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SEPARATION OF GRAVIMETRIC ANOMALIES WITH DIFFERENT DEGREES OF REGIONALITY

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Abstract. The anomaly separation operation consists in determining the number of sources, the characteristics of each (depth, density, shape, and dimensions) so as to result in cumulative total anomaly, measured at the Earth's surface. This separation has to be done in the context of the fundamental ambiguity of gravimetric information, based on the cause-effect ratio. There are various methods for achieving this separation of gravimetric anomalies. This paper presents some examples of the use of the moving average method and the polynomial trend surfaces. In particular, we presented the results of the mobile mediation with different windows compared to the trend surfaces with different degrees, for a case study in Vrancea seismogenic area. For this study we used data from the International Gravimetric Bureau for geoglobal model WGM2012: Bouguer anomaly for density 2.67 g/cm^3, Free Air anomaly, isostatic anomaly, gravity disturbance and altitude. The moving average is a direct method for separating regional effects and local (residual) effects. Polynomial trend surfaces analysis contributes to the recognition, isolation and measurement of trends that can be calculated and represented by analytical equations, thus achieving a separation in regional and local variations. The analytical expressions of the polynomial trends based on the least squares method were calculated, highlighting the regional trend caused by the deep structures. Then, by calculating the residual values resulting from the difference between the initial values and the trend values from the network nodes used, we highlighted the superficial local effects. We also obtained information about the regional trend caused by geological structures at medium and large depths, by calculating the difference between gravity parameters, obtained with different moving average windows or tendency surfaces with different degrees, interpolated in same network.

Keywords: trend surfaces, Moving average, Bouguer anomaly, Free Air anomaly, gravity disturbance.

Rezumat. Separarea anomaliilor gravimetrice cu grade diferite de regionalitate. Operația de separare a anomaliilor constă în determinarea numărului de surse, a caracteristicilor fiecăreia (adâncimea, densitatea, forma și dimensiunile) astfel încât să rezulte o anomalie totală cumulată, măsurată la suprafața Pământului. Această separare trebuie făcută în contextul ambiguității fundamentale a informațiilor gravimetrice, bazată pe raportul cauză-efect. Există diferite metode pentru realizarea acestei separări a anomaliilor gravimetrice. Această lucrare prezintă câteva exemple de utilizare a metodei mediei mobile și a suprafețelor de tendință polinomiale. În particular, am prezentat rezultatele medierii mobile cu ferestre diferite comparativ cu suprafețele de tendință de diferite grade, pentru un studiu de caz în zona seismogenă Vrancea. Pentru acest studiu am folosit date de la Biroul Internațional de Gravimetrie pentru modelul geoglobal WGM2012: anomalia Bouguer pentru densitatea 2,67 g/cm^3, anomalia Free Air, anomalia izostatică, perturbația gravitațională și altitudinea. Medierea mobilă este o metodă directă de separare a efectelor regionale și a efectelor locale (reziduale). Analiza suprafețelor polinomiale de tendință contribuie la recunoașterea, izolarea și măsurarea tendințelor care pot fi calculate și reprezentate prin ecuații analitice, realizând astfel o separare a variațiilor regionale și locale. Au fost calculate expresiile analitice ale tendințelor polinomiale pe baza metodei celor mai mici pătrate, evidențiind tendința regională cauzată de structurile profunde. Apoi, prin calcularea valorilor reziduale rezultate din diferența dintre valorile inițiale și valorile de tendință din nodurile de rețea utilizate, am subliniat efectele locale superficiale. De asemenea, am obținut informații despre tendința regională cauzată de structurile geologice la adâncimi medii și mari, prin calcularea diferenței dintre parametrii gravitaționali, obținuți cu diferite ferestre medii mobile sau suprafețe de tendință cu grade diferite, interpolate în aceeași rețea.

Cuvinte cheie: suprafețe de tendință, mediere mobilă, anomalia Bouguer, anomalia Free Air, perturbația gravității.

INTRODUCTION

The observed gravity is given both by the topographic surface and the density variations of the geological formations in the basement. Thus, in the regions with a positive altitude (e.g. mountainous areas) the average density of Earth Crust is lower than in the ocean basins, where the basaltic layer is predominant and implicit, the average density is higher. The Free Air anomaly is positive on high altitude and negative in depressions. The Bouguer Anomaly is opposite (in the mirror) to the topographic surface. The thickness of the Earth's Crust, determined by seismic methods, varies considerably, being thin under the oceans and thick under the continents. Density suddenly increases at the Crust / Mantle interface (density is 2.800 – 2.900 g/cm^3 in the lower Crust, density 3.200 – 3.300 g/cm^{3}in the upper Mantle). This means that under the high altitude regions of the continent, Crust is thicker and compensates the isostatic balance through the size of its thickness, while Crust under the oceans is much thinner and heavy materials in Mantle are closer to the surface.

