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A NEW BOUGUER GRAVITY MAP OF AUSTRIA

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ABSTRACT

All gravity data acquired in Austria during the past 50 years by different institutions have been reprocessed and homogenized in order to compile a new and accurate Bouguer gravity map of the Eastern Alps. Reprocessing was based on modern methods of terrain correction procedures and a digital terrain model (DTM) with 50 m spacing in order to get accurate corrections even in rough and mountainous areas. The DTM and digital cadastre also helped correcting the station coordinates that had been extracted from topographic maps in some of the early surveys. The final data set consists of 54000 stations with an average station distance of less than 3 km, even in the mountains. Commonly, the Bouguer gravity is based on orthometric rather than on ellipsoidal heights. Based on the newest geoid models, the Bouguer anomaly for the new map was determined using ellipsoidal heights, and the geophysical indirect effect was estimated. Additionally, mass corrections were determined by applying a 2D density model in order to investigate the errors introduced by assuming constant density in the standard processing. Finally, a stripped gravity map was derived to enhance the effect of sources within the upper crust. The new homogenized gravity data set refers to the absolute gravity datum and provides a much improved base for present and future Austrian Geoid solutions in Austria and neighbouring countries. This paper covers collection and processing of gravity data in Austria and presents a new Bouguer gravity map. Results of geological interpretation will be subject of future papers.

Alle in Österreich während der letzten 50 Jahre von verschiedenen Institutionen beobachteten Schweredaten wurden homogenisiert und einheitlich prozessiert, um eine neue und genaue Bouguerschwerekarte der Ostalpen zu erstellen. Das Reprozessing stützt sich auf moderne Massenkorrekturverfahren und auf ein digitales Geländemodell (DTM) mit einer räumlichen Auflösung von 50 m, um auch in rauer alpiner Topographie genaue Korrekturen zu erhalten. DTM und digitales Kataster wurden zur Verbesserung jener Stationskoordinaten eingesetzt, die in den frühen Vermessungsperioden aus den damals verfügbaren topographischen Karten gewonnen wurden. Der Datensatz enthält gegenwärtig 54000 Stationen mit einem mittleren Stationsabstand von weniger als 3 km, auch im Gebirge. Aus Gründen der Verfügbarkeit beruhen Bouguerschwerewerte meistens auf orthometrischen und nicht auf ellipsoidischen Höhen. Auf der Grundlage neuester Geoidmodelle wurde die neue Bougueranomaliekarte erstmals unter Verwendung von ellipsoidischen Höhen berechnet und der sogenannte geophysische indirekte Effekt abgeschätzt. Außerdem wurde bei den Massenkorrekturen ein 2D Dichtemodell verwendet, um die Fehler des Standard-Prozessings zu untersuchen, bei dem eine konstante mittlere Dichte angenommen wird. Zur Visualisierung der gravitativen Effekte von Quellen in der oberen Erdkruste erfolgte schließlich ein gravimetrisches Abdeckverfahren auf der Basis von seismischen Modellen der Krusten-Manteldiskontinuität. Die neue Schwerekarte im absoluten Schwereniveau dient als wesentlich verbesserte Basis für gegenwärtige und zukünftige Geoidberechnungen in Österreich und seinen Nachbarländern. Die vorliegende Arbeit beschreibt die Erhebung und das einheitliche Prozessing der Schweredaten in Österreich und stellt die neue Bouguerschwerekarte vor. Die geologische Interpretation der Schwereverteilung wird Gegenstand zukünftiger Publikationen sein.

1. INTRODUCTION AND EARLIER GRAVITY MAPPING IN AUSTRIA

Gravity data available in Austria have been acquired during the past 50 years by following institutions:

- Federal Office of Metrology and Surveying, Austria
- Institute of Meteorology and Geophysics, University of Vienna, Austria
- Institute of Geophysics, Mining University of Leoben, Austria
- Institute of Geophysics, Technical University of Clausthal, Germany
- OMV AG, Austria,
- Institute of Geophysics, Technical University of Vienna, Austria

In the early days, gravity network design was motivated by desire to establish an orthometric height system in Austria. The first gravity map of Austria was an important by-product (Senftl, 1965) of these efforts. Accordingly, the gravity stations were mainly established on leveling lines and thus often along Alpine valleys. In those cases, measurements often reflected local anomalies caused by the gravity effect of sedimentary valley fillings, for example. While each station's vertical coordinates were well determined, their horizontal coordinates are less accurate because they were read from topographic maps available at that time. Oil exploration companies built up the first gravity networks of areal character. However, as the purpose was the detection of hydrocarbon traps, surveying was confined to the Alpine Foreland, the Vienna Basin and to parts of the Flysch Zone and the Northern Calcareous Alps of the Eastern Alps (Zych, 1988). To reach a better understanding of the crustal structure of the Alps, additional gravity profiles were established across the Eastern Alps (Ehrismann et al., 1969, 1973, 1976; Götze et al., 1978) during the late 1960s and 1970s. In all these cases, vertical coordinates were derived from precise leveling methods while the horizontal ones were just read from topographic maps. Moreover, stations were scarce in rugged mountainous terrain due to limited accessibility.

