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Geophysical results

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Bouguer anomaly map

One of the main topics of the DANREG programme was the construction of a unified Bouguer anomaly map for the project area. Since the area forms a part of three different countries, the first step was to review the state of the art of the respective gravity base networks and surveys.

The available gravity values may be regarded reliable since the early 1950s. Each country had some sort of a national Bouguer anomaly map, but as their parameters were different from each other the national maps did not match along the borders. Since the Bouguer anomalies referred to different dates and Bouguer- and terrain-corrections were calculated by means of different densities, we had to go back to the basic data and set up a common gravity data set containing the co-ordinates, elevations, observed gravity (converted to a common gravity system) and terrain correction of each gravity station.

We started by checking the national gravity base networks. At the time of the measurement of the first gravity networks it was standard procedure to link the national fundamental gravity station directly to Potsdam. Since each national gravity network was based on its own single fundamental point, the possible distortions of the networks cannot be excluded. To improve the accuracy of the networks, interconnecting measurements were carried out between the gravity networks of the neighbouring countries.

These interconnecting observations between Slovakia and Hungary were carried out formerly in the framework of cooperation between the socialist countries. The gravity networks of the socialist countries were based on the corrected Potsdam gravity date of 1971, later converted to an absolute system (CSAPÓ *et al.* 1995). Different was the case with Austria: although the Austrian network was based on the IGSN–71 system, using the same corrected Potsdam value and was converted recently to an absolute system, there were no interconnecting gravity measurements between the neighbouring countries, so they had to be carried out in the framework of the DANREG programme (CSAPÓ *et al.* 1993).

Though the interconnecting measurements between Austria and Hungary revealed a 40 m Gal discrepancy between the dates of the two national gravity networks, this difference practically did not interfere with the construction of a unified Bouguer anomaly map. Similar measurements were carried out along the Austrian–Slovak border.

A further problem was that a significant part of the Austrian gravity data, obtained by ÖMV, were observed in a local gravity network. These data had to be converted to the Austrian national gravity system. The conversion was done by B. MEURERS.

The unification of the height systems presented no problem because the difference between the Adriatic system used by Austria and the Baltic one used by Hungary and Slovakia is a constant value:

$$H_{\mathrm{Adriatic}} - H_{\mathrm{Baltic}} = +0.675 \text{ m}$$

The gravity experts of the three participating countries decided to use the following parameters for the unified Bouguer anomaly map:

Gravity system: absolute
Normal gravity: WGS-80
Height system: Adriatic
Density: 2670 kg/m^3

Contouring of the map was done by a computer programme developed by ELGI. The randomly distributed anomaly data were interpolated to an 800 m grid by spline interpolation and this 800ˇ800 m grid furnished the input for the contouring programme. The final version of the Bouguer anomaly map is presented in a scale of 1:200 000 as appendix.

With regard to the accuracy of the Bouguer anomaly map the estimated error of ±0.35 mGal was determined for the Slovak part by Molodensky's method (ˇEFARA 1987). Since the accuracy of measurements and the determination of corrections are comparable in all three countries, the standard error of the map depends only on the density of measurements. Based on the actual station/km^2 point distribution, the overall accuracy of the unified map is estimated to be ±0.8–1.0 mGal. This is the limit to be taken into account in model calculations.

The station coverage of the region is far from being uniform. The density and distribution of gravity stations show gross variations in the project area, thus influencing the accuracy and quality of certain parts of the map.

The Bouguer anomaly map reflects the gravity effect of all subsurface geological bodies. The anomalies are sharper and variable and have high gradients on those parts of the area, where the older rocks, constituting the basement, are at or near the surface, *i.e.* in the western and eastern parts of the region. In the central part, where the basement lies at a depth of 7000–8000 m, the anomalies are flat and have low gradients due to the masking effect of the thick sedimentary cover.

