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Gravity anomaly map of the CELEBRATION 2000 region

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Abstract: The interpretation of the gravity field in the 2D and 3D space requires an accurate Bouguer gravity anomaly map. This requirement is of particular importance, when different techniques, instrumentation and data processing methods have been used in different parts of the area of interest. This paper presents the Bouguer gravity anomaly map of the CELEBRATION 2000 countries (Austria, Czech Republic, Hungary, Poland and Slovak Republic) and reports on the calculation of Bouguer gravity data. The gravity map will serve as basis for 2D and 3D modeling of the gravity field in the CELEBRATION 2000 region (45°–54° latitude and 12°–24° longitude). To avoid truncation problems in the following quantitative interpretation, the map area consists of both the CELEBRATION 2000 countries and adjacent areas. Due to different average station density of gravity measurements in the countries (Austria — 1 station/9 km^2, Czech Republic — 1 station/2.6 km^2, Hungary — 4 stations/km^2, Poland — 2.74 stations/km^2 and Slovak Republic — 5 stations/km^2) the gravity data were interpolated to grids by using different spacing and projection in each country. In the entire CELEBRATION area the average station density is approximately 2.4 stations/km^2 and the gravity data set contains more than 1,620,000 measurement points. Additionally, the most important regional gravity anomaly patterns of the map are presented with commentary.

Key words: East European Platform, Alps, Western Carpathians, Bohemian Massif, Pannonian Basin, Polish Basin, Vienna Basin, Bouguer gravity anomaly map.

Introduction

Due to the very complex structure and tectonic evolution of the continental lithosphere in Central Europe, this region has been subject to numerous geological and geophysical field experiments already in the past. Recently, the most important investigation is the CELEBRATION 2000 refraction seismic experiment (**C**entral **E**uropean **L**ithospheric **E**xperiment **B**ased on **R**efr**A**c**TION** 2000). This international project involves 28 institutions from Europe and North America (Guterch 2003a,b). The huge dataset resulting from this experiment is based on a network of seismic profiles with a total length of 8900 km (Fig. 1) and will provide a 3D velocity image of the Central European crust. The network covers the Trans-European Suture Zone (TESZ), the southwest part of the East European Craton, the Carpathian Mountains, the Pannonian Basin and the Bohemian Massif (Fig. 2). It has recently been followed by the projects ALPS 2002, SUDETES 2003 and the BOHEMIA teleseismic experiment.

The main goal of the CELEBRATION 2000 seismic experiment is to broaden the knowledge of deep-seated structures and of the geodynamics of the complex continental lithosphere and to study the relationships between the main tectonic units of Central Europe. For achieving the project goals it is necessary to integrate the seismic refraction data and their interpretation with the data of other geophysical fields too. In consequence the potential field working group has been formed. This group consists of representatives from all five countries: Austria, Czech Re-

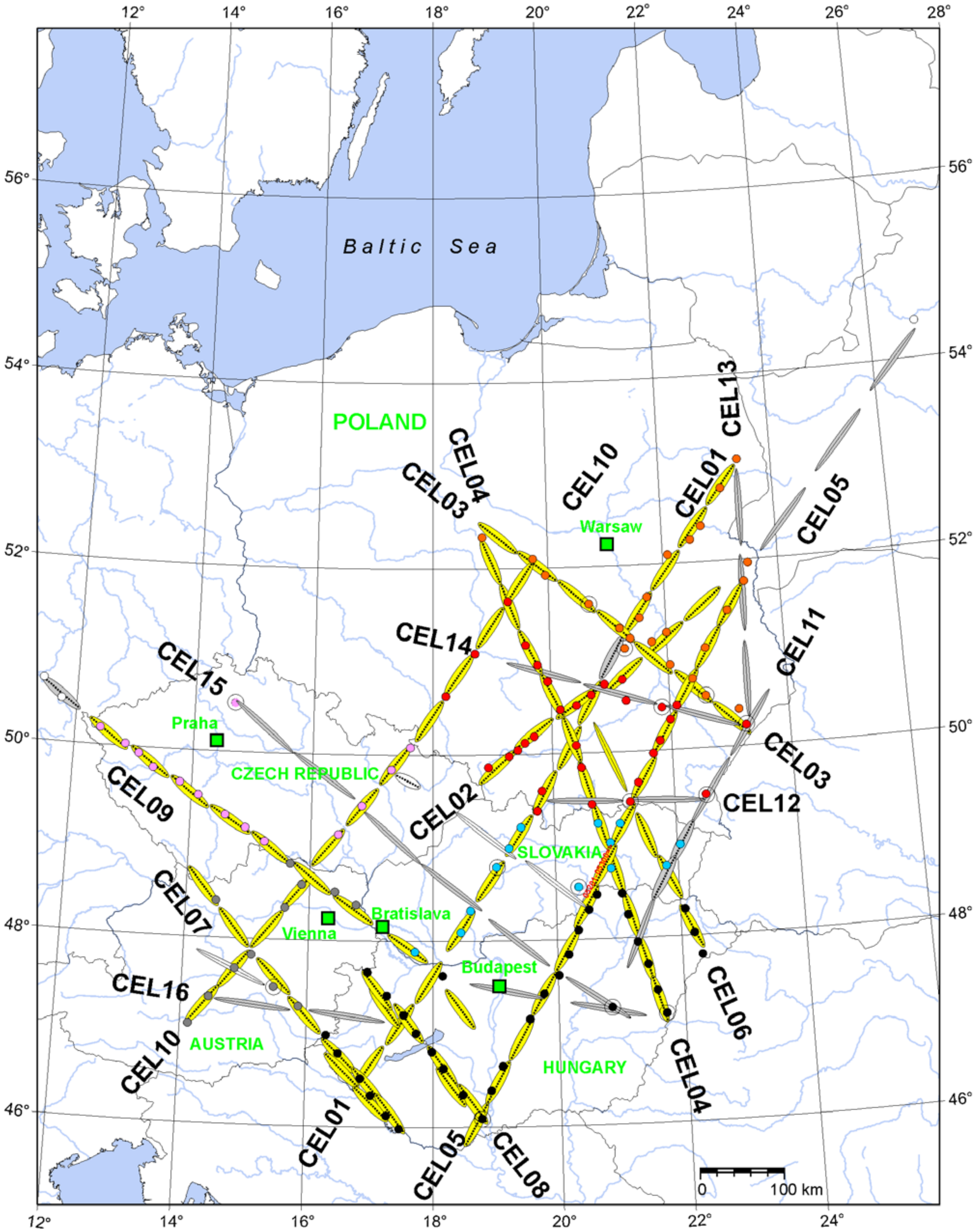

Fig. 1. Location of the profiles of the CELEBRATION 2000 experiment (modified after Guterch et al. 2003b). The red, pink, blue, black, orange and grey coloured circles show shot points. Yellow lines are high density recording profiles, the other lines are low density recording profiles.

