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Comment on 'A crustal thickness map of Africa derived from a global gravity field model using Euler deconvolution' by Getachew E. Tedla, M. van der Meijde, A. A. Nyblade and F. D. van der Meer

Alan B. Reid,[1,2] Jörg Ebbing[3,4] and Susan J. Webb[5]

[1] *Reid Geophysics Ltd, Eastbourne, UK. E-mail: alan@reid-geophys.co.uk*
[2] *School of Earth and Environment, University of Leeds, Leeds, UK*
[3] *Geological Survey of Norway (NGU), Trondheim, Norway*
[4] *Department of Petroleum Engineering and Applied Geophysics, Norwegian University of Science and Technology (NTNU), Trondheim, Norway*
[5] *School of Geosciences, University of the Witwatersrand, Johannesburg, South Africa*

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SUMMARY

We discuss a recent publication by Tedla *et al.*, which presents a crustal thickness map of Africa determined by Euler deconvolution of gravity. In our comment, we first outline the limitations of the data set used by the authors and the deleterious effects of working with free air gravity. Next, we discuss the grievous parameter choices (grid interval, Euler window size, structural index) and incorrect assumptions made by the authors and their serious effects on the results. Finally, we demonstrate with two examples why their results are not helpful in understanding crustal thickness and consequently the tectonic history. This is not specific to Africa, but also true for the application to other parts of the Earth.

Key words: Satellite geodesy; Gravity anomalies and Earth structure; Dynamics: gravity and tectonics; Crustal structure.

1 INTRODUCTION

Tedla *et al.* (2011) present a new crustal thickness estimate for Africa, which is based on Euler deconvolution of a global gravity field model. Interpretation of the gravity field potentially offers valuable insights into the crustal structure of Africa because no deep seismic data are available for large parts of the continent. Seber *et al.* (2001) demonstrated how careful analysis of the gravity field over Northern Africa and a discussion of the isostatic state can help to improve our understanding. However, for parts of Africa their estimates are clearly marked as geological interpretations, as no seismic constraints were available.

Since that study, more accurate gravity data from satellites and combined models (Förste *et al.* 2008; Pavlis *et al.* 2008; Pail *et al.* 2011) and more information from seismological studies has become available (e.g. Nyblade *et al.* 2008; Fishwick 2010). These new data should improve our understanding of the crust and lithosphere of Africa, as passive seismological studies can provide crustal thickness estimates to calibrate and validate crustal thickness estimates based on gravity data.

Although, there is a need for new studies for Africa, we would like to comment on the choice of methodology applied by Tedla *et al.* (2011) and the results they obtained. We outline why their approach is flawed and their use of the free air gravity data is inappropriate. Our comment first addresses the data use, then discusses how the analysis was performed and finally presents two examples to illustrate the limited and misleading results generated by their work.

2 THE GLOBAL GRAVITY MODEL

Although wrongly cited, Tedla *et al.* (2011) apparently use the EIGEN-GL04C global gravity model published by Förste *et al.* (2008). This is a spherical harmonic model, which is based on a combination of satellite and terrestrial data up to degree and order 360. The degree and order indicates that wavelengths longer than 1° ($\lambda = 110$ km at the equator) are represented in the data.

In contrast, EGM-2008 (Pavlis *et al.* 2008) provides Earth's external gravitational potential via a spherical harmonic model complete to degree and order 2159, with additional spherical harmonic coefficients extending up to degree 2190 and order to 2159 from which gravity data can be calculated with $5' \times 5'$ nominal resolution ($\sim 9 \times 9$ km on the ground at the equator).

In the inversion of gravity data to estimate crustal thickness, often a short-wavelength attenuation filter is applied (e.g. Ebbing *et al.* 2001). The filter is needed to suppress the gravity signal from crustal sources (e.g. sedimentary basins, intrusions), which otherwise affect the gravity inversion. Although the authors have effectively accomplished this by selecting the 360° data set, the largest sedimentary basins (e.g. the Taoudeni and Congo Basins) and sharp changes in Moho structure will have overlapping wavelength content.