Aspects of gravity interpretation

The objective of the interpretation of gravity maps is to deduce the geological build-up of the subsurface from the anomalies of the gravity field. All gravity anomalies originate from horizontal density variations. If the Earth was built up by layers of horizontally uniform density, there would be no gravity anomalies even if vertical variation in density exists.

Since the Bouguer anomaly map reflects the integrated effect of subsurface masses, the anomaly map is a complex image of subsurface geology; however, in special cases single sources can be identified. This means that the interpretation can never provide an unambiguous answer to a given geological problem because there is no single mathematical solution to the determination of the sources of anomalies. As a rule, sharp anomalies are caused by near-surface sources and broader anomalies by deep ones.

The crucial point of gravity interpretation is to separate the effects of different sources. This is a difficult task and needs the skill of the interpreter to choose the most convenient procedure and parameters.

In order to separate different elements, many procedures are known — from manual "smoothing" to the more sophisticated computer-based filtering techniques. The common aim in all procedures is to enhance certain elements and to suppress others, depending on the aim of the investigation.

As a result of anomaly separation we can speak about regional, residual and derivative maps. But the term "regional" is also subjective, referring to broad anomalies with sources normally deeper than the target of prospecting. To differentiate between residual and derivative maps is also complicated, but important because the residual maps reflect the gravity effect of local sources relatively near to the surface while the derivative maps reflect the gradient of the gravity field. Residual anomaly maps reflect the gravity effect of near-surface bodies, whereas derivative maps enhance the zones of maximum gravity variations which in most cases indicate the existence of structural lines with density contrast across them.

The resolution of a gravity survey depends on the measurement spacing but decreases with increasing depth of source no matter how accurately we know the gravity field.

Filtering techniques are very sensitive to the size of the applied filter. With the combination of the matrix elements and the size of the filter, many map variations can be produced. The proper designation of the resulting maps, however, depends very much on the skill of the interpreter not to mention the target of prospecting: the meaning of the term "residual" in the case of ore prospecting means something completely different than in the case of oil exploration.

According to Pintér & Stomfai (1979) a possible characterization of map variations can be based on the distribution of anomaly values. Maps with broad anomaly distribution curves can be regarded as residual and those with sharp distribution curves, as derivative ones.

To interpret a gravity map, the above-mentioned characteristics and limitations have to be kept in mind otherwise we can reach wrong conclusions by interpreting a residual map as a derivative one or *vice versa*. Accordingly we can state that there is no single or direct solution to eliminate regional effects and isolate local anomalies. All methods have their merits and limitations but a combination of them can provide useful information on the geological sources of the different anomalies.

The practical ambiguity of the inverse gravimetric task is always smaller than the theoretical one and it depends on a variety of other information. As an exception of the initial assumptions, there is the Kolárovo anomaly with an evident deep source, but because of the high gradient— most probably due to sharp density contrast— the anomaly is very distinct in the residual and in the regional maps as well.

Mathematical separation by convolution requires randomly distributed elementary bodies, without mutual dependence. In structural interpretation this requirement is not fulfilled because of highly different parameters (ˇefara 1986) tending to arrange the lithospheric masses in isostatic equilibrium, which is a natural trend of each system. As further shown in stripping, such a system leads to mutual compensation of gravity effects of separate masses. In addition, the individual fields (Bouguer's) undergo coherence (ˇefara 1986) and the frequency content of the resulting field can be highly different from the frequency fields of the individual geologically defined inhomogeneities. In no case and by no convolution method can we separate the field into negative and positive anomalies, which in our case means separation into the gravity effect of sediments and that of the basement. The task of separation can be solved either by stripping, or by model calculations controlled by a priori information.

Filtered maps

Within the framework of the DANREG programme, we have prepared several versions of regional-, residual- and derivative-like maps in order to separate the different components of the gravity field. All calculations were based on the original Bouguer anomaly values obtained as a result of the unification of the gravity data of the three interested countries. The randomly distributed data were gridded in an 800ˇ800 m data set and these created the input for further transformations.