However, interpolation errors as high as 100 µms^{-2} can occur in the Bouguer anomaly pattern when stations are arranged along profiles exclusively (Steinhauser et al., 1990). Therefore, the first areal investigation including many stations even at high up mountain flanks and tops has been done during the late 1970s along the so called Gravimetric Alpine Traverse (Meurers et al., 1987). Since that time, both horizontal and vertical coordinates were determined predominantly by classical geodetic surveying. The central part of the Eastern Alps adjoining the Gravimetric Alpine Traverse was covered by measurements of the Technical University Clausthal (Germany) (e.g. Götze et al., 1979; Schmidt, 1985). The westernmost and the south-eastern part of Austria were surveyed by the Mining University Leoben (Posch and Walach, 1989; Walach and Winter, 1994). The entire Northern Calcareous Alps have been investigated for OMV between 1981 and 1986, while different research projects between 1983 and 1990 were focused on the Austrian part of the Bohemian Massif (Meurers, 1993; Aric et al., 1997). The gaps remaining especially along the crest of the Eastern Alps have been filled since 1990 in cooperation of the Institute of Meteorology and Geophysics (University of Vienna), the Central Institute for Meteorology and Geodynamics (Vienna) and the Department of Physical Geodesy of TU Graz by applying GPS techniques and helicopter transportation in otherwise unaccessible mountainous regions. Gravity data of southern Bavaria has been provided by Bayerisches Landesvermessungsamt, Munich. Presently the gravity map of Austria is supported by 54000 stations (Fig. 1). The average station interval is less than 3 km even in the high mountains resulting to an average station density of 1 station/9 km^2 or higher.

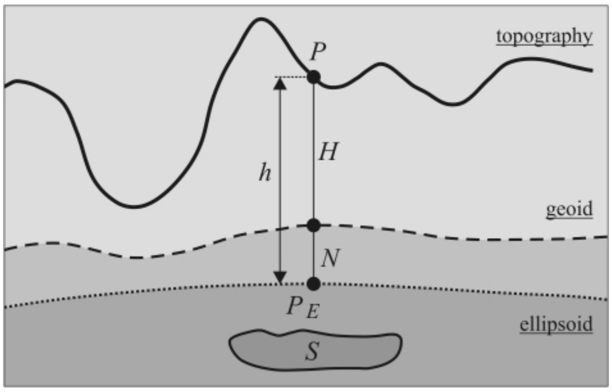

Figure 2: Orthometric vs. ellipsoidal heights and relation to the geoid undulation. *h*: ellipsoidal height, *H*: orthometric height, *N*: geoidal height.

2. Data processing

During the past 50 years both data acquisition and processing methods have been dramatically improved. Depending on the origin, the available gravity data refers to different da-