In the free-air anomaly, as used by Tedla *et al.* (2011), the first-order signal is topography. We show in Fig. 1 the topography over the African continent for the spatial resolution of the EIGEN-GL04 model, which defines the (free-air) gravity anomaly on the ellipsoid (Förste *et al.* 2008). Topography is not constant for Africa and shows

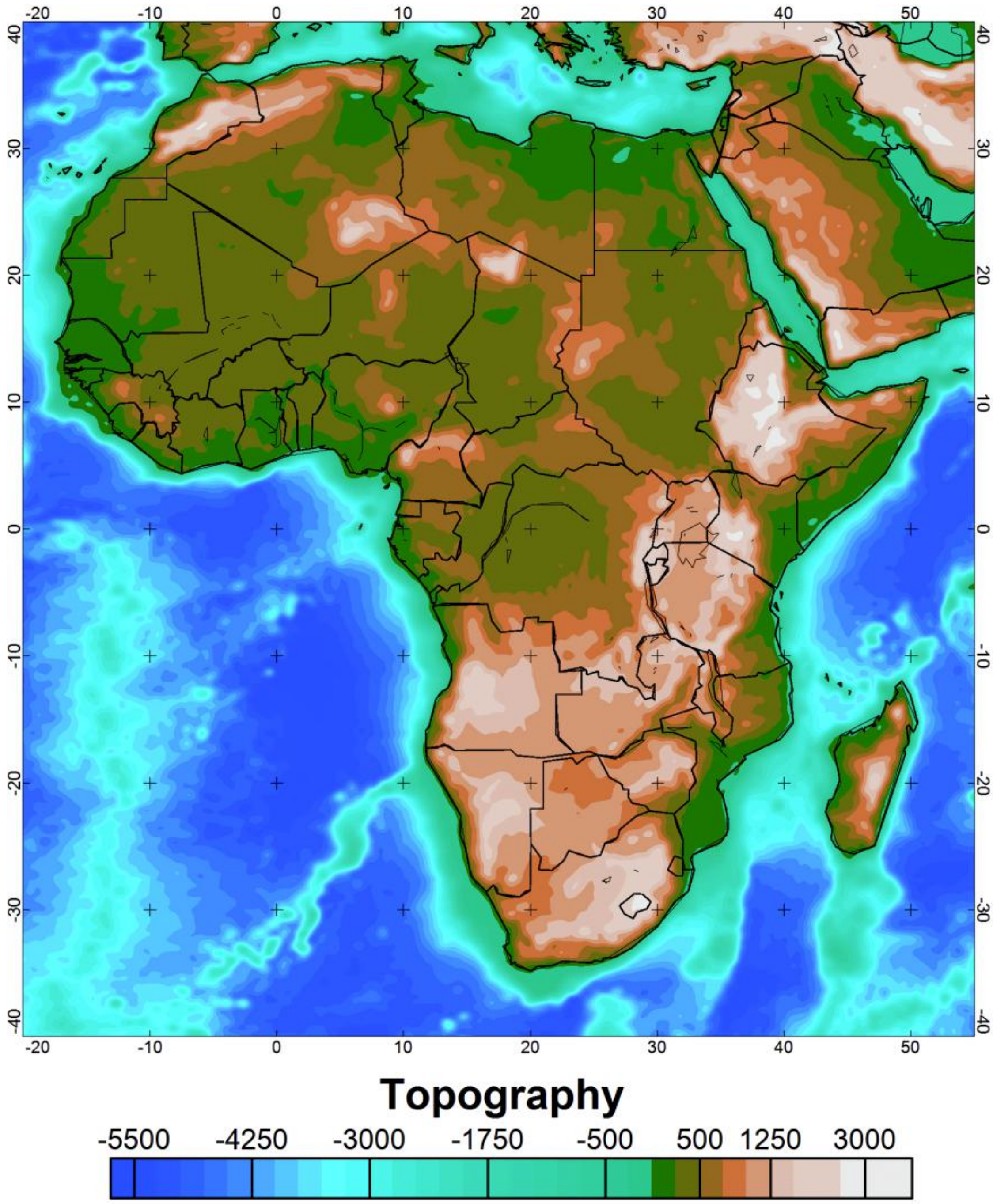

Figure 1. Long-wavelength topography of Africa based on ETOPO1. Wavelengths <10 km were removed from the map.

clear regional variations, which will be reflected in the gravity signal and crustal thickness. Conventionally, to illustrate crustal sources and crustal thickness, the gravity effect of topography is removed by calculating Bouguer anomalies.

This means that the use of the global gravity model may be well suited to estimate the crustal thickness, with the following two limitations.

(1) Crustal thinning at shorter wavelengths (i.e. <100 km) cannot be resolved and the topographic signal should be removed from the data. The topographic signal dominates the free-air anomaly.

(2) The gravity effects of large sedimentary basins must be recognized and included in any analysis.

Forward and inverse modelling of satellite fields is helpful, especially in combination with ground data. Over the scale of Africa, a simple gravity inversion would be misleading as different tectonic domains are present which result in variable thicknesses. These need to be constrained by seismic data.

3 USE OF EULER DECONVOLUTION

Euler methods as applied to geological interpretation were originally developed for use on magnetic field profile measurements (Thompson 1982) and extended to gridded data by Reid *et al.* (1990), who also recognized that it had potential for application to gravity data, but did not show any gravity models or examples. They derived an incorrect structural index for the gravity field of a finite step. Most subsequent work has concentrated on applications to magnetic fields, but work on gravity fields has been presented by a few workers. Three different approaches to the Euler deconvolution of gravity have been used.

(1) Klingelé *et al.* (1991) and Marson & Klingelé (1993) exploit Poisson's relation to recognize the fundamental relationship between gravity and magnetic fields from the same source and treat the vertical gradient of gravity as a pseudo-magnetic field, proceeding thereafter as if the data were magnetic data. They demonstrate that this approach is effective on an engineering scale (up to 1 km wavelengths).