Three kinds of classical filtering were performed and the maps were constructed. Although interesting conclusions could be drawn from the maps, we obtained more relevant information for the structure of crust and mantle using two other methods. Therefore instead of the filtered maps we present these, the stripped gravity map and the gravity lineament map.

Stripped gravity anomaly map

Since in basin areas the density of the sedimentary layers is normally lower than the density of the underlying consolidated rocks forming the basement, in the Bouguer anomalies the effect of the basement topography dominates thereby masking the effects of intrabasement density anomalies. To get information from deeper sources, the effect of the sedimentary "mass defect" has to be taken into consideration. Having information on the topography of the basement and on subsurface density data we can produce a gravity map free of the effect of any unconsolidated sedimentary layers.

As the central part of the DANREG programme area coincides with the Danube–Rába Basin where the thickness of sedimentary cover reaches 7000–8000 m, it seemed worthwhile to construct a gravity map corrected for sediment effect, thus enhancing the anomalies originating from deeper sources.

Before the beginning of the DANREG programme, stripped gravity maps were prepared both for the

Hungarian (Meskó 1984) and for the Slovak [ˇefara (ed.) 1987] part of the project area. In Hungary, Meskó based his calculations on the basement contour map of Fülöp & Dank (eds 1987). The density data were derived from the literature. An attempt was made to find a correlation between velocity and density data obtained from boreholes, but the result was not convincing. The gravity data were derived from a regional Bouguer anomaly map based on relatively few data. Meskó regarded the constructed map as a first attempt due to the fact that the data set available to him at that time was incomplete.

In Slovakia, ˇefara and his team prepared a stripped gravity map (ˇefara *et al.* 1987). The basic presumption was uniform density distribution of Tertiary sediments, *i.e.* s= $F(x,y,z)$, subdivided into two functions s= $f(h)+f_1(x,y)$. The first function is the dominant one in basins, the second gets significance in neovolcanic areas.

In the Danube–Rába and Vienna basins functions $f(h)$ were determined according to density measurements on borehole samples (of 36 and 12 boreholes, respectively). Models in the form of polygonal prisms along basement contour lines were chosen (their gravity effects were calculated in the network of 1ˇ1 km) (Table 1).

		.04

The maximum depth in which observations of density were carried out was ca. 3200 m in the Danube–Rába Basin, while ca 4200 m in the Vienna Basin. For greater depths the density model was extrapolated. Former models of the basement relief were the results of the chosen input criteria (maximum possible depth of the source, inevitable smoothness of shapes of the stripped map). In the final form (Kilényi *et al.* 1991) the maximum depth of the Danube–Rába Basin on the Slovak side has dramatically changed: from –5600 m —according to seismic cross sections of low information content (Fusán 1987)— to depths of 7000–8000 m. Reprocessing of seismic profiles later confirmed this calculation. Corrections of the stripped map as to the lateral changes of density [functions $f_1(x,y)$] were calculated only in the northern part of the Danube–Rába Basin where the basin fill is partly built up by sediments of older age producing higher compaction.

The accuracy of this part of the stripped map was assessed by standard deviation as ±1.8 mGal. Later revision of the map within the frame of the DANREG programme pointed to higher relative accuracy.

A stripped map was calculated by (Bielik 1991) using a similar technique in a net of 10ˇ10 km and on the basis of less detailed Bouguer anomalies according to the model in the table. The accuracy of the map was not characterized; we assume it is considerably lower than that of other parts.

For preparing a stripped gravity map for the project area the following data were at our disposal:

a) The contour map of basement topography was prepared within the framework of the DANREG programme by updating a formerly published map (Kilényi *et al.* 1991). That map provided the geometry of the sedimentary complex.

b) In the absence of boreholes penetrating the deepest parts of the basin no direct density data were available for those parts of the area. The density function we have used was based on several thousands of laboratory measured density data (Szabó & Páncsics 1994). The measured drill cores originated from different parts of the Pannonian Basin so the result can be regarded as an average density function approximating the sedimentary complex of the area.