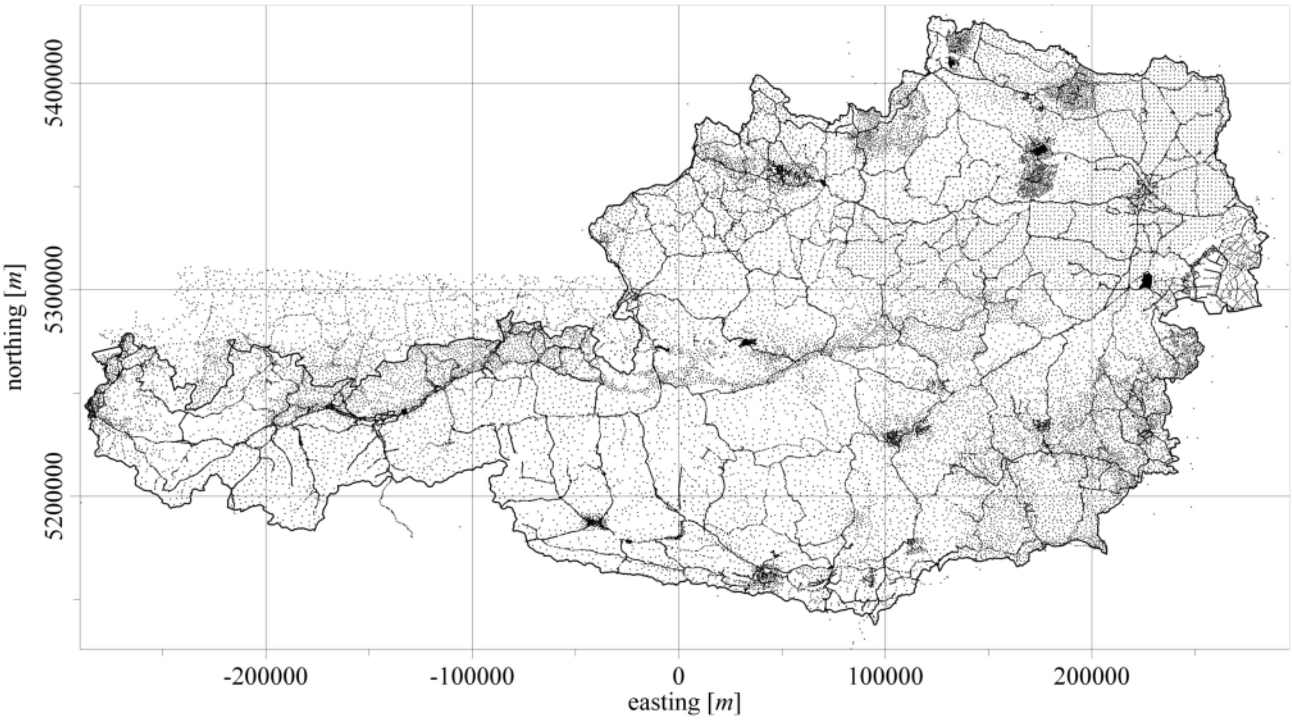

Figure 1: Station distribution of gravity stations used for the new Bouguer anomaly map of Austria.

tum levels and exhibits variable quality and accuracy. Therefore, data homogenization is required focussing on the gravity datum and calibration as well as on coordinate determination and mass correction.

2.1 Gravity datum and calibration

The industrial data (OMV) was tied to a local gravity base net. Compared to the Austrian gravity base net (AGBN), which is supported by absolute gravity observations (Ruess and Gold, 1996), the OMV base net exhibits a constant offset of about 15.13 mGal (1 mGal = 10^{-5} ms^{-2}). Additionally, due to limited calibration accuracy of the gravimeters used in that time, all gravity differences between the OMV gravity stations and the reference station of the OMV net are systematically affected. Both the correction factor for gravity differences and the offset have been determined by a common least squares adjustment of numerous ties between the OMV base net and AGBN (Meurers, 1992a). Based on these parameters, all gravity data has been finally transformed to the absolute gravity datum established by Ruess (2002).

2.2 Correcting erroneous coordinates

Horizontal coordinates have been obtained in many cases by topographic map digitization based on those maps which were available when the stations have been established. Maps with scale of 1:50000 have been used. Therefore, generally the coordinate accuracy for those stations is estimated as ±25 m, but even higher errors may occur occasionally. However, apart from these random errors, low quality of some older maps causes systematic errors. In order to check gross coordinate errors we compared the station heights with those obtained by interpolating a high resolution digital terrain model (50 m spacing). This method works only well where interpolation does not seriously smoothen-out the true topography. Erroneous coordinates have been corrected by making use of modern topographic maps and by utilizing the digital cadastre (Meurers and Ruess, 2007).

2.3 Mass correction

The gravity effect of topographic masses δg_T was calculated by applying a high accurate mass correction method. In the close vicinity (< 1200 m) of the gravity stations the topography is approximated by arbitrarily shaped (polyhedral) bodies (Meurers et al., 2001) instead of flat topped prisms. The topography was represented by a digital terrain model (DTM) with 50 m spacing (Graf, 1996). The gravity effect of polyhedral bodies can be calculated exactly (e.g. Götze and Lahmeyer, 1988). Correction for major lakes has been applied additionally. Taking the earth curvature into account, all mass corrections have been calculated in spherical approximation up to a distance of 167 km radius (Hayford zone O_2) assuming constant density of 2670 kgm^{-3}. This value is close to the mean surface rock density in the investigated area.

3. Bouguer anomaly determination

Commonly, height systems are based on orthometric or normal heights. However, ellipsoidal heights are required to allow for a clear physical interpretation of Bouguer anomalies with respect to their sources (e.g. Meurers, 1992b). Otherwise Bouguer anomalies, which, in the sense of physical geodesy, actually are gravity disturbances corrected for topographic mass effects, are disturbed by the geophysical indirect effect