(2) Keating (1998), Zhang *et al.* (2000) and Reid *et al.* (2003) work directly with gravity observations and their calculated or measured gradients and choose the structural index keeping in mind that they are dealing with gravity data.

(3) Stavrev (1997) and Stavrev & Reid (2007, 2010) recognize that the strict concept of homogeneity requires that all variables with the dimension [Length] should be included in the analysis. This allows them to treat more realistic model types including sources such as thick steps which cannot be fully located with a single (X, Y, Z) source point.

Approaches (1) and (2) above are restricted to models which can be located by a single (X, Y, Z) source point and display an integer non-negative structural index, because their derivation effectively assumes a power-law field fall-off with distance (Thompson 1982). Tedla *et al.* (2011) use approach (2). They use commercial software obtained from Geosoft. This commercial package is an exact (and licensed) implementation of the algorithm published by Reid *et al.* (1990). As Reid *et al.* (1990) make clear, this approach is powerful but it has limitations and can only be expected to produce reliable results with carefully chosen grid interval, window size and structural index.

In our view, Tedla *et al.* (2011) make several errors in their data preparation and in the choice of processing parameters, sufficiently serious to cast grave doubt on the validity of their results. We enumerate them here.

3.1 Data preparation

The paper itself has sparse information about the data preparation. It refers to a high-pass filter with 1000 km cut-off wavelength and mentions a 0.25° grid used for input to the Euler software, but that is all. The authors have been kind enough to provide extra detail (G. E. Tedla, personal communication, 2011). The original data from the EIGEN-GL04C gravity model were in the spherical geodetic coordinate system with a grid interval of 0.25°. They were then projected to a World Mercator system and resampled to 5-, 6- and 7-km grid intervals and one of these grids was used for input to the commercial Euler deconvolution software.