In Table 2 below we present —besides the density contrast function used for our calculations— two more functions suggested by other authors (Bielik 1991, Bucha *et al.* 1994) for the same area.

The calculation of the gravity effect of the sedimentary complex was carried out in two steps:

1. To calculate the effect of the upper 4 km, a table was prepared containing the gravity effect of a 2ˇ2 km sedimentary block for each 100 m depth interval and for each 2 km distance beginning from the centre of the block to 20 km distance. The effect of blocks beyond 20 km from the actual grid point was neglected. The calculation was carried out by the MAGIX programme (INTERPEX Co.). The effect was determined by summing, point by point, the data of the table corresponding to the actual geometry.

2. In the depth interval below 4 km the 2ˇ2 km sedimentary blocks were substituted by vertical mass lines and their gravity effects were calculated.

The effects for the two depth intervals were added to the Bouguer anomaly at each 2ˇ2 km grid point.

The anomaly values obtained after the correction are free from the effect of mass defect due to the lower density of the sedimentary complex. Since the correction is based on the basement contour map and an average density function, the resultant map reflects their limitations. The total error, resulting from the errors of the density function, from approximating the basin fill by prisms and from taking into account only the 20 km neighbourhood of each point, can be estimated as not more than 10 mGals.

			–0.10

This 10 mGal should be considered as the absolute error (*i.e.* a 10 mGal shift of the anomaly range), the relative error does not exceed 2 mGals. The biggest discrepancies between model and reality exist at the foot of the various surrounding hills (Sopron Hills, Transdanubian Range, *etc.*).

The most conspicuous feature of the corrected map (see the attached maps) is the maximum range in the axis of the Danube–Rába Basin, with values generally above 40 mGal, which turns eastward at the Kolárovo maximum. The source of this anomaly range is bordered on the south and south-east by the Rába–Hurbanovo Line detected by both seismic and magnetotelluric data. Coinciding with the gravity anomalies, geomagnetic anomalies can be found as well.

These anomalies of different physical phenomena probably may be attributed to a common source, namely to an elevation of the Mohorovi discontinuity bounded by the Rába–Hurbanovo Line. The northern and western borders of this elevation are unknown, the assumption of a continuous deepening or a deep fault seems to be plausible too.

The elevation of the Mohorovièiæ discontinuity cannot be detected by seismic data between Bratislava and Győr, on the right side of Danube, partly because that part of section K–1 registered and processed till 12 s, stops just at the anomalous range and, partly, because at its easternmost part the Mohorovièiæ discontinuity reflections disappear, indicating a change in the deep structure.

The elevation of the Mohorovièiæ discontinuity under a deep basin is not a unique phenomenon; one can find several similar examples in the literature (NEMESI *et al.* 1994). Within the Pannonian Basin, in the Békés Basin, deep seismic sections of the last few years have revealed such an elevation involving even the asthenosphere. Its gravity and geomagnetic anomalies are similar to those of the Danube–Rába Basin.

A 10 mGal relative anomaly shows up against the maximum range of the corrected map at Kolárovo. It can be supposed that its source is in the basement. This area is of outstanding tectonic importance, as the SW–NE trend of the anomaly zone changes to a W–E trend at Kolárovo. The tectonic interpretation of this phenomenon has not yet been finalized.

Gravity lineament map

Description of the procedure

This technique is designed for estimating the location of density contrasts using gridded Bouguer anomaly data. To obtain the regional geological features and to remove small and insignificant local effects of the gravity field, the primary grid of Bouguer anomalies was smoothed by a 9-point Hanning filter.

