GOCE OBSERVATIONS IN EXPLORATION GEOPHYSICS

Carla Braitenberg, Patrizia Mariani, Tommaso Pivetta

Department of Geosciences, University of Trieste, via Weiss 1, 34100, Trieste, Italy, email: berg@units.it

ABSTRACT

The satellite GOCE has produced an extraordinary global gravity field with a spatial resolution of 80 km at a precision of 1-2 mGal. When considering geologic structures, the wavelengths of interest for exploration purposes are smaller. We show that the GOCE data produce a new quality assessment tool for fields of higher resolution, which all necessarily rely on terrestrial data. The space-borne control of terrestrial data is necessary in order to obtain 100% reliability of existing data or to assess the quality of newly acquired data. We propose a scheme for controlling and testing the quality of higher resolution data, for example airborne campaigns or the EGM08 global gravity field. EGM08 has the higher resolution of 10 km, but with varying quality, depending on the terrestrial data availability. We show how the quality assessment can be made using the GOCE data, giving confidence in the successive modelling results. Specifically we consider the African continent. Africa is an example where terrestrial data area scarce and where the reliability of EGM08 is very variable, jeopardizing the usefulness of the field if the quality assessment with the GOCE data is not fulfilled.

1. INTRODUCTION

At time of writing the second edition of the GOCE derived Earth Gravity Models have been published ([1],[2],[3]), with maximum degree of the spherical harmonic expansion of N = 250, 240 and 210, respectively. All three fields are independent of terrestrial data, as they have been developed incorporating the satellite missions GRACE and GOCE. The GOCE observations are global, except for a circular area above the two poles, and thus independent of the particular conditions of a geographical area of interest. The maximum degree of N = 250 limits the spatial resolution to about 80 km (20000 km/250). Compared to existing global gravity fields as EGM08 [4] and EIGEN05C [5], with maximum degree N=2159 and 360, respectively, this may seem of no advantage. This argument does not consider the fact that the higher resolution is nominal, tied to the degree of the spherical expansion and does not express the varying availability of the terrestrial data. The realistic local resolution of these latter fields above the level (20000/120 km) depends entirely on the database of terrestrial data that entered the calculations. The models are given as gridded data at a certain height level or in terms of Stokes coefficients, with which the gravity values can be globally calculated. The models are accompanied with the error values of the Stokes coefficients, which give an average estimate of the error levels for each degree, but which are difficult to translate into a local quality assessment of the fields. The lack of knowledge of the local error hampers the use of these data in geophysical exploration, where reliability of the data is an important issue. We show that the GOCE data are adequate to assess the quality of terrestrial observations, also if the spatial resolution of the terrestrial data is higher than that of GOCE. We show with the example of Central North Africa, that the study of geological structures requires a field with higher resolution than that of GOCE, as is the EGM08 field, but that not all areas are reliable and that GOCE is necessary to assess in which areas the EGM08 field can be used to study the structures.

2. SIZE OF GEOLOGICAL STRUCTURES IN AFRICA

Africa is a continent where geophysical data are insufficiently known over large areas. The social and economic growth of the country relies on a better knowledge of the crustal and lithospheric structure, which is essential in the exploration of geo-resources and in the risk assessment due to seismic and volcanic hazard. The geological units are the essential starting point for further studies, and can be seen in the geological map [6]. The full extent of the geological units cannot be evaluated when these are concealed below a superficial cover, because the geological mapping relies on identifying surface rocks. The gravity field is one means to delineate the full extent of the structures as long as they bear a density change with respect to the neighbouring rocks. In order to distinguish the units the gravity field must have a resolution that is smaller than the units we are interested to map. The main geological structures that are presumably accompanied by a density variation are rifts and their associated basins, sedimentary basins in general, magmatic intrusions and deposits, mobile belts and fold belts, orogenic ranges, faults. In Fig. 1 we show a schematic map of the geology in North-Central Africa, highlighting the principal features. We have summarized the sizes of the geological units, in terms of width and length in Tab. 1. We see that interesting geological structures have sizes below 100km, which demonstrates that the task of improving the knowledge

Proc. of ‘4th International GOCE User Workshop’, Munich, Germany 31 March – 1 April 2011 (ESA SP-696, July 2011)

of the African crust requires a field with the resolution of at least 10 km, the resolution of EGM08.