Even assuming perfect input data, we see two problems with this procedure.

(1) The reprojection introduces a scale distortion at significant distances from the equator. At the latitude of Cairo (30° N) the scale is exaggerated by 15 per cent. At the latitude of Cape Town (34° S), the scale is exaggerated by more than 20 per cent. The lateral scale exaggeration will give rise to the same depth exaggeration, using almost any numerical depth estimation procedure. To overcome this, it would be necessary to use something like a Lambert Conformal Conic projection and a banding approach.

(2) The resampling interpolates from an original spherical harmonic model containing wavelengths longer than 1° via a grid interval of 0.25° (23–28 km, depending on latitude) to 5–7 km. The Nyquist wavelength (shortest wavelength represented—Nyquist 1928) in the original data source is about 110 km. The interpolation necessarily adds no independent information to the data set. The finest scale valid information that can possibly be in the data set is at the Nyquist wavelength of the original spherical harmonic model.

3.2 Choice of window size

Tedla *et al.* (2011) discuss the choice of window size and misquote Reid *et al.* (1990) as saying that 'reliable solutions could be obtained within a maximum depth of three times the window size or within a minimum depth equivalent to the window size'. On this basis, they use a window size of 20 km × 20 km. In fact, Reid *et al.* (1990) wrote 'Minimum depths returned are about the same as the grid interval. Maximum depths are about twice the window size'. This is altogether different. We hope that this comment will help set the record straight. We note that Tedla *et al.* (2011) tested a range of window sizes (their table 3) and settled on 20 km square because it gave the best overall fit to the chosen seismic stations in Tanzania. However, in fact, their fig. 4 shows that even this window size gives results which are so poor as to be near meaningless, showing almost no correlation between their depth estimates and seismic depths. The science underlying the window size rule is that any depth estimation procedure ultimately relies on the field curvature within the data window used. Any window smaller that the original data interval (before interpolation) is unlikely to contain a good sampling of any curvatures present. In our view this data set requires a window size between 100 km and 200 km square to be consistent with the spherical harmonic data used.

3.3 Choice of structural index

Tedla *et al.* (2011) misquote Mushayandebvu *et al.* (2001) as recommending the use of a structural index value of 0.5 for a horizontal sheet or sill-type interface for gravity data. The misquoted paper is exclusively concerned with magnetic fields and not gravity fields and does not at any point use or advocate the use of 0.5 as a valid SI for magnetic or gravity fields! The correct SI for the gravity field of a thin sheet is in fact 0.0, as is explained fully in Stavrev (1997). The equivalent magnetic SI is 1.0, as would be predicted on the basis of Poisson's relation between the two.

We would like to take this opportunity to remark that the SI value is not a 'tuning' parameter which may be chosen to achieve a 'best fit' to depths obtained by other means. It carries direct implications for the geometry of the source. Stavrev (1997) gives a full table of valid SI values and their implied geometries, both for the simplified case of idealized extreme source bodies and for the more general case.

3.4 Depth biases and depth uncertainties

The choice of input data and the data treatment will necessarily attenuate detail, so that the sharpest features in the gravity field will be represented by lower curvatures than exist in reality. This will bias any depth estimates to higher values. The small deconvolution window size will tend to return depths in the lower part of the possible range, biasing depth solutions towards shallower values. The high structural index (0.5 instead of zero) will bias deconvolution depths to deeper values (Reid *et al.* 1990). Since each of these biases will be associated with increased uncertainty and the biases operate in both directions, we think it has been possible to arrive at a plausible final average depth.

However the depth uncertainty returned by the deconvolution software is only the window statistical estimate of uncertainty. It assumes the gridpoints in the window are independent observations, which is certainly not true. The true uncertainty is always greater (in this case we surmise it is very much greater).