The smoothed grid of Bouguer anomalies was used as an input for calculating the magnitude and direction of the horizontal gradients using the gravity differences between grid points in the *X* and *Y* directions. The g_x- and g_y-components of the gradients were calculated by linear regression, applied to the smoothed Bouguer anomaly values in grid intersections. Differences were calculated for every grid intersection with reference to the central grid point. Linear regression was applied to all gravity differences within a radius of R = 4.5 km to determine the g_x- and g_y-components of the horizontal gradient. Having obtained the gradient components from the linear regression, the magnitude and the direction of the gradient were calculated and stored.

The gravity lineaments were determined according to the method described by BLAKELY & SIMPSON (1986). The values of horizontal gradient magnitude were compared with its eight nearest neighbours in four directions (along the row, column and both diagonals), to see if a maximum is present. This comparison test was applied to every direction if the gradient value of the central grid point was greater than that of its two neighbours. If this happened, a counter *N* was increased by 1. Counter *N* ranges from 0 to 4 and provides a measure of the quality of the maximum. The authors referred to parameter *N* as “significance level” of the maximum. In the final step of the procedure, a small line, perpendicular to the direction of the horizontal gradient was drawn representing the gravity lineament in all grid points where parameter *N* was greater than 0.

Description of the lineament map

The above-described procedure was applied to the original Bouguer anomaly map without any modification. That is why the lineament map (see the maps attached) reflects all geological structures irrespective of their age and depth.

Blakely and Simpson's method approximates the edges of causative bodies as can be seen, for example, in the case of the Kolárovo anomaly on the map, besides the isometric shapes, at certain places linear patterns prevail, characterizing the tectonic elements of the region.

Based on the pattern of the lineaments, the area can be divided into four districts.

1. The central part is characterized by long and continuous lineaments —parallel with the Rába–Hurbanovo Line— with subordinate, short transverse directions.
2. The area of the Transdanubian Range (the SE part of the map) is characterized by a pattern of short and discon-

tinuous lines of dominantly N–S direction, whereas in the eastern part it changes to the dominance of NW–SE directions.

3. The lineaments have a different character in the NW part of the map: in the Bruck–Stupava direction the Mur–Mürz Line —the main, south-eastern tectonic line of the Vienna Basin— is reflected, while in the Bratislava–Pezinok Line the main tectonic directions of the Little Carpathians can be recognized. East of the latter, the N–S directions become dominant.

4. The Sopron–Bruck area (that of the Leitha Hills) is characterized again by short, discontinuous directions, such as that of the Transdanubian Range, reflecting the minor shallow structures.

Analysis of the lineament map is a useful tool for the tectonic interpretation of the region, especially in the deep basin areas.

Summarized geological interpretation of the gravity maps

In the foregoing we restricted ourselves mainly to presenting the procedure and the method of preparation of the various gravity maps and we mentioned only their main features.

By way of a summary, it can be concluded that the anomaly patterns of the Bouguer anomaly map characterize quite well with their smooth forms the deep basin areas and with their more disturbed forms those parts where the pre-Tertiary rocks are at or near the surface. In the contact zones of basement highs and deep basins the closely spaced, elongated isolines indicate fault lines such as the Mur–Mürz and Hurbanovo–Diósjenõ lines.

We would like to call attention to two curious features of the Bouguer anomaly map: the first is that the Vienna Basin in spite of its shallower nature is characterized by higher negative anomalies than the deeper Danube–Rába Basin. The second main feature of the map is that the Kolárovo gravity maximum lies in the intersection of the Rába and Hurbanovo–Diósjenõ lines. It is our conviction that the Kolárovo anomaly plays a key role in the understanding of the geological structure and history of the region.

These characteristics inspired us to prepare different versions of gravity maps to emphasize local, regional and directional features of the original Bouguer anomaly map.

It is clear, however, that gravity itself with its inherent ambiguity does not give clear-cut answers to our geological problems but due to the dense gravity survey over the whole region, the gravity data represent a continuous information system.

By integrating the gravity data with the results of other geophysical methods (geomagnetic, geoelectric, seismic) and with the geological information available for the area, to the Mohorovièiæ discontinuity will increase.

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