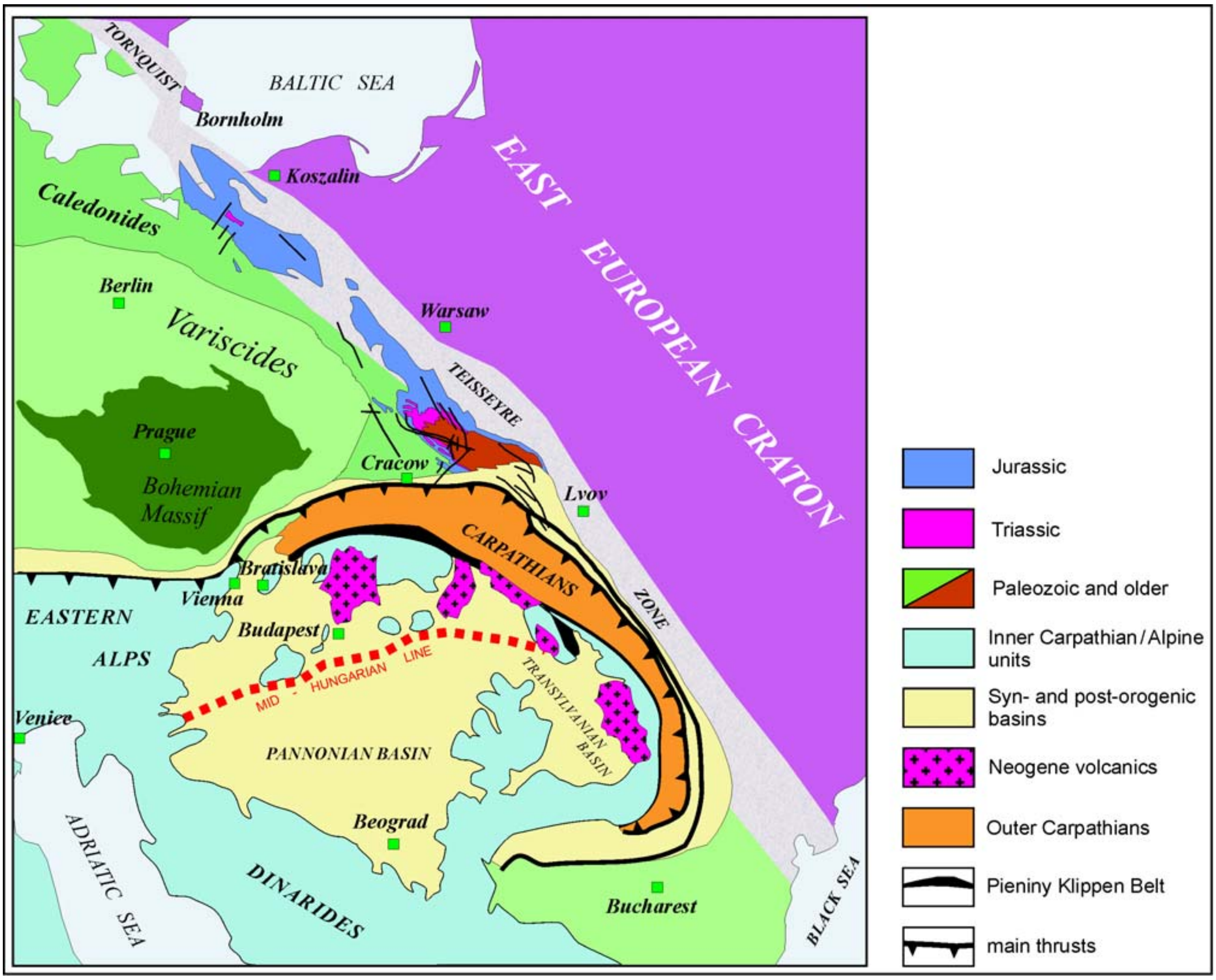

Fig. 2. Schematic tectonic map of the CELEBRATION 2000 region (after Guterch et al. 2003a).

public, Hungary, Poland and Slovak Republic. The main goal of this working group is the joint interpretation of potential field data (gravity, magnetic field and geothermal field) using CELEBRATION 2000 project seismic refraction results as a base. The area of the CELEBRATION 2000 project is outlined by 45°–54° N latitude and 12°–24° E longitude.

The interpretation of the gravity field in the 2D and 3D space requires a unified Bouguer gravity anomaly map of high quality and accuracy. This is particularly important because different techniques, instrumentation and data processing methods have been used in different parts of the area of interest. Therefore, at the beginning the main task of the potential field working group of CELEBRATION 2000 was the compilation of a common Bouguer gravity anomaly map. This paper deals with this problem, which relates to the calculation of Bouguer gravity anomaly in the CELEBRATON 2000 countries. Additionally, we present the regional gravity anomaly patterns of this map that will serve as a basis for 2D and 3D modeling of the gravity field in the CELEBRATION 2000 region.

Calculation of Bouguer gravity anomaly

The history of gravity measurements is quite different in each country contributing to CELEBRATION 2000. Field measurement, processing and calculation of the Bouguer gravity anomaly have own particularities in each country and changed in the course of time. The resolution and accuracy of gravity data in each country depends on the type of gravimeters, processing methods and roughness of topography. Therefore, the data processing scheme for calculating the Bouguer gravity anomaly will be described for each country separately.

Austria

The gravity data from Austria have been acquired during the past 40 years. At the early beginning gravity stations were installed mainly along leveling lines due to limited accessibility and the scarcity of geodetic stations in rugged mountainous terrain. Senftl (1965) published the first Bouguer gravity map of Austria based on this information. Consequently stations were predominantly situated within regions of very local anomalies due to the gravity effect of sedimentary valley fillings, for example. In order to get more detailed information about the structure of the Alpine crust a few cross-sections were surveyed 30 years ago along N-S directed profiles (Ehrismann et al. 1969, 1973, 1976; Götze et al. 1978). However, interpolated gravity values do not reproduce correctly important features of the Bouguer gravity. Interpolation errors of up to 10 mGal (100 μms^{-2}) can occur in the Bouguer gravity anomaly pattern when stations are arranged along profiles exclusively (e.g. Steinhauser et al. 1990). Therefore gravity stations have to be distributed regularly with a lot of stations even high up mountain flanks and tops which necessitates remarkable changes in measuring techniques and reduction procedures. The first areal investigation was done during the seventies on the so-called Gravimetric Alpine Traverse (Meurers et al. 1987) and by the gravimetric research group of the Technical University of Clausthal (Germany) (e.g. Götze et al. 1979; Schmidt 1985) in the adjoining central part of the Eastern Alps. The most western part of Austria was investigated by the Mining University of Leoben (Posch & Walach 1989). The Calcareous Alps are mainly covered by industrial data (Zych 1988). A selection of this data set meanwhile has been contributed for scientific purposes by the Austrian Oil Company. Nevertheless, some gaps still remained especially along the crest of the Eastern Alps. Therefore additional gravity investigations in the central Alps area of Tyrol have been performed since 1990 in cooperation between the Institute of Meteorology and Geophysics (University of Vienna), the Central Institute for Meteorology and Geodynamics (Vienna) and the Department of Physical Geodesy of Technical University in Graz. These supplementary measurements were performed by applying GPS techniques and helicopter transportation in otherwise in-accessible mountainous regions. Presently in most areas of Austria the maximum station interval is about 3 km or less resulting in an average station density of 1 station/9 km^2 or higher.