Tedla *et al.* (2011) show plots of their Euler depths versus seismic depths for a range of SI between 0 and 2 (their fig. 4). On the basis of their fig. 4 alone, the most robust conclusion should be that their gravity depths are very poor predictors of seismic depth at any SI.

4 COMPARISON WITH SEISMIC DATA

The reliability of Euler analysis for these gravity data is in grave doubt, as has been shown above. Nevertheless, we would like to demonstrate that the data provided by Tedla *et al.* (2011) as supplementary data to the paper are of limited use and should best not be used.

To examine the validity of the results, we compare in Fig. 2 the difference between the Tedla *et al.* (2011) crustal thickness and a crustal thickness estimate for southern Africa from Webb (2009). The latter is based on combination of gravity modelling and a series of seismic data acquired over several decades (e.g. Willmore *et al.* 1952; Durrheim *et al.* 1992; Hanka *et al.* 2000; Nguuri *et al.* 2001). The compilation by Webb (2009) of these seismic data demonstrates large crustal thickness variations from 50 to 30 km with wavelengths of less than 100 km across southern Africa, which indicate different tectonic settings.

The compilation by Tedla *et al.* (2011) does not show the same features. Crustal thickness here, as for the rest of Africa, is very homogenous. The link to tectonic province is less clear, even though most seismic depth estimates are within ±5 km difference to their estimates. However, substantial areas have a larger difference and this cannot be explained by narrow rifts or gradual Moho, but only by an incorrect crustal thickness. The crustal thickness estimates by Tedla *et al.* (2011) do however correlate to some extent with topography, which indicates that the results partly reflect the use of the free-air instead of the Bouguer anomaly.

As a second example, we applied the methodology as outlined by Tedla *et al.* (2011) to the Fennoscandian shield. For this region, a well-defined database has been developed recently (e.g. Grad *et al.* 2009; Stratford *et al.* 2009). Fig. 3 shows the 'crustal thickness' following the methodology by Tedla *et al.* (2011) and from seismic estimates. Although large parts of the area show a difference of less than ±5 km, the 'Euler' thickness has a completely different character from the seismic thickness estimates. Large parts show deviations up to 20 km in difference and this can be explained by the complexity of the density distribution in the crust and uppermost mantle. In Fennoscandia, the peculiar situation occurs that the deepest crust (>40 km) occurs beneath areas of low topography and that beneath high topography crustal thickness is moderate (30–40 km). This is similar to southern Africa, where the Limpopo belt has thick crust (∼50 km Nguuri *et al.* 2001) with locally lower topography, but the seismic stations closest to Lesotho have moderate crustal thickness values. For both regions, this observation is in opposition to the gravity signal, which would imply the presence of a crustal root, when assuming simple Airy isostasy.

The 'Euler' method as proposed by Tedla *et al.* (2011) does not present this characteristic and so presents a misleading picture of the tectonic situation of Fennoscandia. Hence, in addition to the flaws in the application of Euler deconvolution, it can be misleading to explain the observed long-wavelength gravity field by changes in crustal thickness only, disregarding lateral density variations associated with tectonic regions. In Africa, crustal structure beneath the cratons certainly can be expected to be different from the situation in the rift systems. This is already indicated by seismological studies of Africa, which show clear changes in the upper mantle structure (e.g. Begg *et al.* 2009; Fishwick *et al.* 2010).