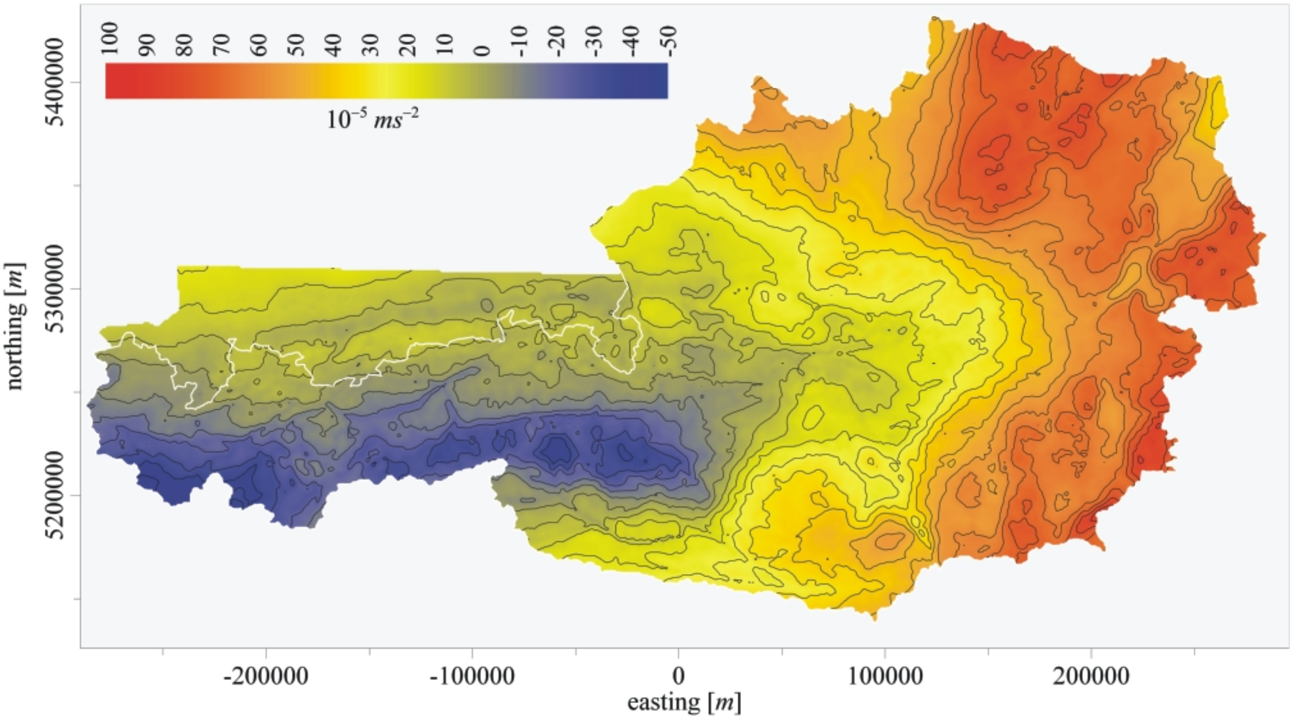

Figure 3: Bouguer anomaly of Austria (BA_{ell}) based on the ellipsoidal height system. Contour interval: 10 mGal.

(GIE, e.g. Hackney and Featherstone, 2003).

The gravity g observed at any arbitrary point P on topography is given in scalar approximation by equation (1):

$$g(P)=\gamma(P_E)+\underbrace{\int_0^H \frac{\partial\gamma}{\partial z}dz+\int_H^{N+H}\frac{\partial\gamma}{\partial z}dz}_{\int_0^h \frac{\partial\gamma}{\partial z}dz}+\underbrace{\delta g_{T,0\rightarrow N}(P)+\delta g_{T,N\rightarrow N+H}(P)}_{\delta g_{T,0\rightarrow h}}+g_S(P) \qquad (1)$$

where P_E is the projection of P down to the ellipsoid along the ellipsoid normal crossing P. N is the geoid height and H the orthometric height of the station P (see Fig. 2 for explanation); γ represents the normal gravity; g_S(P) is the gravity effect of all density inhomogeneities (represented by S in Fig.2) at P; δg_T denotes the gravity effect at P of all topographic masses located between ellipsoid and geoid ($\delta g_{T,0\rightarrow N}$), between geoid and topography ($\delta g_{T,N\rightarrow N+H}$) and between ellipsoid and topography ($\delta g_{T,0\rightarrow h}$) respectively. If the Bouguer anomaly BA is based on orthometric heights, then the following relation holds:

$$BA_{orth}(P)=g(P)-\gamma(P_E)-\int_0^H \frac{\partial\gamma}{\partial z}dz-\delta g_{T,N\rightarrow N+H}(P)=g_S(P)+\overbrace{\underbrace{\int_H^{N+H}\frac{\partial\gamma}{\partial z}dz}_{\text{gradient effect}}+\underbrace{\delta g_{T,0\rightarrow N}(P)}_{\text{mass effect}}}^{\text{Geophysical indirect effect}} \qquad (2)$$

It differs from the gravity effect of all sources (density inhomogeneities) below topography just by the GIE, which has no clear physical meaning in terms of sources. Only if the Bouguer anomaly determination is based on ellipsoidal heights h, then it represents exactly the gravity effect of any density inhomogeneity below topography and within the ellipsoid at P:

$$BA_{ell}(P)=g(P)-\gamma(P_E)-\int_0^h \frac{\partial\gamma}{\partial z}dz-\delta g_{T,0\rightarrow h}(P)=g_S(P) \qquad (3)$$