The data set available in Austria is quite inhomogeneous as it consists of contributions from different institutions and agencies acquired over a period of four decades. Therefore reprocessing was required to obtain high quality gravity maps. This concerns especially the basic equations and the geodetic reference system used for calculating the Bouguer gravity but also the mass correction procedures. Thus the Bouguer gravity anomaly was re-calculated using the following common assumptions (Meurers 1992):

- Geodetic Reference System 1980 (Moritz 1984).
- Absolute gravity datum (Ruess 1988).
- Closed expression for the gravity of the normal ellipsoid.
- Height correction by a Taylor series expansion of normal gravity up to 2^{nd} order in geometric flattening and height (Wenzel 1985).
- Atmospheric correction (Wenzel 1985).
- Spherical mass correction up to 167 km radius (Hayford zone O_2) assuming a constant density of 2670 kg/m^3. This value is close to the mean density of the surface rocks in Austria.
- All calculations are based on an orthometric height system referred to the Adriatic sea level.

A new digital terrain model developed at the Federal Office of Surveying of Austria (BEV) covers the entire Austrian territory with a resolution of 50 m even in rugged topography. It enables us to introduce more exact and more economic procedures for calculating high precise mass corrections (Meurers et al. 2001). In the distant zones (> 1 km) the topographic mass is presented by flat-topped rectangular prisms while in the station vicinity the topography is approximated by arbitrary polyhedral surfaces that define the upper boundary of homogeneous prisms extending down to the reference level. The corresponding gravity effect at the stations is calculated by applying Gauss' theorem in 3D and 2D in order to transform the volume integrals into line integrals along the polygonal edges. The line integrals are evaluated analytically (Götze & Lahmeyer 1988).

Czech Republic

In the territory of the Czech Republic there are two gravity data sets. The 1:200,000 data set consists of 30,400 gravity stations of the regional coverage and the 1:25,000 data set comprises more than 280,000 gravity stations of the current detailed gravity mapping. For the construction of the Bouguer gravity map of Central Europe we have decided to release the 1:200,000 gravity data set with an average density of one station per 2.6 km^2. The gravity station network was tied to the local Gravity System S-Gr57 used in the territory of former Czechoslovakia. The mean error of the gravity differences was less than 0.5 mGal (Švancara 2004). Elevation measurements are based on the Baltic system B46. Later on the 1:200,000 data set was transformed to the improved Gravity system S-Gr64 using the following formula:

$$g_{S-Gr64} = g_{S-Gr57} - 1.08 - 0.0021 \times (g_{S-Gr57} - 981{,}002.72) \text{ [mGal]},$$

where g_{S-Gr57} and g_{S-Gr64} are the observed gravity tied to the Gravity system S-Gr57 and S-Gr64 respectively.

To adjust the gravity data to the International Gravity Standardization Network (IGSN71) we performed the following transformation:

$$g_{IGSN71} = g_{S-Gr64} - 13.8 \text{ [mGal]},$$

where g_{IGSN71} is the observed gravity tied to the IGSN71 and −13.8 mGal comprise the correction of the Potsdam gravity system (−14 mGal) and a minor adjustment (+0.2 mGal) of the Gravity system S-Gr64.

The Bouguer gravity anomaly was calculated using the WGS84 ellipsoidal normal gravity formula. The Bouguer gravity anomaly, the terrain correction and the Bullard term were calculated for the reduction density of 2670 kg/m^3. The terrain correction was calculated for Hayford zones A–O_2 that is up to the distance of 166.735 km from the gravity station. The same distance was used as the outer radius of a spherical cap replacing the infinite Bouguer gravity slab by calculating the Earth curvature correction.

Hungary

In the Eötvös Loránd Geophysical Institute of Hungary (ELGI) the gravity measurements began in 1919, when it was founded. It means, that the gravity dataset of Hungary has been acquired during the past 85 years.

Between 1930 and 1945 oil exploration companies (EUROGASCO, Wintershall AG.) carried out gravity measurements in the country (Bérczi & Jámbor 1998). Since 1968 the Hungarian oil industry has carried out a lot of new gravity measurements. Gravity measurements of ELGI were located generally along the roads or for local exploration in local square grids with 500 m spacing each, while oil industry measurements were always established in square grids of 500 m spacing.

Nowadays ELGI stores all observed gravity data in Hungary. The Hungarian gravity data set contains more than 382,000 measurement points. Thus the density of gravity data is more than 4 stations/km^2 on average, but it varies within the territory.

The elementary data of gravity measurements (identification, coordinates, height, g value, and so on) are stored in the gravity database, therefore we can easily draw up different maps (e.g. Bouguer anomaly, Faye anomaly) from these data with different processing and parameters (density for reduction, different formulas for normal gravity, system of coordinates, and datum of height).

In this study the Bouguer gravity anomaly and terrain correction were calculated for the reduction density of 2670 kg/m^3, and the terrain correction was calculated up to a distance of 22.5 km from the gravity station. The Bouguer gravity anomaly was calculated using the WGS84 ellipsoidal normal gravity formula. The grid of digitalization was 2×2 km.

Poland

The basic gravity land data result from detailed gravity surveys (at the scale of 1:50,000) executed between 1957 and 1989. About 900,000 gravity stations have been occupied with an average density of 2.74 stations/km^2. The gravity data were measured in the Potsdam gravity system and using the geodetic Borowa Góra local Transverse Mercator (Gauss-Krüger) system and Bessel ellipsoid. They have been transformed into the IGSN71 gravity system and the GRS 80 geodetic reference system respectively by using the Krassovski ellipsoid and the 42 Gauss-Krüger projection. The Bouguer gravity correction for the data used in the map is 2670 kg/m^3 (Królikowski & Petecki 1995).