The Crust usually behaves as a rigid layer capable of withstanding stress, but at a certain depth, with increasing of temperature and pressure, it has a plastic deformation under the influence of the stress caused by the adjacent environment.

Thus, the notion of modern tectonic plates requires the existence of a deformation region in Mantle under the effect of tensions applied at the geological time, favoring the movement of the tectonic plates in relation to the Deep Mantle.

Isostasy concept arose a century ago as a result of gravitational observations, seismic measurements and rheology responses that competed with the theory of compensation for the gravitational effect of topographic masses.

Thus, the importance of separating gravitational anomalies with different degrees of regionality for deciphering deep geological structures appears. This can be done by many methods, among which we mention the moving average method with different windows, the tendency surface method, upward continuation (Laplace equation) and downward continuation (Poisson equation), spectral analysis method, multispectral methods, wavelet, etc.

An important role in deciphering the profound geological structure is the filtration of gravimetric data of the "low pass filter" type. In this paper we conducted filtering of this type based on programs we have developed according to the least squares methodology. In this regard, we mention the results obtained by Unwin D (1978), where the algorithm for the calculation of the trend surfaces up to the second degree is presented, as well as examples. About the least squares method, which underlies the calculation of the coefficients of the analytical expressions of the trend surfaces, there are many works, among which we can mention: FARHANG-BOROUJENY (2013), DUMITRIU et al. (1972), HARBAUGH (1972), POULARIKAS & RAMADAN (2006), where various techniques of this method and examples are presented. Trends of hypersurfaces were mentioned by authors such as KARAKUS et al. (2011), DUMITRIU et al. (1972), etc.

Parameters processed in this way are: Bouguer anomaly, Free Air anomaly, isostatic anomaly, gravity disturbance, and elevation of the terrain. All these parameters are described in HEISKANEN & MORITZ (1967), VAJDA et al. (2004), BARTHELMES & KÖHLER (2016), PAVLIS et al. (2008) and many others.

The "low pass" filters we have made in this paper are mobile medals with windows of various sizes and polynomial surfaces of various degrees. In the case of mobile environments, the used window is larger (it contains several values), the more information obtained is relevant for larger depths. In case of polynomial trends, the higher the polynomial degree of the surface, the more information is relevant for smaller depths.

Residual anomalies calculated for both mobile average and trend surfaces reflect the shallow structure and local effects. These residual abnormalities are filtered data with "high pass" filters.

We also calculated the filtered data with "band pass" filters, represented by the difference between mobile averages with different windows. These data reflect the mean depth, without the depth being quantified. However, their interpretation in relation to depth, allows us to correctly input the parameters into the modeling program.

DATA USED

The information and data used in gravimetric anomalies maps (Bouguer, Free-Air, isostatic) are related to the EGM 2008 geopotential model (Pavlis et al., 2008) / DTU 10 gravity field (ANDERSEN, 2010). The Free Air anomaly was calculated in the context of the Molodensky theory (HEISKANEN & MORITZ, 1967) and includes corrections for atmospheric mass. The reference density used for the Bouguer and isostatic maps was 2,670 kg / m^3 and the spatial resolution of 1 'x1'.

The World Gravity Map (WGM) denotes the use of a large-scale gravity resolution set in digital grids on a global scale from the available Earth gravity and digital terrain models. WGM 2012 is the first global map of gravity anomaly maps (free air anomaly, complete Bouguer anomaly, isostatic anomaly) derived from the EGM 2008 geopotential model and the ETOPO 1 model - the overall relief model; WGM2012 also takes into account the contribution of atmospheric masses, earth, oceans, inland seas, lakes and glaciers, providing maps of the scale of gravity on a regional or global scale, also available in digital format.

The used gravimetric data were derived from Earth Geopotential Model EGM 2008 through spherical harmonics development to 2190 degree by the National Geospatial Intelligence Agency (NGA) (PAVLIS et al., 2008). The EGM 2008 model includes surface gravimetric (land, sea and air) measurements, satellite altimeters and satellite gravity (Grace mission).

METHODS

The mobile averages method is a direct technique for leveling anomalies, which highlights wide anomalies and removes small anomalies. The residual map retains and localizes local anomalies, their value depending directly on the size of the used window.