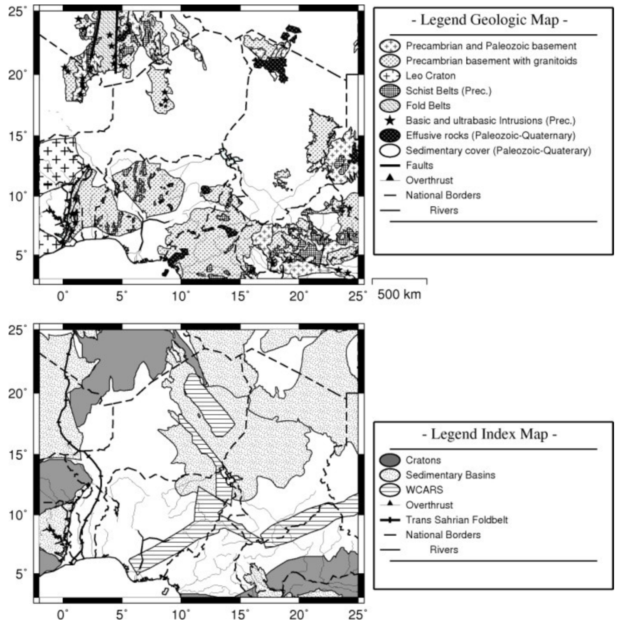

Figure 1. Geological map of Central North Africa showing principal geological units and features. WCARS: West and Central African Rift System (after [7]).

Geologic unit	Width	Length
Central Africa Rift	50-150 km	800 km
Chad "Banana high"	100 km	1200 km
Mobile belt Western African craton	30-100 km	1500 km
Chad basin	800 km	800km
Tibesti volcanic province	100km	400 km
Effusive rocks Cameroon	100km	100-200km

Table 1. Width and length of relevant geological features in North-Central Africa.

3. GRAVITY AND TENSOR FIELD FOR AFRICA

The gravity field and the vertical derivative of gravity (Tzz), both corrected for topography, leading to the Bouguer anomaly and the terrain corrected Tzz tensor component are illustrated in Fig. 2. Comparison with the geological map (Fig. 1) shows that the fields reflect geological units as: the fold belt lining the West African craton, the West and Central African rift system (WCARS), the Benue trough, the volcanic Cameroon line. An anomaly which has no geologic counterpart is the banana shaped high in Chad (Chad lineament): it is 1200 km long, 100km wide and its source-rocks are entirely buried by the sediments of the Chad basin (see also [7]). We can see that many geologic units marked in the map of Fig. 1 can be studied in more detail by modelling the gravity or gravity gradient field shown in Fig. 2 (see also [8]). A key question is to what extent the field of Fig. 2 is reliable, and can be considered to be free from errors. One gravity signal which is not identified in the geological map is the strongly positive signal positioned at longitude 7°, latitude 10°; another one is the banana shaped Chad lineament.