Slovak Republic

The territory of Slovakia is covered by gravity measurements with a density of 4–6 stations/km^2. The measurements in a scale 1:25,000 began in 1956 and were finished in 1992. In 2001 a new gravity database was created (Grand et al. 2001). This new database includes about 240,000 stations of the regional gravity mapping.

All existing data from Slovakia have been recalculated and uniformed with standards used in most of European countries. Previous archive gravity measurements have referred to the Potsdam system. Presently, all gravity data are referred to the IGSN71 system. The transformation of the gravity data into IGSN71 was performed in the same way as in Czech Republic.

The Bouguer gravity anomaly has been calculated by using:

- WGS84 ellipsoidal normal gravity formula on the basis of Somigliana's formula (Torge 1989).
- Height correction by a Taylor series expansion of normal gravity up to 2nd order in geometric flattening and height (Wenzel 1985).
- Spherical Bouguer gravity slab with radius of 166.7 km.

In the framework of a compilation of the new gravity measurement database the Cassinis-Dore-Ballarin formula (Cassinis et al. 1930) has been applied.

The terrain correction with a radius of 166.7 km is based on the T_1, T_2, T_{3i} and T_{3o} digital elevation models (DEM) for different distances from the station. T_1 and T_2 use a planar DEM, T_{3i} and T_{3o} use spherical DEMs related to the WGS84 ellipsoid.

Atmospheric correction was applied according to Wenzel (1985).

Data integration

The Bouguer gravity anomaly map of the CELEBRATION 2000 region (Fig. 3) was prepared using nine gravity data sets, which can be divided into two different groups. The first one is represented by regularly distributed data (grids) from CELEBRATION 2000 countries:

1. Austria — 1×1 km grid of Bouguer anomaly data, co-ordinates in Gauss-Krueger projection.
2. Czech Republic — 2.5×2.5 km grid of Bouguer anomaly data, co-ordinates in Gauss-Krueger projection.
3. Hungary — 2×2 km grid of Bouguer anomaly data, co-ordinates in Gauss-Krueger projection.
4. Poland — 1×1 km grid of Bouguer anomaly data, co-ordinates in Transverse Mercator projection with the central point at 19° E and 52° N corresponding to the co-ordinates −500 km (Easting) and −350 km (Northing).
5. Slovakia — 1×1 km grid of Bouguer anomaly data, co-ordinates in Gauss-Krueger projection.

The second group consists of regional data of the whole area of interest:

6. A regional grid (0.5°×0.5°) of free-air anomaly prepared for calculating the EGM96 geopotential model (Lemoine et al. 1997).
7. A data set with irregular spacing compiled during the European Geotraverse (EGT) Project. Partly original data, partly from digitized analogue gravity