Another method, similar to the mobile averages applications, which is also a data filtering system, is the analysis of the polynomial trends. These surfaces contribute to the recognition, isolation and measurement of trends, by separating large-scale variations and local variation trends. This separation is done by adjusting the trend function to different degrees. Tendency analysis is part of the field of regression analysis satisfying the smallest squares criterion. The difference between the calculated value of the trend surface at a certain point and the value observed in that point is the residual value. The sum of the squares of these residual values must be minimal according to the smallest squares criterion. If the trend area is considered to be a regional or large scale component, then the residual value should be considered as the local or small scale component. Removing the regional trend has the effect of highlighting local components represented by residual values. Also, the principles of trend analysis are applicable for hypersurfaces in any number of dimensions. A surface occupying a three-dimensional space is a mathematical function with a dependent variable and two independent variables. We can operate mathematically and with functions of four or more variables (in hyperspace) that have great importance in some applications.

An efficient analyzing method of data using trend surfaces is based on the progressive application of this method, starting with the smallest degree of surface, then going to higher degrees. Thus, in the first place, the residual to the trend plan can be calculated. Then, for these residual values, upper-order trend surfaces (for example: for grade 3 or 6) can be calculated. In this way, successive residues can be calculated from which components that reflect certain degrees of regionality and depth of anomalous sources will be removed.

RESULTS AND DISCUSSIONS

Map of the Bouguer anomaly in Romania, was based on data from BGI (Fig. 1), on a latitude grid of 43^0 to 49^0 and longitude from 20^0 to 30^0, obtaining a number of 54480 data in geographic coordinates. We transformed these in coordinates STEREO 70 to have the dimensions in km.

We used a grid of 210 lines x 250 columns = 52500 nodes (values) for each map. The mesh density has 3.25 km x 3.20 km, i.e. approx. 10 km^2.

The studied area (Vrancea seismological extended zone) is marked by a rectangle and has an extension of 155.33 Km in the East-West direction and 164.64 Km in the North-South direction, representing an area of 25,573.5 Km^2.

On the map, we overlaid the isobates at the base of the Crust, as well as the main tectonic elements in the detail area (Peceneaga-Camena Fault and Capidava-Ovidiu Fault). These isobaths at the Moho surface were obtained by RĂDULESCU (1988) from the seismic prospecting. There were represented on the map the isobath interval for 40 km to 52.5 km, with the increment of 2.5 km from the study zone.