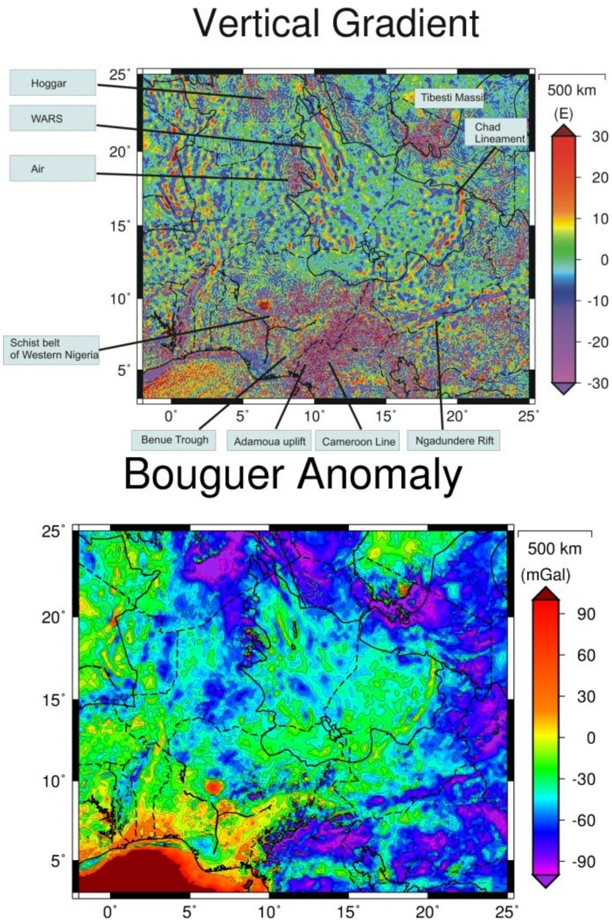

Figure 2. Vertical gravity gradient corrected for topography and Bouguer anomaly, both derived from EGM08 [8] for Central-North Africa. The fields representing principal geological units are marked on the vertical gradient field. Calculation height 4000m. Rivers: black lines; basin outlines: black lines; national borders: dashed lines.

In Fig. 3 the Bouguer gravity field for the GOCE model is shown. Here we have used the gravity anomaly of the timewise approach [1] which has the highest degree between the three GOCE- EGM models direct [2] and spacewise [3]. The maximum degree in the spherical harmonic expansion is N = 250, which corresponds to a wavelength of 80 km. We see that many features of the geologic map show up in the GOCE-Bouguer map. Nonetheless the maps of Fig. 2 trace some more details. The problem with Fig. 2 is that we need a quality assessment to be confident in the reliability of the anomalies, in particular for those signals which do not have a counterpart in the geologic map.

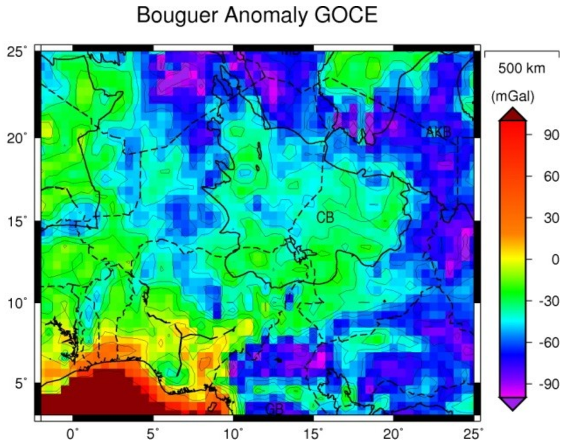

Figure 3. The Bouguer anomaly for the GOCE-derived gravity field, according to the timewise earth gravity model [1]. Calculation height 4000m. CB: Chad basin; AKB: Al Kufra basin; GB: Ghadames Basin. Rivers in black; basin outlines: black lines; national borders: dashed lines.

4. ESTIMATED ERROR OF MEASUREMENTS

Consider a gravity campaign of N measurements g_i, $i=1,N$, with average distance between the measurements of r_g as shown in Fig. 4. In order to compare these observations with the gravity grid derived from GOCE, with grid-sampling of r_{GOCE}, K observations must be averaged to produce one downscaled value $\bar{g}_{lm}^K$. The number of values K depends on the ratio of the original sampling r_g and the grid sampling of GOCE r_{GOCE}.

$$\bar{g}_{lm}^K = \frac{1}{K}\sum_{i=1}^{K} g_i \tag{1}$$

Assuming Gaussian distribution of the observation errors, we define the root mean square error of the observations to be σ_g; the error on the downscaled value is then:

$$\sigma_K = \alpha\, \sigma_g/\sqrt{K} \tag{2}$$

In equation (2) we have introduced the correction factor α, that allows for a bias due to inhomogeneous sampling of the gravity field by the terrestrial data. The difference between the gravity value of the GOCE derived field and the downscaled observation $\bar{g}_{lm}^K$ is an experimental estimate of σ_K as we know the error on the GOCE measurement σ_{GOCE}. The root mean square (rms) error on the difference between the GOCE-derived gravity field and the downscaled error should be then:

$$\sigma_{diff} = \sqrt{\sigma_K^2 + \sigma_{GOCE}^2} \tag{3}$$

We therefore obtain an estimate of the observation errors of the gravity campaign by:

$$\sigma_g = \frac{\sqrt{K}}{\alpha}\sqrt{\sigma_{diff}^2 - \sigma_{GOCE}^2} \tag{4}$$

This approach allows us to make a regional quality assessment of the observation errors, and to obtain differences of data quality by analyzing the spatial variation of σ_{diff}.