5 CONCLUSIONS

Satellite gravity data complement the existing local and regional data sets by providing a globally unified data set. However, local structures below the minimum wavelength content cannot be resolved in such a data set, while superposition of the gravity contributions of crustal (large scale basins and features), Moho variations and upper mantle sources makes a unified interpretation difficult for a large area such as Africa where these contributions are likely to overlap in wavelengths. The gravity field might not be a good

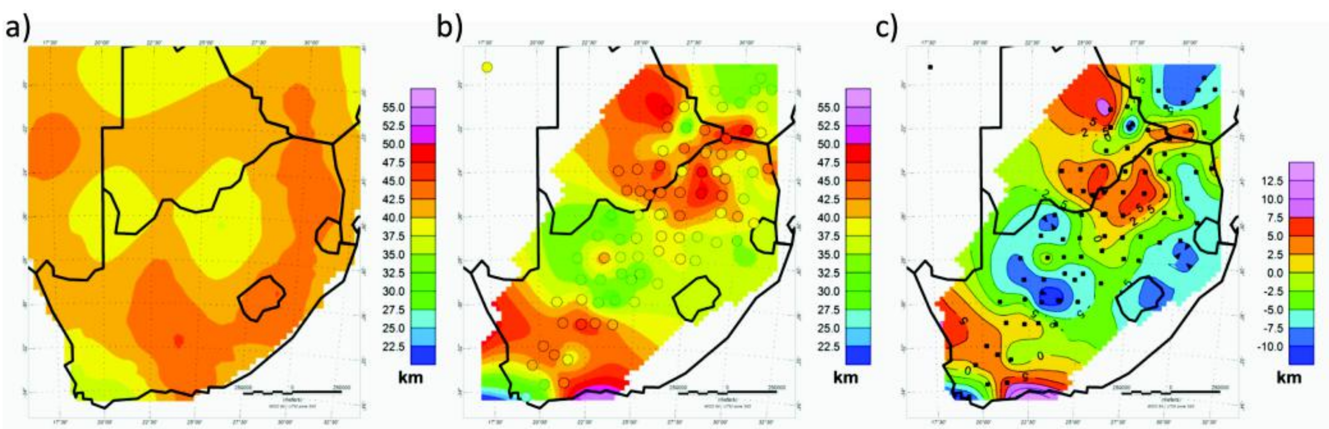

Figure 2. Southern Africa: (a) crustal thickness after Tedla *et al.* (2011), (b) after Webb (2009) based on Nguuri (2004). The circles indicate seismic stations used in compiling the thickness maps. (c) Difference between the compilations in (a) and (b). Black squares indicate locations of seismic stations.