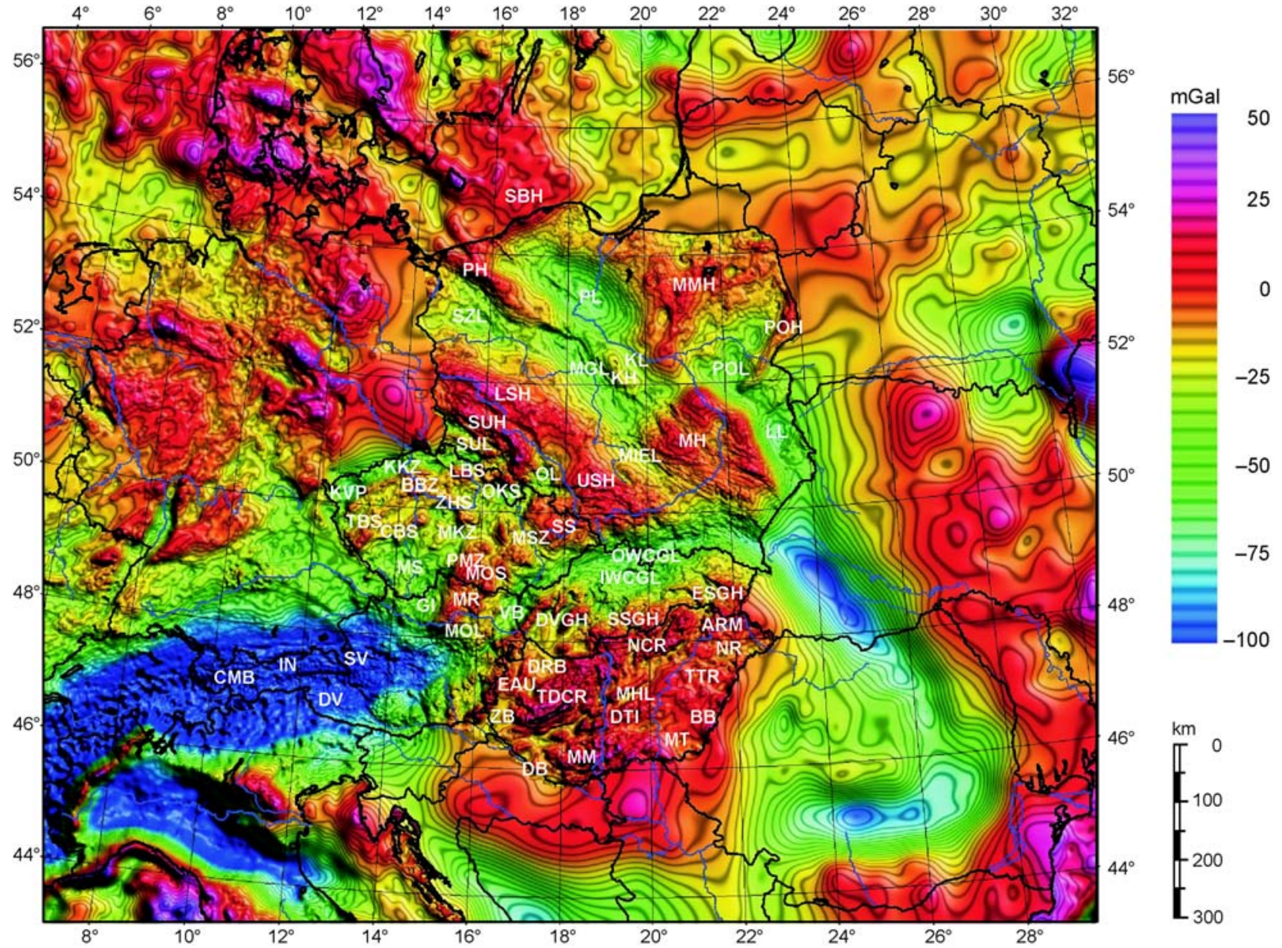

Fig. 3. Bouguer gravity anomaly map of the CELEBRATION 2000 region. **Austria:** CMB — crust-mantle boundary gravity low, GI — granitic intrusion gravity low, MR — metamorphic rocks density high (or VSZ — Vitis Shear Zone), MOL — Molasse gravity low, VB — Vienna Basin gravity low, IN — Inn gravity low, SV — Salzach gravity low, DV — Drau gravity low. **Czech Republic:** KKZ — Krušné hory (Erzgebirge)–Krkonoše Zone, KVP — Karlovy Vary pluton, BBZ — Barrandian-Broumov Zone, TBS — Teplá-Barrandian sub-region, LBS — Labe (Elbe)-Broumov sub-region, CBS — Central Bohemian Suture, MKZ — Moldanubian-Kłodzko Zone, MS — Moldanubian sub-region, OKS — Orlice-Kłodzko sub-region, ŽHS — Železné hory sub-region, MSZ — Moravo-Silesian Zone, MOS — Moravian sub-region, SS — Silesian sub-region, PMZ — Přibyslav Mylonite Zone. **Hungary:** MHL — Mid-Hungarian Line, DRB — Danube-Rába Basin, ZB — Zala Basin, DB — Dráva Basin, EAU — Eastern Alpine units, TDCR — Transdanubian Central Range, NCR — North Central Range, ARM — Aggtelek-Rudabánya Mountains, DTI — Danube-Tisza Interfluve, BB — Békés Basin, MT — Makó Trough, NR — Nyír region, MM — Mecsek Mountains. **Poland:** SBH — Southern Baltic High, MMH — Mazury-Mazovia High, POH — Podlasie High, PL — Pomeranian Low, KL — Kujawy Low, POL — Podlasie Low, LL — Lublin Low, PH — Pomeranian High, KH — Kujawy High, MH — Małopolska High, SZL — Szczecin Low, MGL — Mogilno Low, MIEL — Miechów Low, LSH — Lower Silesian High, SUH — Sudetes High, SUL — Sudetes Low, OL — Opole Low, USH — Upper Silesian High. **Slovak Republic:** OWCGL — Outer Western Carpathian gravity low, IWCGL — Inner Western Carpathian gravity low, DVGH — Danube-Váh gravity high, SSGH — South Slovak gravity high, ESGH — East Slovak gravity high.

maps: Bouguer anomaly data with geographical co-ordinates on CD-ROM attached to the EGT final publication (Klingele et al. 1992).

8. A data set of world gravity data with irregular spacing compiled by Bureau Gravimetrique International (land data and sea data) (Bureau Gravimétrique International 1996): Bouguer and free-air anomaly data with geographical co-ordinates.
9. A 2’×2’ data set of free-air anomaly sea data with regular spacing obtained using satellite altimetry, the latest (11.2, 2004) version (Sandwell & Smith 1997, //topex.ucsd.edu/pub/global_grav_2min/).

The Transverse Mercator projection was chosen for the main map using 19° E as the central meridian and 52° N as the central parallel, with the same central point as used for Poland.

Every data set from the CELEBRATION countries has been transformed from Cartesian to geographical co-ordinates and afterwards to the co-ordinates of the Transverse Mercator projection. Finally a 1×1 km grid covering all CELEBRATION countries has been interpolated.

Regional gravity data (items 6–9) given in geographical co-ordinates have been transformed directly to Transverse Mercator projection. They have been used for extending the 1×1 km grid to an area covering Central Europe. Both the regional grid covering the whole area and that of the CELEBRATION countries have been merged together to form one common grid, the latter having priority.

The original gravity data from the CELEBRATION countries have been used without any corrections, and they fit together very well. Differences along the state borders can be seen only in some places.

The following open-source software was used during map preparation:

1. for data processing — potential-field software elaborated by the U.S. Geological Survey (USGS) (Cordell et al. 1992);
2. for topography background and projection manipulation — Generic Mapping Tools (GMT) (Wessel & Smith 1998).

The map image was obtained using one of co-author's (SW) software based on the USGS potential field package (Cordell et al. 1992; Wybraniec 1999).

Regional gravity anomaly patterns

Austria

The regional anomaly pattern (Fig. 3) reflects the crust-mantle boundary (CMB) beneath the Eastern Alps increasing to a depth of more than 50 km towards the main crest of the Alps where the Bouguer gravity exhibits its minimum (< −180 mGal). Within the Variscan Orogene in Northern Austria the gravity reflects the low density of the granitic intrusions (GI) near Freistadt in contrast to a zone of high density metamorphic rocks (MR) following to the East. Well pronounced anomaly features include those caused by the Molasse (MOL) and Vienna Basin (VB), as well as local negative anomalies that image the sedimentary fillings of large Alpine valleys like the Inn (IN), Salzach (SV) and Drau (DV) valleys.

Czech Republic

The gravity field of the Czech Republic is divided into several sub-parallel belts with predominantly NE–SW orientation. For the description of the gravity field we use the scheme described by Ibrmajer & Suk (1989), which in some cases does not correspond to the regional geological subdivision of the Bohemian Massif. The Northern and NW part of territory of the Czech Republic belongs to the negative gravity zone Krušné hory (Erzgebirge)–Krkonoše (KKZ). The main upper crustal sources of the negative gravity anomalies of this zone are huge bodies of light granitoids. The most pronounced gravity low is caused by the Karlovy Vary pluton (KVP), whose maximum thickness approaches half of the Earth's crust thickness in this region.

The middle part of the Bohemian Massif characterized by positively disturbed gravity field is called Barrandian-Broumov Zone (BBZ). The gravity maxima of the Teplá-Barrandian sub-region (TBS) are lined up into three parallel belts of the NE–SW trend. Proterozoic spilite belts with accumulations of basic volcanites and other mafic rocks are the sources of these anomalies. The NE part of the Barrandian-Broumov Zone, the Labe (Elbe)-Broumov sub-region (LBS), is characterized by anomalies turning towards the W-E direction. Several positive gravity anomalies of this sub-region are interpreted as a manifestation of basic volcanites.

The Central Bohemian Suture (CBS) is an important tectonic line separating the positively disturbed gravity field of the Teplá-Barrandian Zone from the negative gravity field of the Moldanubian-Kłodzko Zone (MKZ). Negative gravity anomalies of the Moldanubian sub-region (MS) are mainly caused by huge bodies of light granitoids of the Central Bohemian and the Moldanubian plutons. The negatively disturbed gravity field of the Moldanubian sub-region continues towards the NE, to the Orlice-Kłodzko sub-region (OKS) whilst interrupted by the positive anomaly of the Železné hory sub-region (ŽHS). The main sources of the negative gravity field of the Orlice-Kłodzko sub-region are bodies of light orthogneises and granitoids.