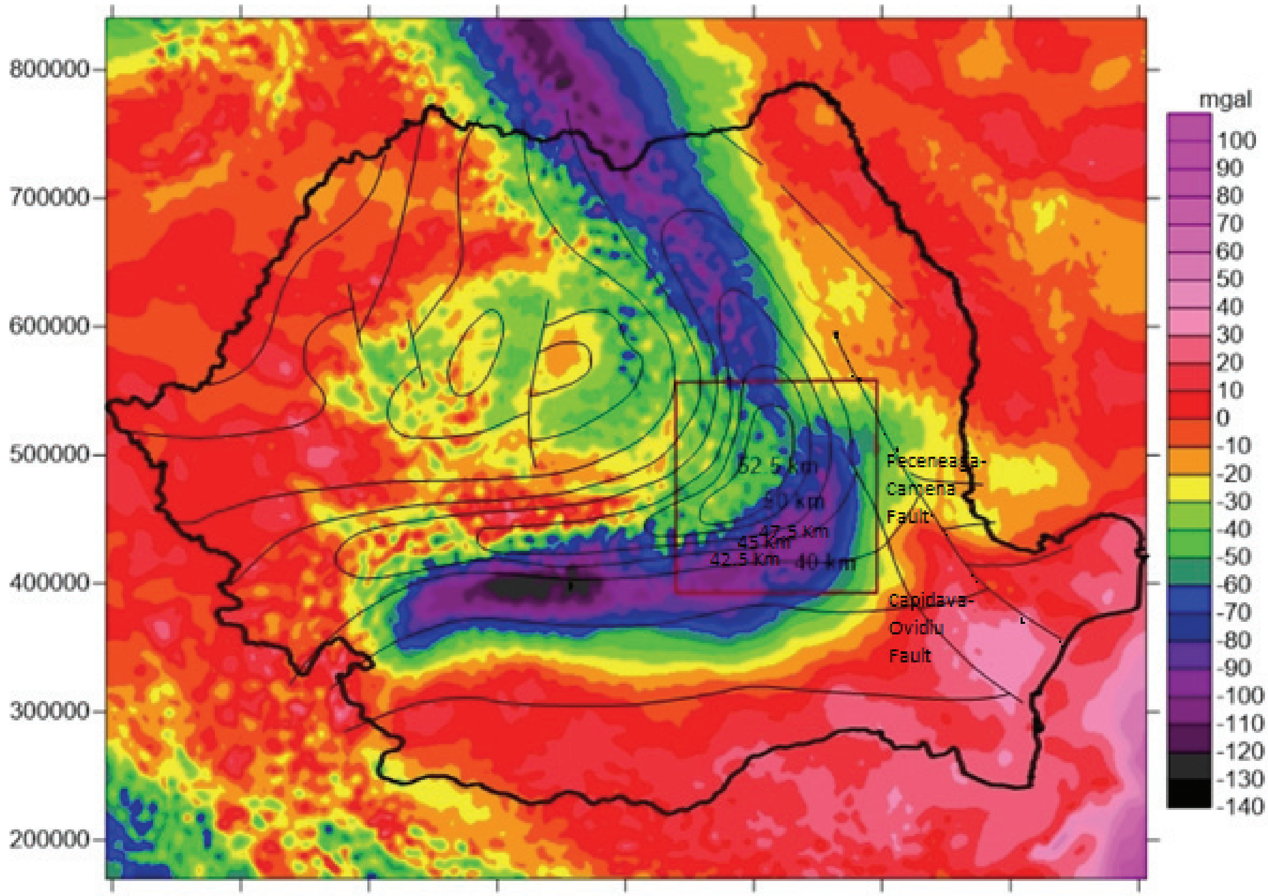

Figure 1. WGM2012 - Complete spherical Bouguer gravity anomaly, with Moho isolines of deep and main fault.

Peceneaga - Camena Fault and its prolongation to NV and SE is found both in the Crust and under Crust, being a major active fracture.

Along Peceneaga - Camena fracture, as well as its prolongation to the NW, two continental lithospheric portions with different particularities come into contact. Close to it, alongside contact, seismological data show that there have been earthquakes, both normal and deep.

Vrancea area is affected by a crustal and mantle fracture system, NE-SV orientation, delineating between Focsani and Covasna a submerged area that can be traced to Bucharest and Ploiesti.

In Vrancea region, there exist both compressive and extensional events, with focal planes having different directions. This can be attributed to the possibility of the coexistence of several physical, geodynamic and rheological processes, each acting at various scales of time and space gravitational diving, phase transitions and dehydration of rocks (ZADEH et al., 2005) thermal barriers (BEȘUTIU, 2006), etc.

The seismicity of Vrancea region, the crumbly deformations and the lack of volcanism usually associated with the subduction zones have been channeled in three directions in the conception of various scientists: subduction of the ocean crust "in place", rupture of the ocean Crust and its roll-back, respectively lithospheric delamination (Fig.2).

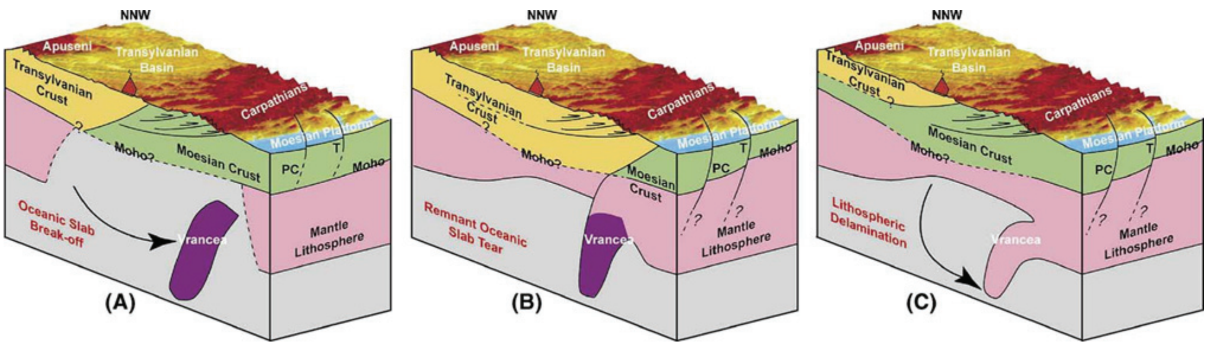

Figure 2. The main geodynamic scenarios are: (A) the subduction of an ocean plate and its break-off, B) the subduction of an ocean plate, and (C) progressive lateral tearing under the Carpathian vortex and delamination of the continental lithosphere (after KNAPP et al., 2005)

We used 3 windows of mobile average (with: 3x3 values, 5x5 values and 7x7 values) with which we traveled the entire network from point to point of the selected area with 50x50 values. The length of mesh on the X axis of the grid (in the West-East direction) are 3.17 km and the length of the Y axis of the grid (in the North-South direction) are 3.36 km, resulting a surface of network mesh about 10.65 km^2. This grid was chosen to have a similar resolution with the initial data used (from BGI) for Romania.