Pail et al. (2008) have recently calculated a new geoid for Austria using the homogenized gravity data presented in this paper as essential input as well as deflections of the vertical, GPS and levelling data. In addition, combining terrestrial data and a recent global gravity field model derived from GRACE data significantly improved representing long to medium wavelengths. This geoid model permits the transformation of orthometric into ellipsoidal heights. Therefore, for the first time, the Bouguer anomaly BA_{ell} in the ellipsoidal height system as well as the GIE has been determined exactly. The European Geoid EGG97 (Denker and Torge, 1998) has been utilized for all areas beyond the Austrian territory. Based on these geoid models both the orthometric heights of all gravity stations and the DTM could be transformed into ellipsoidal heights. Instead of evaluating the integral in equation (3) the normal gravity at P was represented by a Taylor series truncated after 2nd order terms both in elevation and geometrical flattening (Wenzel, 1985). All calcu-

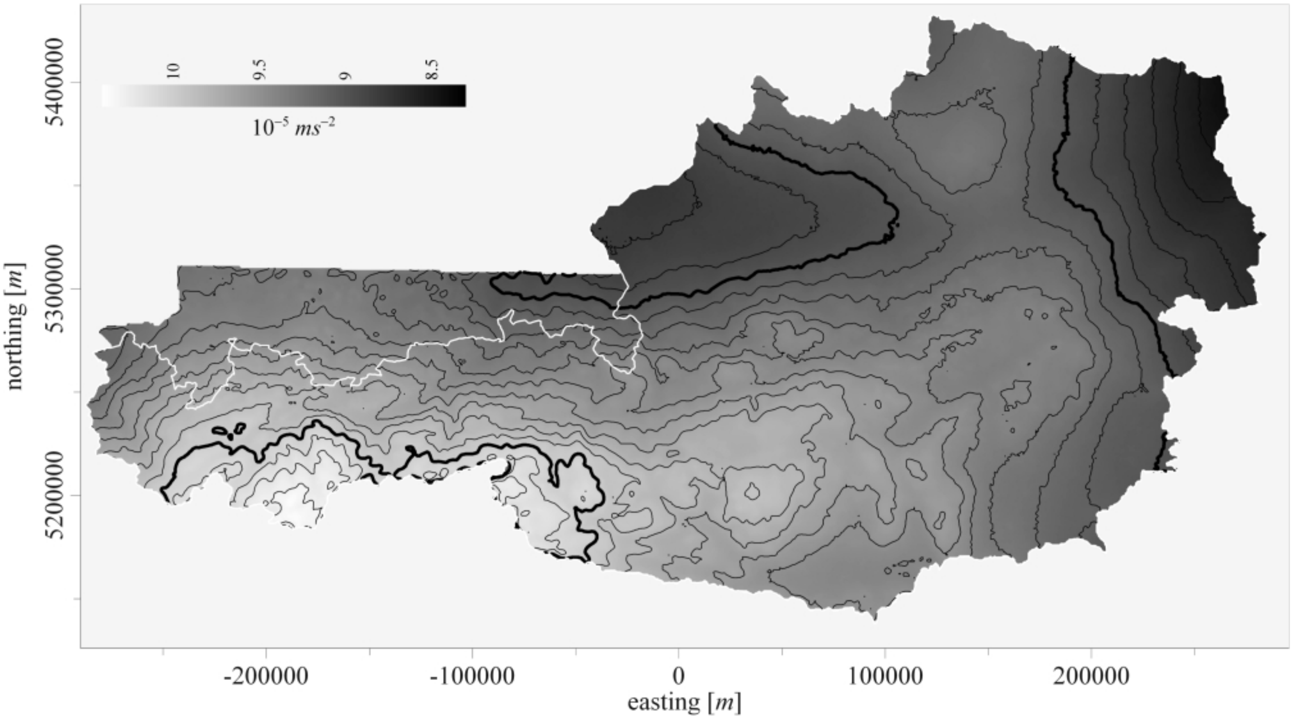

FIGURE 4: Geophysical indirect effect (GIE) in Austria. Contour interval: 0.1 mGal.

