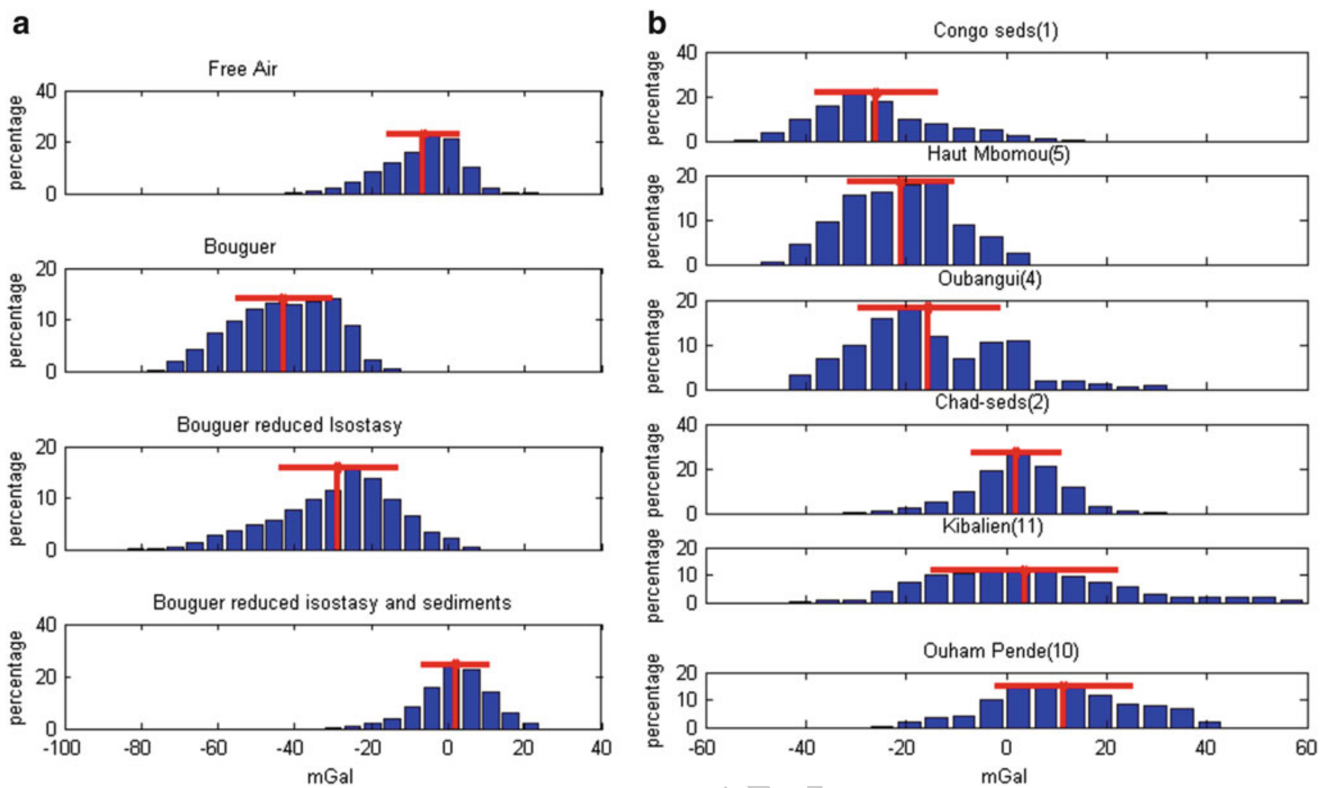

Fig. 4 The histogram of the observed and residual gravity values for a certain geologic domain. (**a**) Geological domain is the Chad basin. The histograms refer to the GOCE free air values, the GOCE Bouguer values, the GOCE Bouguer values reduced for crustal thickness variations, and then reduced also for sediments. (**b**) Histograms of the GOCE isostatic-sediment reduced Bouguer residuals for increasingly dense geologic domains. The numbers refer to the numbered domains of Fig. 2. *Red horizontal line*: average value of anomaly. *Vertical red line*: standard deviation of the values

Discussion and Conclusions

The Oubanguides and Kibalian units must be several km thick, considering that the anomalies reach up to 50 mGal. A rough estimate assuming the effects of an infinite plate layer of finite thickness, analogous to the Bouguer plate, gives us 3 mGal for a 1 km thick unit with 100 kg/m^3 density contrast. Referred to a standard upper crust of 2,670 kg/m^3, a basalt, gabbro, amphibolite reaches 200–300 kg/m^3 density contrast, a sediment nappe a negative density contrast of 170 kg/m^3. This translates to 9 km thick metamorphic unit of Kibalian and 5 km of nappes in the Oubanguides fold belt, demonstrating that the density inhomogeneities of the crust are severely affected by the geologic units reaching the surface. The lateral extent and considerable thickness implies these units to be representative of major geologic unit which must be considered when the evolution and accretion of the Congo craton is studied (e.g. Toteu et al. 2004). After having ascertained that the precision of the GOCE observations is enough to discriminate geologic units, we use the anomalies to follow the units where they are absent (or interpolated) on the geological map, either because they are covered by other units or because of lack of direct observations. The extent of the anomaly is a means to optimize the planning of integrative terrestrial geologic cartography. The linear positive anomaly in the Kibalian belt or North East Congo block (11) is much narrower than the geologic unit marked as uniform in the geologic map. This demonstrates that there is considerable difference in the rocks of this unit, with a marked narrow belt of rocks with increased density that must be due to a major geologic event that produced this increase in density. This belt could be of interest in the research of natural resources, as it merges at its southern extreme with the Kilo-Moto greenstone belt, where a large gold-deposit is productive, the Kilo-Moto gold mine (Agayo 1982).

The results show that for the first time a geodetic gravity satellite has the required precision and resolution to distinguish geologic units of different age and rock type. The data are available globally, so the procedure illustrated here has a direct applicability in other areas of Africa and east Asia, providing a remote geophysical tool for geologic mapping. The results for North Central Africa show that tectonic events since 2.5 Ga have left an imprint on the densities of the crust, even greater than the more recent Central African Rift or Shear zone which has been thought to have an impact also at deeper levels (Ebinger and Sleep 1998). The Central Africa Rift (or Shear zone) develops in NE_SW orientation starting from the Cameroon Volcanic line and suddenly bends clockwise by about 90° to a NW-SE orientation. This rift takes up the direction of a succession of geologic elements all bearing the same orientation, and having an alternation of high and low densities, as evidenced by the GOCE data, that show aligned alternating gravity lineaments parallel to the eastern segment of the CAR rift and leading to the Eastern margin of the Congo craton, and being near to parallel to the main arm of the east African rift. Towards the western side of the Congo craton a similar alignment of gravity highs and lows is found, the most western one following the basins of the western African coastline. The rifting of America and Africa then was superimposed on this package of geologic subunits. It demonstrates a long lasting orientation of macro-tectonic forces that could be a further evidence to the longlasting mantle cell proposed by Collins et al. (2011) for the Phanerozoic orogenic systems dating back to 550 Ma. In the classification of Collins the sequence east of the Congo craton would be an internal orogenic system, extending the sequence to 2.5 Ga, and showing that the megacell not only leads to a sequence of orogens but involves backward rifting, in case the plate does not follow the movement of the cell as compact unit, but tears at a point of weakness, leading to rifting.

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AQ1. “Rummel et al. 2011” is cited in text but not given in the reference list. Please provide details in the list or delete the citation from the text.
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