For tendency surfaces, we have developed programs for calculating analytical expressions for the following types of surfaces: plan (first degree): $Z_{tend} = A + Bx + Cy$,

2nd degree: $Z_{tend} = A+BX+CY+DX^2+EXY+FY^2$,

3rd degree: $Z_{tend} = A+BX+CY+DX^2+EXY+FY^2+GX^3+HX^2Y+IXY^2+JY^3$ și

6th degree: $Z_{tend}=A+BX+ CX^2+DX^3+EY+FXY+GX^2Y+HX^3Y+IY^2+JXY^2+KX^2Y^2+LX^3Y^2+MY^3+NXY^3+OX^2Y^3+PX^3Y^3$, where X and Y represent the independent variables (in the coordinates system STEREO 70 in the directions W-E, respectively N-S) and Z represents the variable dependent on X and Y.

The residual value is $Z_{rez} = Z_{obs} - Z_{tend}$ highlights the local aspects of anomalies.

In Fig. 3 (A, B, C), there are rendered the residual Bouguer anomalies. From the initial values we lowered the values of the mobile averages with different windows. These anomalies are the result of "high pass" filters, so it refers to causes from the surface to a certain depth that is proportional to the size of the used window.

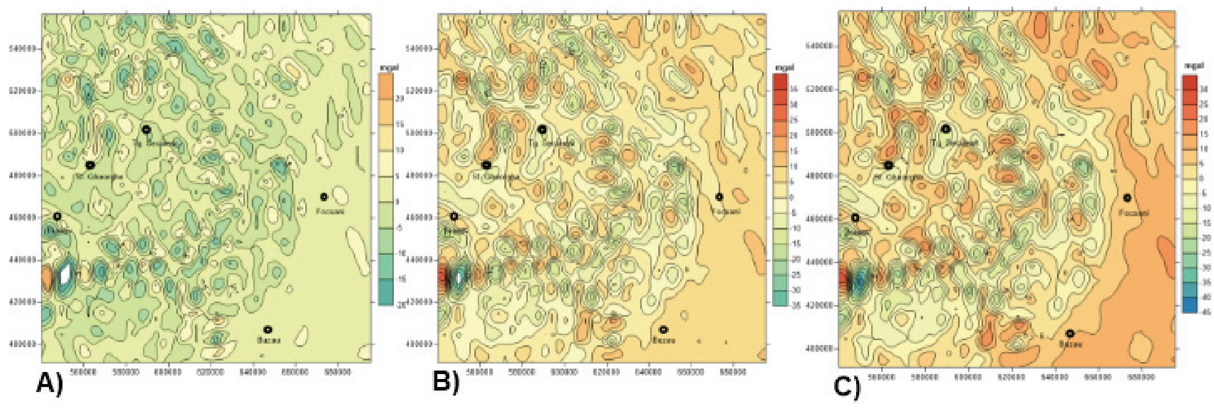

Figure 3. Residual Bouguer anomaly calculated with the mobile averages of 3 different square windows:
A) Residual Bouguer anomaly calculated with the mobile averages of 9 values;
B) Residual Bouguer anomaly calculated with the mobile averages of 25 values;
C) Residual Bouguer anomaly calculated with the mobile averages of 49 values.

Figs. 4 and 5 (A, B, C, D, E, F) show the effects of mobile averages and tendency surfaces for Bouguer and Free Air anomalies. These images in each figure are presented in the order of the degree of averages (the size of the window used), which is reflected in the extension and depth to which the information refers.