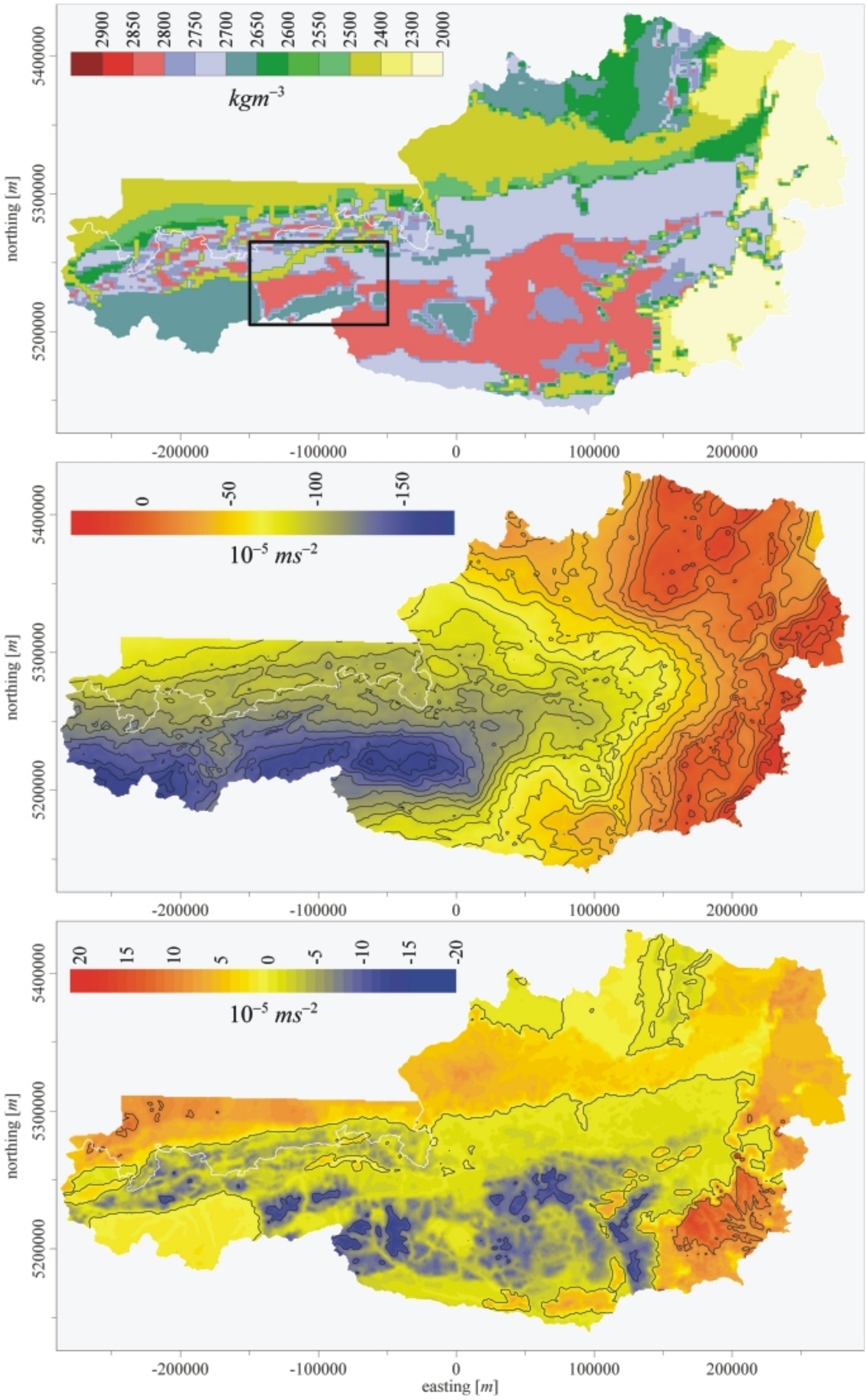

Figure 5: Top: Two dimensional density model of Austria. The black box indicates the section displayed in Fig. 6. Middle: Bouguer anomaly of Austria (BA_{ell}) calculated by applying the 2D density model for the topographic mass correction. Contour interval: 10 mGal. Bottom: Difference between the Bouguer anomaly calculated by applying the 2D density model for the topographic mass correction (shown in Fig. 5, middle panel) and constant density of 2670 kgm^{-3} (shown in Fig. 3) respectively. Contour interval: 10 mGal.

lations were based on the Geodetic Reference System 1980 (Moritz, 1984). Additionally, atmospheric correction (Wenzel, 1985) has been applied for avoiding height dependant errors. Figs. 3 and 4 show the Bouguer anomaly of Austria according to equation (3) and the geophysical indirect effect (GIE) respectively. The GIE consists of an average offset of about 9.3 mGal and varies between 8.4 mGal and 10.4 mGal within a region as small as Austria. Therefore, knowledge of the GIE is important for interpretation in terms of upper mantle structures or isostatic balancing. GIE is closely related to geoid undulations. This allows deriving a geoid admittance factor, which turns out to be 0.197 mGal/m on average as expected.

4. BOUGUER GRAVITY DETERMINATION BY USING A 2D SURFACE DENSITY MODEL

Many local anomalies appearing in Fig. 3 are due to density inhomogeneities within topography. 3D models for gravity interpretation on regional scale commonly do not incorporate such sources. Otherwise models of extremely high spatial resolution would be required. However, controlling such a huge amount of geometrical parameters in interactive modeling procedures is difficult. Therefore 2D surface density models generally help to improve the mass correction (e.g. Meurers et al., 1990). Granser et al. (1983) and Walach (1987), who evaluated density information from rock samples and seismic velocities, developed a surface density model, which is well suited for that purpose. It has been improved essentially by intensive rock sampling, especially within the Northern Calcareous Alps and within the southern Bohemian Massif. Figure 5 presents the surface density model (top panel), the Bouguer anomaly (BA_{ell}) (middle panel) derived by using this 2D density model for the mass correction instead of constant density and, in the bottom panel, the difference between the 2D density (Fig. 5, middle panel) and standard (Fig. 3) approach. The low density sedimentary filling of the Inn valley has not been corrected for. Applying the 2D density model does not only affect high frequency patterns but also long wavelength anomalies and the regional trend. Figure 5 (bottom panel) shows that the difference between both approaches exhibits both local and regional features with amplitudes up to 20 mGal. In 3D modeling based on the standard Bouguer gravity, those long wavelength features would erroneously be interpreted as deep seated sources unless topography and density distribution is incorporated into the models in high spatial resolution, which is commonly not the case. Thus, applying 2D density models for the mass correction reduces drastically the complexity regarding the model geometry in quantitative interpretation of regional gravity fields. In order to demonstrate the high frequency distortions, the Bouguer anomalies (BA_{ell}) - constant density versus horizontally varying density - of the western Tauern window (*TW*) area are compared in Fig. 6. Many high frequency features associated with the gravity station pattern are clearly visible in the map resulting from standard processing (constant density of 2670 kgm^{-3}, top panel of Fig. 6). If more realistic density assumptions are made (Fig. 6 bottom panel) by applying the 2D density model, such features disappear or are strongly diminished like the amplitude of the local gravity low following the Ziller valley (*Z*).