An illustration of the above method is given in Fig. 4.

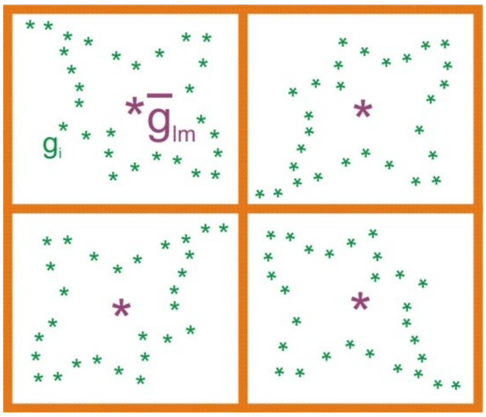

Figure 4. Illustration of the downscaling of observed data and the quantitative quality assessment through the GOCE-gravity grid.

5. QUALITY ASSESSMENT OF EGM08 IN AFRICA

We proceed to evaluate the quality of EGM08 in Central North Africa. We calculate the gravity anomaly fields on a 0.5° by 0.5 ° grid at 4000m height for both GOCE and EGM08 and the absolute value of the difference field (EGM08-GOCE). These three fields are seen in Fig. 5 for Central North Africa. The absolute values of the residual range between 0 and 50 mGal. The differences must be due to problems in the EGM08 field, because the mean error of the GOCE field does not have any considerable variations over Africa. The areas where the two fields agree are those in which the data coverage of terrestrial was best. In order to further explore the observations, we compare a high-quality region with a low-quality region in terms of the