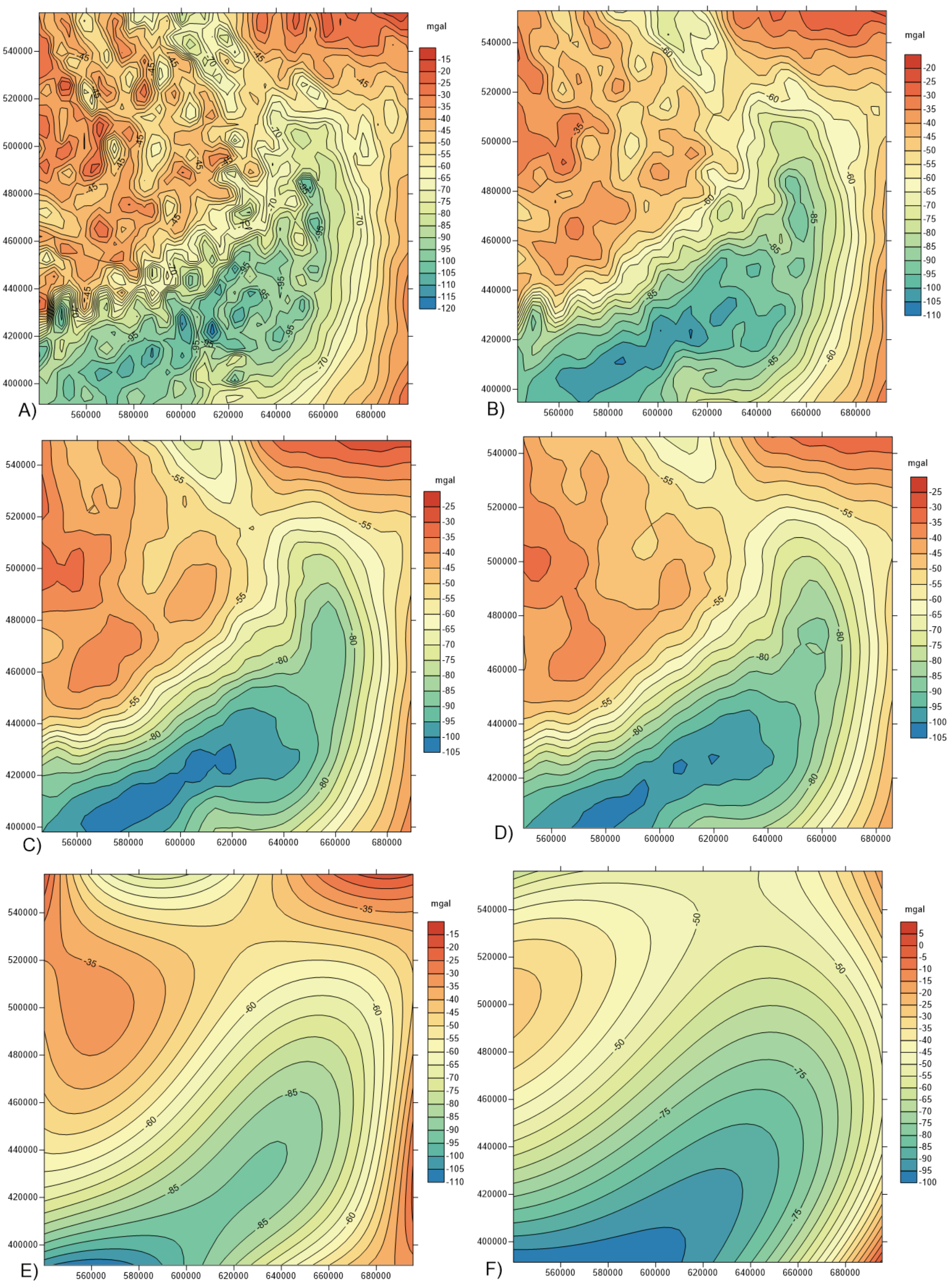

Figure 4. Bouguer Anomaly in the studied area (marked in fig.1; from BGI data):
A) The representation of unfiltered data;
B) Representation of the data averaged in moving windows of 9 values (3 lines * 3 columns);
C) Representation of the data averaged in moving windows of 25 values (5 lines * 5 columns);
D) Representation of the data averaged in moving windows of 49 values (7 lines * 7 columns);
E) The tendency surface with 6th order; F) The tendency surface with 3rd order.