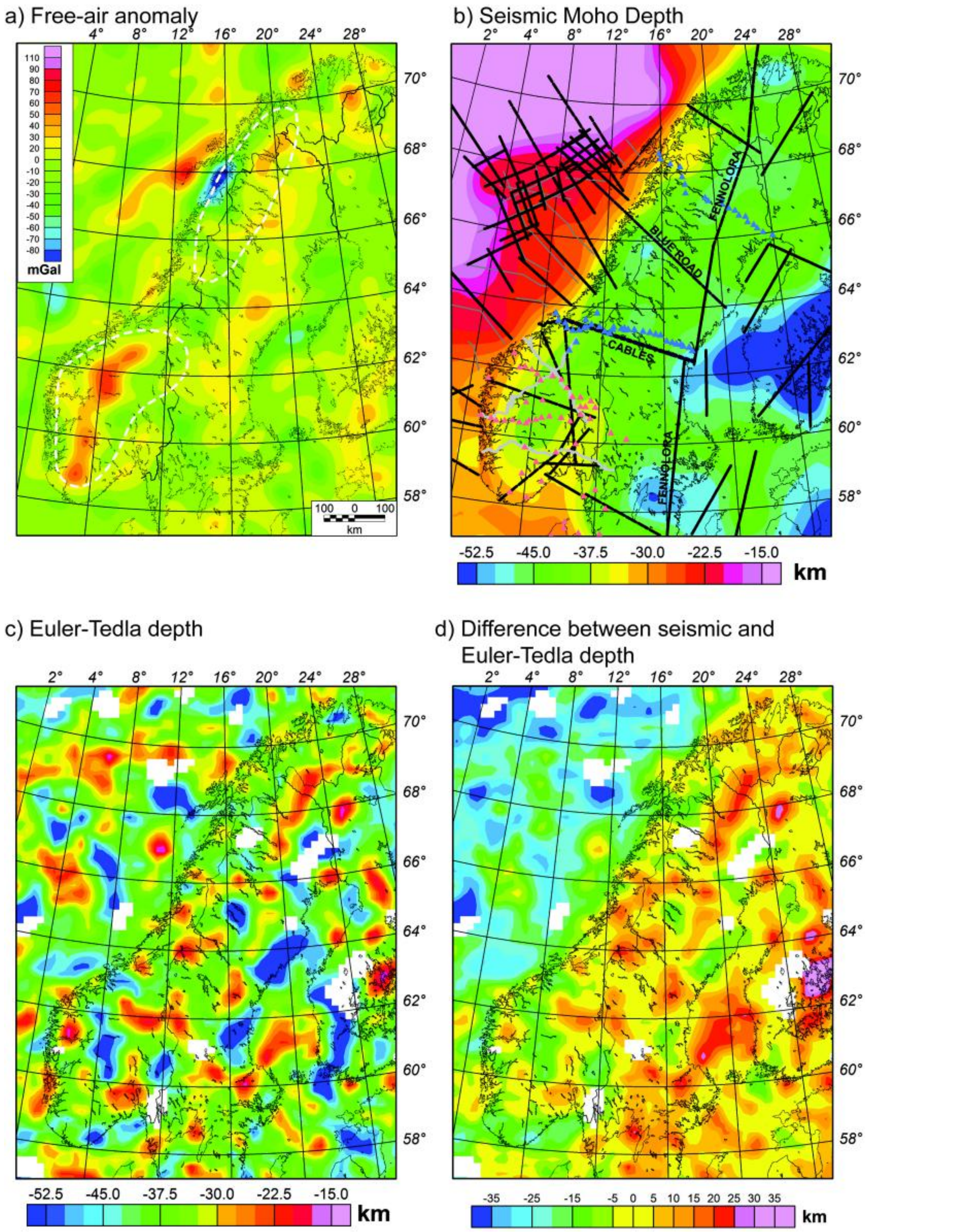

Figure 3. Fennoscandia: (a) long-wavelength free-air anomaly (wavelength >110 km), (b) Moho depth compilation based on Grad *et al.* (2009) and Stratford *et al.* (2009), (c) crustal thickness after the Euler–Tedla method and (d) difference between the seismic and 'Euler–Tedla' depth.

indicator of crustal thickness variations and hence any reasonable estimates of crustal thickness by inverting or forward modelling must use the available seismic data and models as constraints as much as possible.

If carefully done, depth estimates from gravity data, ideally combined with isostatic studies, can provide valuable insights into a study area. A first step in such a careful analysis is to remove the well-known topographic signal from the gravity field. The next step is to choose a suitable method.

The use of the Euler deconvolution method as applied by Tedla *et al.* (2011) does not provide new and useful results, but merely demonstrates that potential field data can produce misleading results, if used without proper understanding. Tedla *et al.* (2011) base their calculations on misquotation of previous studies and very poor choice of parameters.

Application of Euler deconvolution to estimate crustal thickness may well be possible, but will be made more difficult by superposition of sources with similar wavelengths. The source solutions should be carefully validated by comparison against seismic data and all available geological knowledge. The results presented for the African plate do not take into consideration the changes in tectonic setting and even with a correctly applied methodology and reduction of topography, the results might not reflect crustal thickness, but sources within the crust or upper mantle.

We have shown that the results presented by Tedla *et al.* (2011) are markedly different from seismically derived crustal thicknesses in a well-known part of the continent. We have also shown that their technique, applied elsewhere, produces misleading results. We therefore see little reason to trust their analysis and methodology in areas where there are no other constraints.

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