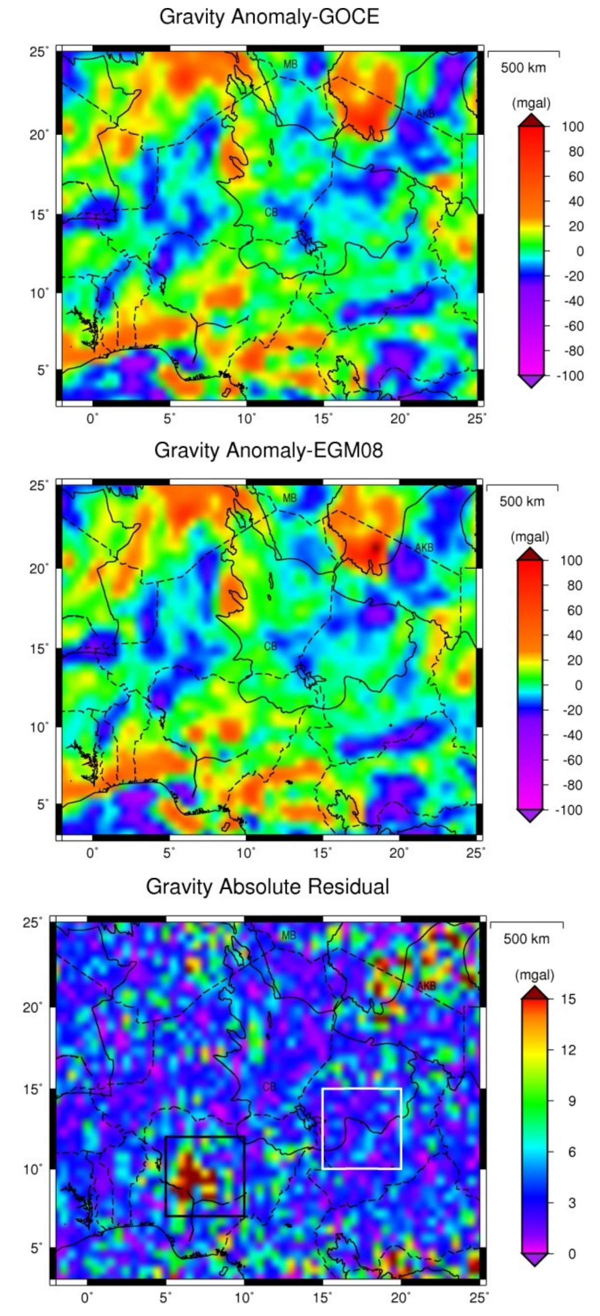

Figure 5. Gravity anomaly up to degree and order N=250 for the models a) EGM08 [4] and b) GOCE-TIM [1] and c) absolute difference between the two fields. The black square shows the area of bad data, the white square the area with good data. Rivers in black; basin outlines: black lines; national borders: dashed lines. The differences between the two fields are due to erroneous terrestrial data or lack of terrestrial data in the model EGM08.

histogram of the residuals. The black square in Fig. 5c marks a 5° by 5° area with degraded quality, which is compared to a square (white) of equal size of relatively high quality. The histograms of the residuals (Fig. 6) illustrate the higher values for the black square. A statistical measure of the quality of EGM08 is given by the root mean square (rms) deviation from the mean calculated on sliding windows of 2° by 2°. The result is shown in Fig. 7.

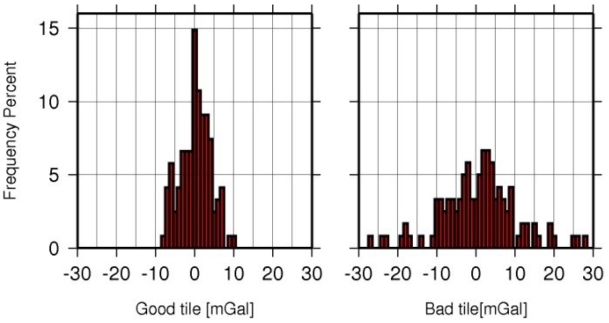

Figure 6. Histogram of the gravity anomaly residual between EGM08 and GOCE (up to degree and order N=250). Left: white square of Fig. 5c. Right: black square of Fig. 5c.

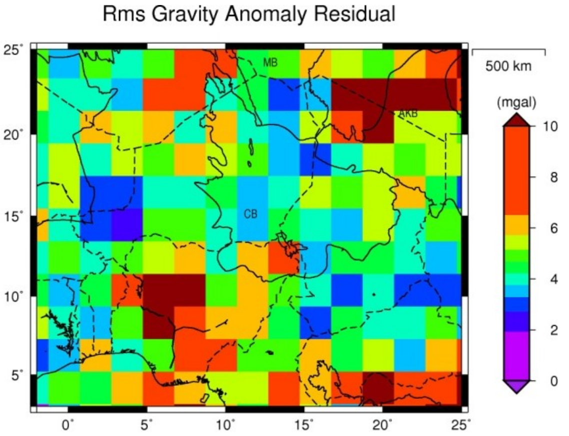

Figure 7. Root mean square of the gravity residual on 2° by 2° tiles.

The most frequent value of the rms deviation is 4 mGal, and has greatly increased values (up to 20 mGal) in some regions, indicating the locations where the terrestrial data have problems. This is well seen in the

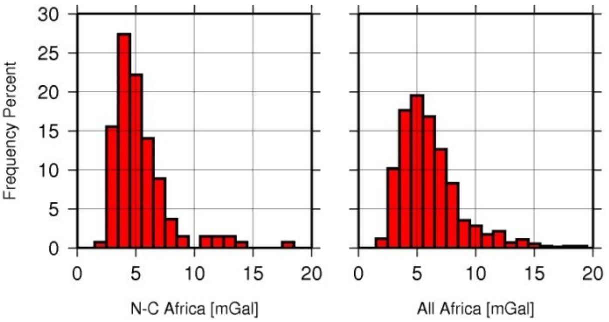

Figure 8. Histograms of the rms deviations on 2° by 2° tiles. Left: north-central Africa; right: all Africa.

histogram of the rms shown in Fig. 8. Here we compare the distribution of the tiles in central-north Africa with those of the entire African plate (see Table 2 for coordinates of the windows). Taking practical use of the quality control, the 2° by 2° tiles on which a reliable analysis of the observation is not recommended, and where a revision of the terrestrial data should be made may be blocked. The average rms over the entire African continent of EGM08 with respect to GOCE is 6.7 mGal for the land areas; over wet areas, including the ocean, the difference is significantly smaller (4.7 mGal). The complete quality assessment over Africa is given by the map of Fig. 8 that shows again the rms over 2° by 2° tiles. The regions straddling the equator are those with the greatest differences, presumably due to the highly developed vegetation and the difficult accessibility, and therefore poor coverage with terrestrial data.