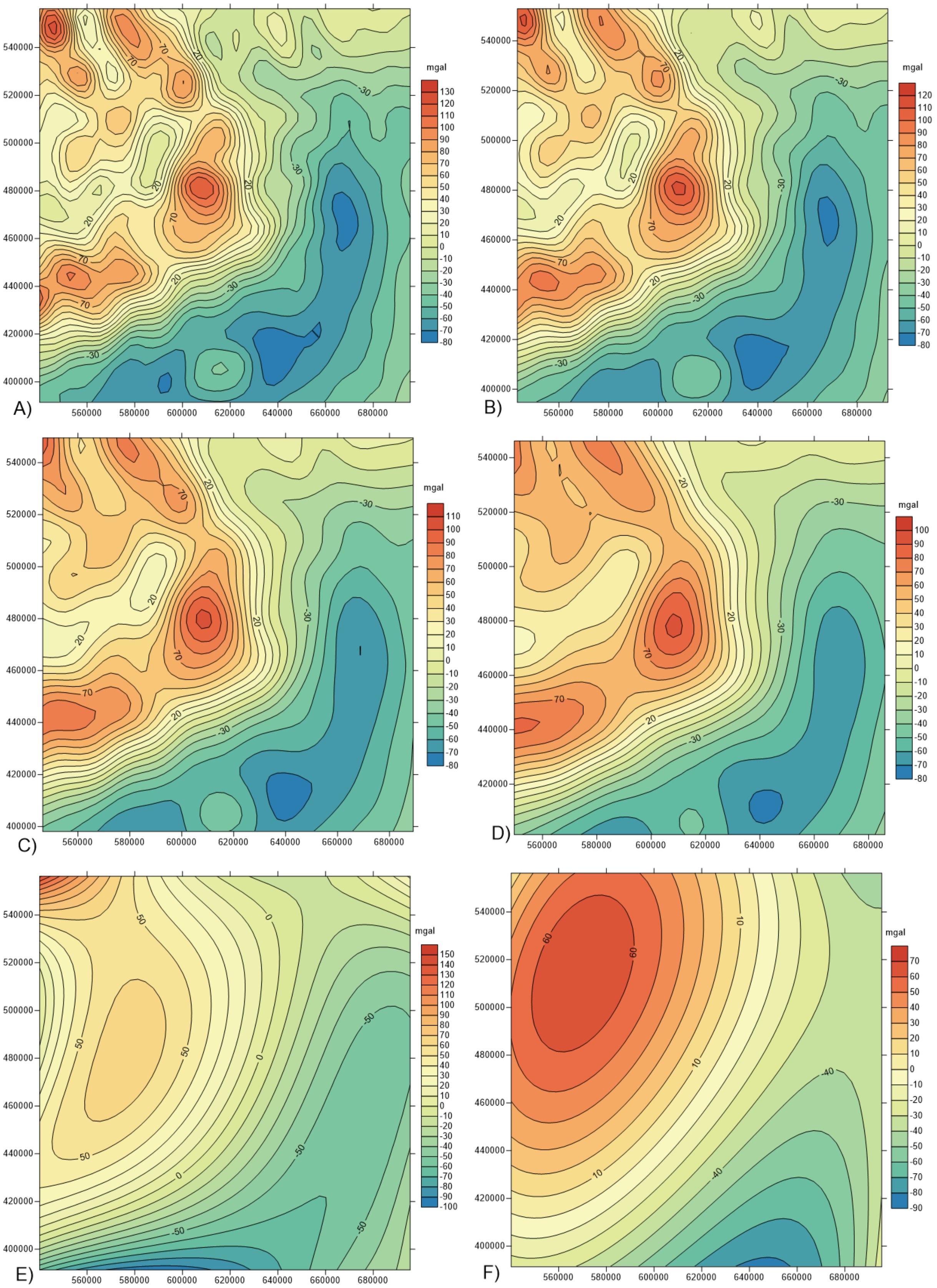

Figure 5. Free Air Anomaly in the studied area (marked in Fig.1 ; from BGI data):
A) The representation of unfiltered data;
B) Representation of the data averaged in moving windows of 9 values (3 lines * 3 columns);
C) Representation of the data averaged in moving windows of 25 values (5 lines * 5 columns);
D) Representation of the data averaged in moving windows of 49 values (7 lines * 7 columns);
E) The tendency surface with 6th order; F) The tendency surface with 3rd order..

The data was interpolated with the Surfer program, the Kriging method. Figs. B, C and D show the mobile averages with 9 values, 25 values and 49 values respectively, reflecting an increase in the wavelength, the regionality of the anomalies and the depth of their causes. In Figs. 4 and 5 (E and F), there are tendency surface for Bouguer and Free Air anomaly (6^{th} degree and 3^{rd} degree). They reflect anomalies with a higher degree of regionality, greater wavelength and deeper causes. In fig.4E, it is the tendency surface with 6^{th} order, the coefficients being: A=499438.5000000000; B=-373202.3671875000; C=81600.5175781250; D=-5520.4898071289; E=-19053.6718750000; F=91387.8554687500; G=-28282.2333984375; H=2245.9517211914; I=-63199.0019531250; J=13665.5058593750; K=619.8403320313; L=-186.4072189331; M=9255.7174072266; N=-3328.0280761719; O=342.1310119629; P=-7.7146945000. In fig. 4F, it is the tendency surface with 3^{rd} order, the coefficients being: A=-11938.42251006; B=4797.3673020601; C=1487.1852331124; D=-652.9127963639; E=-438.9016750949; F=0.0000125275; G=45.8620878794; H=-31.7580106317; I=85.5197506216; J=-37.4263031660.

The tendency plan of Bouguer anomaly has the following equation: Z=-188.707147163*X-0.1554708098*Y+27.0513680505.