The positively disturbed gravity field of the eastern part of the Czech Republic, which is called the Moravo-Silesian Zone (MSZ), is separated by the Upper Morava depression into the Moravian sub-region (MOS) to the south and the Silesian sub-region (SS) to the NE. A pronounced gravity gradient accompanying the contact of the negatively disturbed Moldanubian sub-region and the positively disturbed Moravian sub-region delineates a deep fault zone called the Přibyslav Mylonite Zone (PMZ). The southern prolongation of this tectonic line is known as Vitis Shear Zone (VSZ), in Austria as the zone of metamorphic rocks (MR). The upper crustal sources of the positive gravity anomalies in the Moravian sub-region are huge basic and ultra basic bodies. The positive gravity field of the Silesian region is attributed to heavier Devonian and Lower Carboniferous rocks. Several local gravity anomalies are caused by basic Devonian volcanites.

The easternmost part of the territory of the Czech Republic is characterized by the negatively disturbed gravity field of the Western Carpathians.

Hungary

Most of Hungarian territory (77 %) is covered by young sediments. The rest is formed by the Paleozoic and Mesozoic basement. Smooth anomalies with low gradients characterize the deep sub-basin areas of the Pannonian Basin. On the contrary, the parts where the basement outcrops are indicated by anomalies which are more pronounced and have high gradients.

The most characteristic features are elongated anomalies striking NE-SW. Among them the Mid-Hungarian is the most typical one. The Mid-Hungarian Line (MHL) is a structural line belonging to the Zagreb–Kulcs–Hornád line. These anomalies are due to the topography and structure of the pre-Tertiary basement (Fülöp & Dank 1987). Note that the highest anomaly values are not observed over the highest density basement (built by dolomite and crystalline limestone). The difference between the anomalies of the deep sub-basins are about 25–30 mGal. In the SE part of the country they are characterized by higher gravity values (e.g. the Békés Basin, the Makó Trough) and those in the W and NW parts by lower gravity values (e.g. the Zala Basin). This phenomenon could result from high density crustal sources, which are in a higher position compared to other places (Szabó & Páncsics 1999).

Several regional anomalies can be observed in the gravity field of Hungary: the Danube-Rába Basin (DRB), the Zala Basin (ZB) and the Dráva Basin (DB) are lowlands characterized by sedimentary filling of several km (Kilényi & Šefara 1989).

Alpine Paleozoic rocks are the source of the gravity anomalies of the Eastern Alpine units (EAU) in Hungary. The Transdanubian Central Range (TDCR) is due to Mesozoic rocks (mainly Carbonates) on the surface. The North Central Range (NCR) is caused by Paleozoic and Mesozoic rocks (Fülöp & Dank 1987). The gravity zone of the Aggtelek-Rudabánya Mountains (ARM) images the outcrop of the Mesozoic rocks. The Danube-Tisza Interfluve (DTI) is a result of young sediments and Paleozoic and Mesozoic rocks in the basement. The Békés Basin (BB) and the Makó Trough (MT) are one of the thickest sub-basins within the Pannonian Basin. In spite of the large thickness, their gravity fields are characterized by positive values. It indicates that they are influenced by deeply seated structures of the crust and the lower lithosphere. The Trans-Tisza anomaly is due to the superposition of effects of Neogene sediments, Flysch Belt, Paleozoic and Mesozoic rocks in the basement. The Nyír region (NR) anomaly is due to thick Neogene volcanic rocks and sediments covering the basement. The outcrop of Paleozoic and Mesozoic rocks is reflected in the gravity anomaly zone of the Mecsek Mountains (MM).

Poland

The anomaly pattern is closely related to the geological structure of the country. The North-Eastern part of Poland belongs to the East European Craton (EEC) also called Baltica. Different terranes docked to the EEC during the Phanerozoic (Avalonia, Armorica, Bohemia and Bruno-Silesia) form the rest of the country. The North-Western and central parts are occupied by the Polish Basin which is a part of the big sedimentary basin extending from the North Sea over Denmark and Germany to Poland. The Western Carpathians Mts are located in the south. They are part of the Alpine Orogene.

The EEC anomaly can be separated into the Southern Baltic High (SBH), the Mazury-Mazovia High (MMH) and the Podlasie High (POH). The SBH has a rectangular shape and extends from southern Sweden to the Polish Baltic coast. Bornholm is evidently part of this block. This gravity high is probably connected with thinner crust (Dèzes & Ziegler 2001). The MMH unit shows a mosaic anomaly pattern and is connected with sources of different density and origin. In the northern part two distinct negative anomalies originate from Proterozoic anorthosite massifs: the Kętrzyn Anorthosite Massif (in the west) and the Suwałki Anorthosite Massif (near the Lithuanian border). Other negative anomalies are caused by syenite massifs. Positive anomalies are connected with the high density of mafic rocks. The most prominent one is the Pisz anomaly (Pisz gabro-syenite massif). The POH anomaly is due to the Proterozoic Podlasie Metamorphic Belt composed of gneisses, enderbites, migmatites and amphibolites.

The middle of the country is built up by a collision zone called the Tornquist-Teisseyre Zone, which is a part of the Trans-European Suture Zone. This mega-unit includes the following gravity subdivisions from the North-West to South-East and South: the Pomeranian Low (PL), the Kujawy Low (KL), the Podlasie Low (POL) and the Lublin Low (LL), the Pomeranian High (PH), the Kujawy High (KH), the Małopolska High (MH), the Szczecin Low (SZL), the Mogilno Low (MGL) and the Miechów Low (MIEL). The Pomeranian Low is a very big negative anomaly between the Southern Baltic High and the Mazury-Mazovia High and belongs to the EEC, but looks quite different from its neighbours. It is homogenized to a very high degree without the distinct anomalies seen in both adjacent EEC units.

On the basis of gravity modelling along the LT-7 profile, Petecki (2002) pointed out that the Pomeranian Low is in part caused by a source situated in the uppermost mantle beneath the marginal zone of the EEC. Seismic data along the LT-7 profile (Guterch et al. 1994) do not indicate the occurrence of anomalously low upper mantle velocities, but on the P2 profile a low-velocity body has recently been indicated at the base of the crust beneath the cratonic edge (Janik et al. 2002). It may indicates, however, the occurrence of a transitional zone between the crust and upper mantle as a result of the underplating of mantle material.

Kujawy Low, the Podlasie Low and the Lublin Low have a similar character. The Lublin Low extends into the Ukraine and Romania. The new lithosphere depth map (Dérerová et al. 2005) shows there a sharp increase of lithosphere thickness which coincides with a gravity low both in Ukraine and Romania. The sources of the KL are mainly situated within the Zechstein-Mesozoic sedimentary complex (Petecki 2000).