Area	Lo1	Lo2	La1	La2	Aver. mGal	Rms mGal
Land	-23	57	-43	40	0.0033	6.7
Ocean	-23	57	-43	40	0.0032	4.7
Central-North Africa	-2	25	3	25	0.0006	5.9

Table 2. Statistical parameters of the quality control of EGM08: average difference (Aver.) and root mean square deviation from the mean (rms) respect to GOCE. Degree and order N=250 for both EGM08 and GOCE. Grid spacing 0.5°. Lo1, Lo2, La1, La2: minimum and maximum longitude and latitude values of the geographical window. Calculation height 4000m.

6. DISCUSSION

The terrestrial data which were used in the formulation of the EGM08 grid were available on grid-points of 5' by 5' (N. Pavlis pers. comunication), which corresponds to 36 points which enter the averaging process to obtain the 0.5° by 0.5° grid we used to compare the GOCE-values. The quantitative estimate of the error of the original observations is difficult to achieve in this case, because we compare the GOCE values with data synthesized from the EGM08 model, which are average values, having been calculated from the spherical harmonic expansion. On top of this, the EGM08 used gridded terrestrial data, not the original observations, so a further averaging process has been applied. Our method can be used to quantify the relative quality variations of the EGM08 field, discriminating the regions in which presumably the original data were problematic. We find that the higher quality areas in Africa have rms differences on 2 by 2° tiles of less than 5 mGal, and that the field is reliable because it correlates very well with known geological features. The areas identified by the GOCE-field as bad data, due to the greater residuals (e.g. over 10 mGal), should not be used for the further geological analysis.

We propose the method to be used in the quality-control of aero gravity campaigns, where the spatial distribution of the acquired data is homogeneous and is made at constant height. The homogeneous data coverage eliminates the possible bias in the acquired data towards values along the measurement paths, bias which enters the calculation of the average in the down-scaling process (Eq. 1). Starting with single observations the estimate of the measurement error (Eq. 4) should be more realistic than the value obtained for the quality assessment of EGM08. Our method is also applicable for observations made on terrain, especially over flat topography, where the coverage can be made homogeneously. We expect that the method is difficult to apply for terrestrial data in high topography, as the measurements are made preferentially along the valleys; the downscaled value will therefore be biased towards the gravity in the valleys producing an a-priori difference with the value derived from GOCE. In this case the observation error will be over-estimated, if an empirical correction-factor (α in Eq. 2) is not applied.

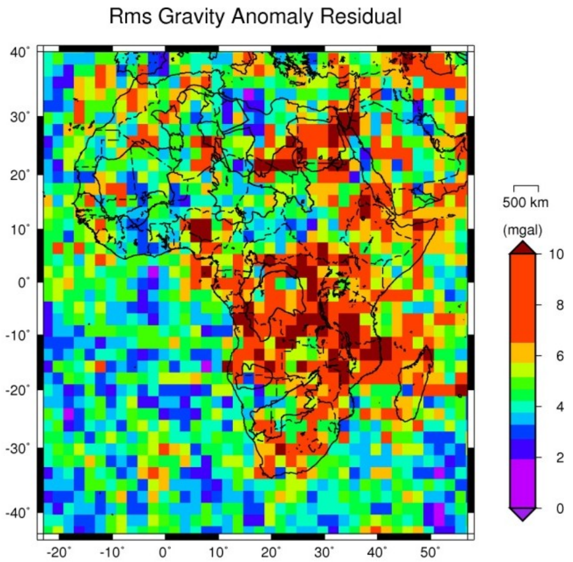

Figure 8. Root mean square of the gravity residual on 2° by 2° tiles for all of Africa.