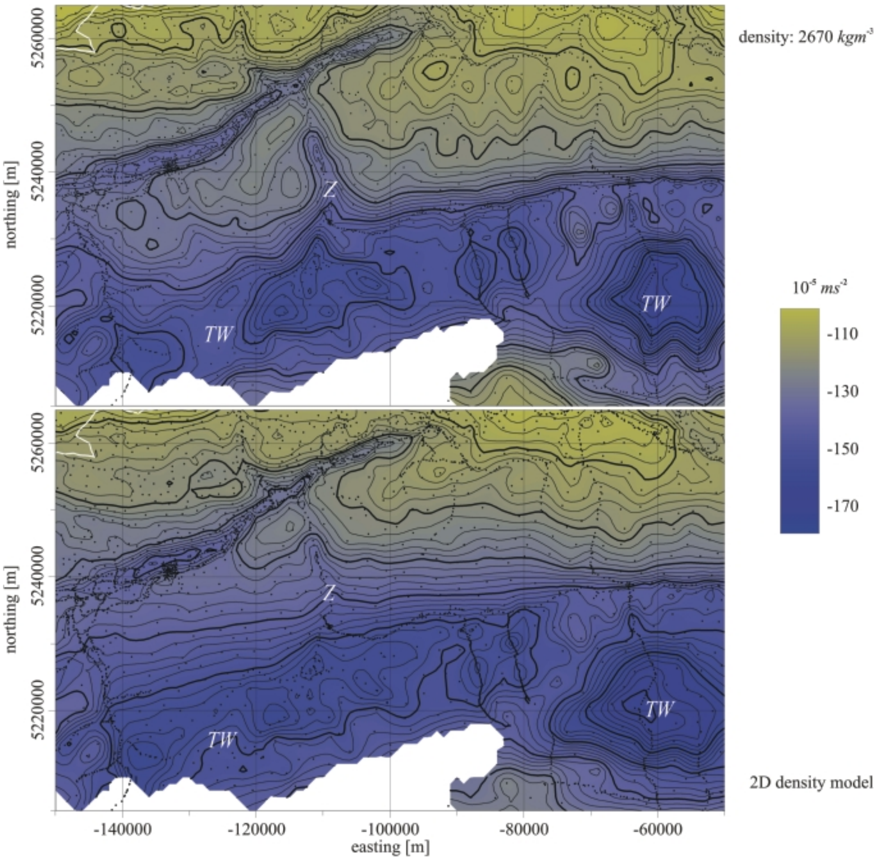

FIGURE 6: Comparison of the Bouguer anomaly calculated by applying the 2D density model (bottom) and a constant density of 2670 kgm^{-3} (top) respectively for the topographic mass correction in the Tauern window area. *TW*: Tauern window, *Z*: Ziller valley. Contour interval: 2 mGal.

5. STRIPPED BOUGUER ANOMALY

In order to enhance the image of upper crust structures the gravity effect of the crust-mantle boundary has been subtracted from the Bouguer anomaly (BA_{ell}, 2D density model applied). New Moho depth data derived from recent seismic experiments in Austria (Behm et al., 2007) were merged with data extracted from a large scale Moho depth model of Europe (Dezes and Ziegler, 2001). The gravity effect of the crust-mantle interface was then calculated in flat approximation by applying discrete Fourier techniques (Parker, 1972) and assuming a density contrast of -300 kgm^{-3} at the crust-mantle boundary. Fig. 7 reflects the Bavarian and Austrian Molasse basement structures (*MB*) much better than Fig. 3. Other remarkable local anomalies coincide with obviously deep reaching metamorphic rock units of the southern Bohemian Massif (*BM*), the Vienna Basin (*VB*) or the Tauern Window (*TW*). Strong positive anomalies characterize the Southern Alps. This indicates either the Moho depth being overestimated in that area or the presence of dense material in the crust. Ebbing (2004) proposed two different 3D density models along the TRANSALP geotraverse covering the Tauern window (*TW*) area, which both match the observed gravity field. Amongst others, the models differ by the depth to the crust-mantle boundary below the Adriatic plate and, consequently, by different densities for the lower crust. Constraints derived from the TRANSALP seismic experiments favor high density sources within the crust as explanation (Ebbing, 2004; Ebbing et al., 2006; Zanolla et al., 2006).