The central part of the Mid-Polish Collision Zone forms gravity highs connected with the Mid-Polish Swell in geological nomenclature. The Pomeranian High is the northernmost part of the gravity high. Near the Baltic coast it bifurcates to two parts. The northern part continues to Bornholm and the southern to Danish Ringkøbing–Fyn High. The source of this anomaly high is situated partly in the Permian-Mesozoic positive structure and partly deep in the crust. On the basis of the analyses of gravity anomalies from the sub-Zechstein basement in the Pomeranian segment of TESZ (Królikowski & Petecki 1997, 2002; Petecki 2002) the PH was interpreted as being caused by upper crustal intrusions of high density and increased density of the lower crust and upper mantle in the TTZ. The Kujawy High is different from the Pomeranian High. Probably the sources are connected with the Permian-Mesozoic structure (here — the Kujavy Swell) and also by older and deep-seated sources, as indicated by Petecki (2000). On the "stripped" gravity anomaly map caused by the structures below the Zechstein, the KH adjoins the strongly expressed Mazury-Mazovia High, located within the EEC (Petecki 2000). The results of interpretation of gravity data, in particular 2D gravity modelling, indicate that the edge of the elevated crystalline basement of the EEC is situated along the SW boundary of the KH, expressed by a very strong gravity gradient (Petecki 2000).

The Małopolska High unit is not a homogenous zone. It covers several geological units of distinctly different character and evolution. They are separated by major fault zones (Dadlez 2001). The MH is separated into two regional segments by an approximately NW–SE trending narrow belt of local negative gravity anomalies. It also coincides with a boundary between crustal units of different magnetic character (Petecki et al. 2003). The results of interpretation of geophysical data, in particular 2D gravity and magnetic modelling, indicate that the edge of the crystalline basement of the East European Platform is situated along this line (Grabowska & Bojdys 2001). The sources of gravity highs in the NE part of the MH are huge dense intrusive bodies which penetrated the cratonic crust. It is also confirmed by seismic investigation along, for example, the CEL01 seismic profile. In the area at the SW margin of the EEC, anomalously high velocities of about 7.0 km/s were found at depth of about 15 km (Środa at al. 2003).

The Szczecin Low, the Mogilno Low and the Miechów Low form a wide band of low gravity values extending from Szczecin in the north-western corner of the country and joining the Carpathian low in south-eastern corner of Poland. The Szczecin Low occupies a geological unit called the Szczecin Trough which is a part of the Polish Basin. According to recent interpretations, together with the Pomerania High they form the easternmost part of the Avalonia Terrane, but the lower crust can be of Baltica origin. The shape of the MGL is similar to that of a geological unit called the Mogilno-Łódź Depression, also a part of the Polish Basin. Interpretation of gravity anomalies from the sub-Zechstein basement (Petecki 2000) indicates that the MGL is also attributed to the presence of pre-Zechstein Paleozoic deposits of considerable thicknesses. MIEL occupies the Miechów Trough (called also the Nida Trough) and the south-eastern part of the Silesia-Cracow Monocline. The sources of these three negative anomalies are not fully known. Most researchers assume a prevailing influence of the crystalline basement on their origin.

In the South-Western part the Lower Silesian High (LSH), the Sudetes High (SUH), the Sudetes Low (SUL) and the Opole Low (OL) can be observed, which form the northern part of the Bohemian Massif. The Southern part of Poland is characterized by the Upper Silesian High (USH) and the Carpathian Low (CL). The LSH gravity unit is close to the Fore-Sudetic Monocline. It is formed by Variscan externides. Its high gravity values are caused by a shallower Moho depth. The USH is a northern part of the Bruno-Silesian Terrane called also Bruno-Vistulian, which begins in Austria, goes across Czech Republic and ends in Poland where it covers the Upper Silesian Basin and the Cracow Monocline. The SUH is called a Fore-Sudetic Block in geological nomenclature and consists of different Paleozoic rocks and mafic intrusions. The NW parts of the LSH and SUH are crossed by the P4 seismic profile (Grad et al. 2003). The seismic data clearly indicate that the sources of these anomalies are related to the elevated upper crustal structure. The LSH is bounded to the north by a regional gravity gradient zone which corresponds to the Dolsk fault zone. This fault zone, expressed also as a magnetic lineament (Petecki et al. 2003), is certainly related to the major crustal discontinuity related to fundamental change in crustal structure (Grad et al. 2003). An integrated gravity and magnetic model along the P4 seismic profile (Petecki 2005) provides evidence of the bivergent nature of the Dolsk fault zone. While the contact in the upper part of the crust shows a dip to the NE the contact in the middle and lower crust dips to the opposite side. The SUL forms two different subunits: the Karkonosze Mts. Low with the North-Sudetic Trough Low in the west and the Kłodzko Low in the middle of the Sudetes. Their sources are granite massifs of Variscan origin. The OL, which is on the eastern end of the Sudetes, has the same origin.

Slovak Republic

The gravity field of Slovakia can be divided into two parts: the Western Carpathian gravity low zone and the Western Carpathian gravity high zone.

The prevailing part of the Western Carpathian gravity low zone extends over the territory of northern and partly also central Slovakia. Its westernmost part interferes with the region of the Czech Republic and Austria and its northernmost part extends into Polish territory. The Western Carpathian gravity low zone consists of two parts: the Outer Western Carpathian gravity low (OWCGL) and the Inner Western Carpathian gravity low (IWCGL). The OWCGL is associated with the Outer Western Carpathians. The prevailing source of the low is the Outer Flysch Belt including its basement (the Outer Carpathian Foredeep). Other deeper inhomogeneities probably participate in its effect only minimally. The IWCGL is associated with the Central Western Carpathians. The anomalous section is interpreted as an effect of greater crustal thickness which is, according to some authors (Buday 1991), related to the continuation of the European plate deeper beneath the Carpathians. Several authors (Ibrmajer 1958; Tomek et al. 1979; Pospíšil & Filo 1980; Obernauer & Kurkin 1983; Pospíšil & Mikuška 1983) worked on the interpretation of this striking anomaly and they had different opinion on the source inducing the minimum (e.g. low density and porous Flysch and molasse deposits or granitoid rocks having lower density in the Tatric area). The effect of the Moho dipping from south to north is confirmed by the results of deep seismic measurements (Tomek et al. 1979; Mayerová et al. 1985).