7. CONCLUSIONS

In remote areas the quality control of newly acquired gravity data presents a significant problem for exploration geophysics. The spatial resolution of the gravity campaigns is typically higher than the resolution of GOCE (80 km), due to the requirement to detect geological structures with dimensions smaller than 80 km. We have shown that the field of GOCE conveys an innovative tool for the quality assessment of these higher-resolution fields. The method consists in assessing the error of the downscaled observations and using it to estimate the error of the original higher-resolution data points by applying basic statistical laws of error-propagation. Our first application of the method over the African continent has shown that the terrestrial data used to construct the EGM08 gravity model were of varying quality which is reflected in a variable correctness of the EGM08 field. We are able to identify the areas with greater errors, where use of the model is not recommended, and distinguish them from areas with good data, which we use for studying the geological units of Africa. Our method shows that the GOCE data have an important role in the quality control of gravity data with higher resolution than the inherent resolution of GOCE.

8. ACKNOWLEDGEMENTS

We thank Juraj Janák (Technical University of Bratislava) for discussions and Alan Reid for reading the manuscript. We thank Statoil for financial support; we thank the Italian Space Agency (ASI) for supporting the GOCE-Italy project. We acknowledge the use of the GMT-mapping software of Wessel and Smith [9] and the use of the EGM2008 gravity model [4].

9. REFERENCES

1. Pail R., Bruinsma S., Migliaccio F., Foerste C., Goiginger H., Schuh W.-D, Hoeck E, Reguzzoni M., Brockmann J.M, Abrikosov O., Veicherts M., Fecher T., Mayrhofer R., Krasbutter I., Sanso F., Tscherning C.C. (2011). *First GOCE gravity field models derived by three different approaches*. Jounal of Geodesy, in review.
2. Bruinsma, S.L., Marty, J.C., Balmino, G., Biancale, R., Förste, C., Abrikosov, O. & Neumayer, H. (2010). GOCE *Gravity Field Recovery by Means of the Direct Numerical Method,* presented at the ESA Living Planet Symposium 2010, Bergen, June 27 - July 2, Bergen, Norway, 2010.
3. Migliaccio, F., Reguzzoni, M., Sansò, F., Tscherning, C.C., Veicherts, M. (2010). *GOCE data analysis: the space-wise approach and the first space-wise gravity field model.* Presented at the ESA Living Planet Symposium 2010, Bergen, June 27 - July 2, Bergen, Norway, 2010.
4. Pavlis N.K., Holmes S.A., Kenyon S.C., Factor J.K. (2008). *An Earth Gravitational Model to degree 2160: EGM2008*. Presented at the EGU General Assembly, Vienna, Austria, April 13-18, 2008.
5. Förste, C., Flechtner, F., Schmidt, R., Stubenvoll, R., Rothacher, M., Kusche, J., Neumayer, K.H., Biancale, R., Lemoine, J.-M., Barthelmes, F., Bruinsma, S., König, R., Meyer, U. (2008). *EIGEN-GL05C - A new global combined high-resolution GRACE-based gravity field model of the GFZ-GRGS cooperation.* Geophysical Research Abstracts, Vol. 10, EGU2008-A-03426, SRef-ID: 1607-7962/gra/EGU2008-A-03426, 2008
6. CGMW/UNESCO (1990). *International Geological Map of Africa at 1:5 000 000.* CGMW/UNESCO, Paris.
7. Braitenberg C., Mariani P., Ebbing J., Sprlak M. (2011) *The enigmatic Chad lineament revisited with global gravity and gravity-gradient fieldsThe Formation and Evolution of Africa: A Synopsis of 3.8 Ga of Earth History,* Geological Society, London, Special Publication Vol.357, in press.
8. Braitenberg C., Mariani P., Reguzzoni M., Ussami N. (2010) *Goce Observations for detecting unknown tectonic features,* Proc. 'ESA Living Planet Symposium', Bergen, Norway 28 June – 2 July 2010 (ESA SP-686, December 2010)
9. Wessel, P., Smith, W. H. F. (1998). *New, improved version of generic mapping tools released.* Eos, Transactions, American Geophysical Union, 79(47), 579.