Also, for Free Air anomaly, in fig. 5E, it is the tendency surface with 6^{th} order, the coefficients being: A=652400.357; B=-573419.16; C=130655.106; D=-8890.1671; E=-13391.961; F=176664.462; G=-53988.576; H=4163.66569; I=-84321.436; J=3692.53278; K=5022.64747; L=-550.96074; M=11806.3857; N=-3037.9968; O=81.2227445; P=16.2677661. In fig.5F is the tendency surface with 3^{rd} order, the coefficients being: A=-17470.82; B=9726.1603; C=-1795.333; D=-1851.304; E=694.84799; F=7.129E-05; G=123.81737; H=-93.70176; I=46.332052; J=-23.12028.

The tendency plan of Free Air anomaly has the following equation: Z=187.9363*X-66.7992*Y+47.01299.

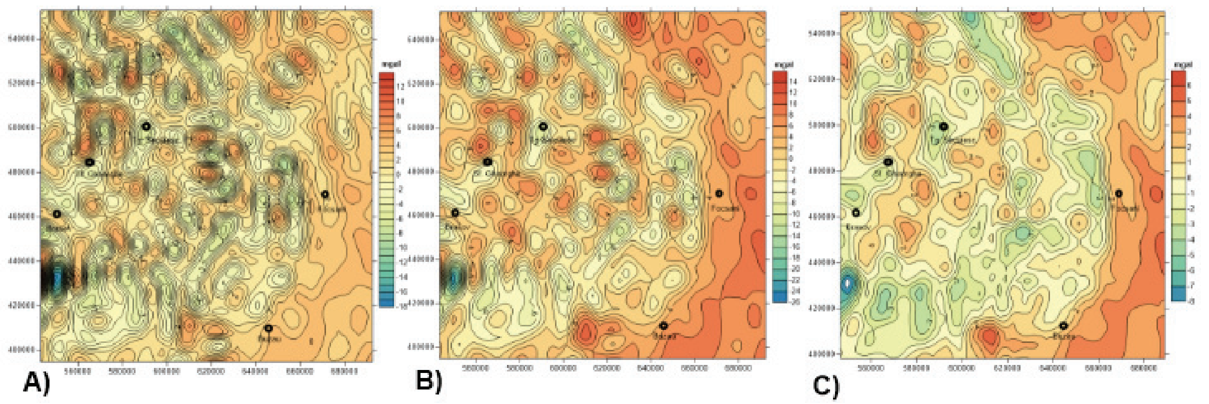

Figure 6. Differences between the moving averages of the Bouguer anomaly, calculated with two different windows;
A) The difference between the moving averages of the Bouguer anomaly, calculated with the windows of 9 values and 25 values;
B) The difference between the moving averages of the Bouguer anomaly, calculated with the windows of 9 values and 49 values;
C) The difference between the moving averages of the Bouguer anomaly, calculated with the windows of 25 values and 49 values.

Fig. 6 shows Bouguer anomalies as a result of the application of "band pass" filters. We made the difference between two averages made with two different windows, in every point of the network. These anomalies refer to causes from a certain depth range that is proportional to the dimensions of the two used mobile windows.

CONCLUSIONS

In the present paper we presented as filtering methods only the mobile mediation with windows of different dimensions and polynomial tendencies of different degrees. These types of filters were compared with the results of other types of filtration that I did not present in this paper (Fourier 2D analysis, Wavelet analysis with different window types, analytical continuation up and down), given the volume, both theoretical and methodological, the programs used and the results of the processes, as well as their geological significance.

The results of all types of filtering can be matched with 2D models (for which we have developed the data profiles and sketched the structure in depth based on the results obtained by various methods and various authors).

Also, the variation of the correlation factor between two sets of parameters brings information for geological and tectonic assumptions. This correlation factor between two sets of data can be calculated, similarly as in mobile averages with windows of different sizes, passing through the entire network of points, bringing information from different depths. The correlation between two sets of parameters may be some indicators that they are dependent on common causes. Contrast of densities juxtaposed in areas with different petrophysical properties at suture zones, usually cause gravimetric anomalies. However, some of the anomalies of gravity that have deep causes may be masked by the presence of geological formations of a very different density compared to deep formations. Anomalies of gravity caused by small-scale formations can be easily recognized in residual maps after regional trends are eliminated.

In conclusion, referring only to the types of filters presented in the paper, we can say that they provide us with information with different degrees of regionality and from different depths, which of course cannot be quantified until all the geological and geophysical information has been corroborated. These filters can bring both information about local and surface effects (residual maps, through "high pass" filters), mid-depth structures (through "band pass" filters), and deep structure (tendency maps, through "low pass" filter).

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