The Western Carpathian gravity high zone continues from the area of the Central and Inner Western Carpathians to Hungary. It is mainly induced by deep density inhomogeneities. The positive effect of the Moho elevation as well as the high density upper and lower crustal anomalous bodies (core mountains, pre-Tertiary basement elevations, basaltic volcanism, metamorphic and basic rocks) in the area superimpose the negative gravity effect of the asthenosphere. The whole area is divided into three parts: Danube-Váh, South Slovak and East Slovak. The Danube-Váh gravity high (DVGH) can be observed in the western part of Slovakia. It is a result of the superposition of positive and negative gravity effects. The positive anomalies are caused by the Core Mountains, submerged ridges of the Tertiary basement and the Moho elevation. The negative effects are due to the Tertiary, partly Paleogene cover of the Danube Basin and the intramountain depressions. In this zone the effect of the deep lithospheric structure (Moho and upper crust elevations) is dominant (Sitárová et al. 1984; Šefara et al. 1987, 1996; Nemesi et al. 1996). The South Slovak gravity high (SSGH) region is divided into three parts. The positive anomalies are due to the elevation of the pre-Tertiary basement (western part), the youngest basaltic volcanism (central part) and the basaltic volcanics, Paleozoic metamorphites and the core mountains (eastern part). In this region local negative anomalies can be observed too. They result from low density depression fills and granite rocks. The East Slovak gravity high (ESGH) region is due mostly to the deep structure of the lithosphere (Moho and upper crust elevations), Core Mountains and neovolcanics. Local negative anomalies are due to depressions and the central volcanic zone.

Conclusion

The newly compiled gravity map is a result of a huge effort of many peoples who participated in acquiring gravity data during the past years of this and the past century. In all five CELEBRATION 2000 countries the total gravity data set contains more than 1,620,000 measurement points and the average station density is approximately 2.4 stations/km^2.

The regional gravity anomalies of the compiled Bouguer gravity anomaly map reflect the main tectonic units of Central Europe.

The highest topography of the Eastern Alps is characterized by the most intensive regional gravity low (< –180 mGal). The crust-mantle boundary gravity (CMB) low is due to the large crustal thickness (> 50 km) beneath the Eastern Alps.

In the Variscan Orogene (Bohemian Massif) several subparallel belts with predominantly NE–SW orientation dominate, which in some cases does not correspond to the regional geological subdivision of the Bohemian Massif. The negative gravity zones reflect mostly the low density of the granitic intrusions [the Granitic intrusion gravity low (GI), the Krušné hory (Erzgebirge)–Krkonoše Zone (KKZ), the Karlovy Vary pluton (KVP), the Central Bohemian Suture (CBS), Moldanubian sub-region (MS), the Orlice-Kłodzko sub-region (OKS] that exhibit large thickness in many cases. Several local gravity anomalies are caused by basic Devonian volcanites. The northern margin of the Bohemian Massif occurs in Poland and is represented by the Lower Silesian High (LSH), the Sudetes High (SUH), the Sudetes Low (SUL), the Opole Low (OL).

Other well pronounced negative anomaly features are those caused by the Molasse (MOL) and Vienna Basin (VB), as well as local negative anomalies that image the sedimentary fillings of large Alpine valleys like the Inn (IN), Salzach (SV) and Drau (DV) valleys.

In contrast to high density metamorphic rocks, spilite belts with accumulations of basic volcanites, mafic rocks and huge basic and ultra basic bodies result in gravity highs [the metamorphic rocks density high (MR), the Barrandian-Broumov Zone (BBZ), the Teplá-Barrandian sub-region (TBS), the Labe (Elbe)-Broumov sub-region, Železné hory sub-region (ŽHS), Moravian sub-region (MOS)].

The regional gravity anomaly pattern of the Western Carpathians can be divided into two parts: the Western Carpathian gravity low zone and the Western Carpathian gravity high zone.

The first part consists of two gravity lows: the Outer Western Carpathian gravity low (OWCGL) and Inner Western Carpathian gravity low (IWCGL). The OWCGL (< –60 mGal) is considerably less than the Eastern Alpine gravity low CMB (< –180 mGal). This gravity low continues along the Carpathian orogene arc with amplitude increasing over the Eastern and Southern Carpathians (> –100 mGal). The prevailing source of the Western Carpathians low is the Outer Flysch Belt including its basement (the Outer Carpathian Foredeep). Other deeper inhomogeneities probably contribute only minimally. But this does not hold in the Eastern and Southern Carpathians, where the influence of the increasing depths of the crust-mantle boundary (> 50 km) and the lithosphere-asthenosphere boundary (> 200 km) also plays a very important role.

The second part (Western Carpathian gravity high) continues from the area of the Central and Inner Western Carpathians to Hungary. It is mainly induced by deep density inhomogeneities (mostly by Moho elevation, then by outcrop and elevation of the pre-Tertiary basement as well as the high density upper and lower crustal anomalous bodies).

The long wavelength Pannonian gravity high is mainly induced by deep-seated density inhomogeneities. The positive effect of the Moho is the main source of this regional gravity high, to which the upper and lower crustal high density anomalous bodies (Core Mountains, pre-Tertiary basement elevations, basaltic volcanism, metamorphic and basic rocks) contribute additionally. The most characteristic features of the Pannonian gravity high are elongated anomalies striking NE-SW. Note that its W and NW part is accompanied by lower gravity values than those in the S and SE part even though the thickness of sedimentary filling of the Pannonian Basin is larger in the S and SE part than in the W and NW one. This abnormal phenomenon could be explained by an influence of high density deep-seated crustal sources, which are in the S and SE part in higher position (Bielik 1988a,b; Szabó & Páncsics 1999). Both parts are divided by the Mid-Hungarian Line.

In the regional, long wavelength Pannonian gravity high several relative gravity lows can be observed [Danube-Rába Basin (DRB), Zala Basin (ZB), Dráva Basin (DB)].

The North-Eastern part of Poland is covered by the East European Craton (Baltica) gravity high, which consists of the Southern Baltic High (SBH), the Mazury-Mazovia High (MMH) and the Podlasie High (POH). Each of these highs has a different source. The first gravity high results from thinner crust, the second one is connected with the high crustal density of mafic rocks and the last one is due to the Proterozoic Podlasie Metamorphic Belt. The TESZ includes several positive and negative gravity anomaly zones with different wavelength and amplitude. The central part of the Mid-Polish Collision Zone forms the gravity highs connected with the Mid-Polish Swell. The Pomeranian High (PH) is the northernmost part of this gravity high, the Kujawy High (KH) can be observed in the central part and the Małopolska High (MH) spreading in the south eastern part of Poland. The Szczecin Low (SZL), the Mogilno Low (MGL), Miechów Low (MIEL) form a wide band of low gravity extending from Szczecin in the north-western corner of the country and joining the Carpathian low in south-western corner of Poland. It is supposed that their main source is the crystalline basement.

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