6. CONCLUSION

The new Bouguer gravity map of Austria is based on a homogeneous gravity data set. All data has been reprocessed by means of mass correction methods, which are accurate even in high mountainous areas, and high resolution digital terrain models. Station coordinates of older data have been essentially improved by utilizing information from DTMs, digital cadastre and modern topographic maps. The data set presently contains 54000 stations with an average station interval of less than 3 km even in the mountains, and will be continuously updated. It refers to the absolute gravity datum and provides the base for gravimetric geoid calculations as well as for future crustal investigations. The 2D density model of Austria permits the calculation of improved mass corrections and the assessment of errors in the standard processing, which are caused by assuming constant density. For the first time, the Bouguer anomaly of Austria was calculated in the ellipsoidal height system. This allows for exact estimates of the geophysical indirect effect (GIE), which varies by about 2 mGal within Austria. Thus, eliminating this effect should become a standard for investigations of sub-crustal sources or isostatic balancing studies. A first attempt of applying new crust-mantle boundary models derived from recent seismic

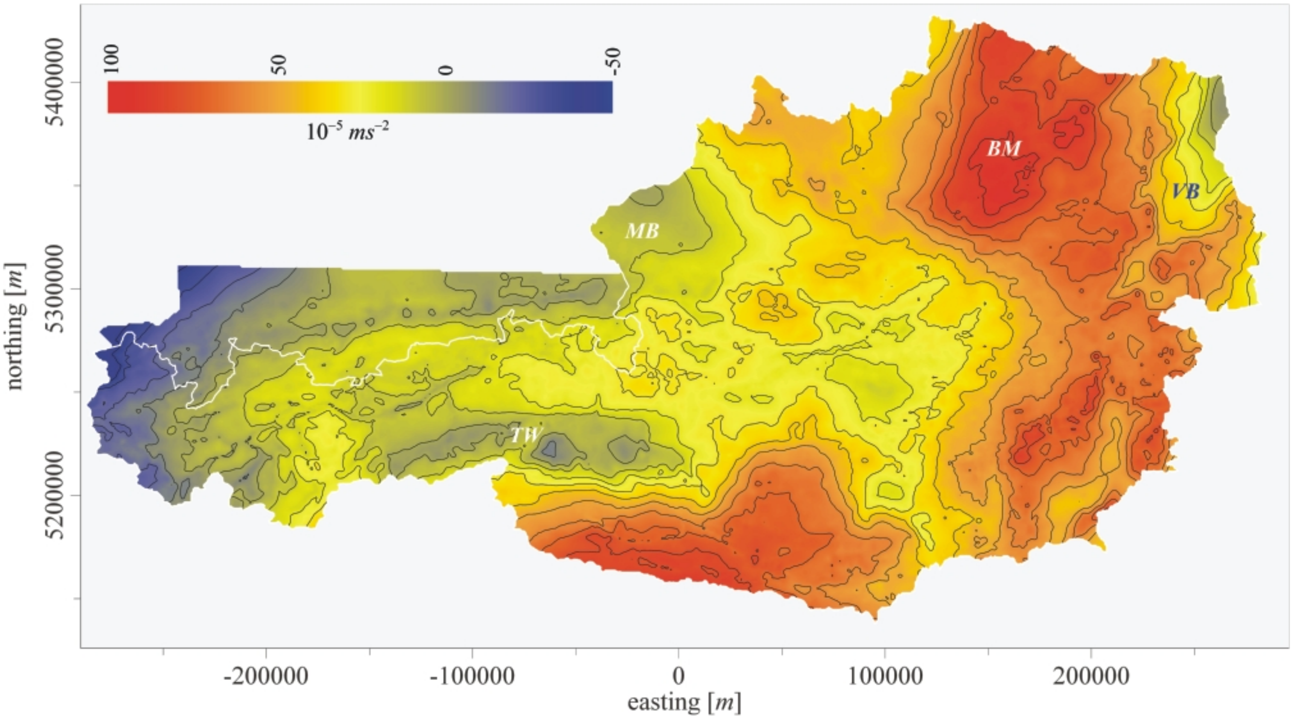

FIGURE 7: Stripped Bouguer anomaly (BA_{ell}, middle panel of Fig. 5) calculated by applying the 2D density model for the topographic mass correction and by subtracting the gravity effect of the crust-mantle boundary (Behm et al., 2007; Dezes and Ziegler, 2001). *BM*: southern Bohemian Massif, *MB*: Molasse basin, *TW*: Tauern window, VB: Vienna Basin. Contour interval: 10 mGal.

experiments has been performed to enhance the image of structures in the upper crust.

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