

1 **INTERPRETATION OF THE TOTAL MAGNETIC FIELD ANOMALIES**
2 **MEASURED BY THE CHAMP SATELLITE OVER A PART OF EUROPE AND THE**
3 **PANNONIAN BASIN**

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16 In this study we interpret the magnetic anomalies at satellite altitude over a part of
17 Europe and the Pannonian Basin. These anomalies are derived from the total magnetic
18 measurements from the *CHAMP* satellite. The anomalies reduced to an elevation of 324 km.
19 An inversion method is used to interpret the total magnetic anomalies over the Pannonian
20 Basin. A three dimensional triangular model is used in the inversion. Two parameter
21 distributions: Laplacian and Gaussian are investigated. The regularized inversion is
22 numerically calculated with the Simplex and Simulated Annealing methods and the
23 anomalous source is located in the upper crust. A probable source of the magnetization is due
24 to the exsolution of the hematite–ilmenite minerals.

25 **Keywords:** *CHAMP*, total magnetic anomalies, Laplacian and Gaussian parameter
26 distributions, regularized inversion, Simplex and Simulated Annealing methods, exsolution of
27 hematite–ilmenite minerals

28 **Introduction**

29
30 Satellite altitude magnetic anomalies, while lacking in the ability to measure short-
31 wavelength anomalies, act as a low-pass filter and record the long-wavelength regional
32 magnetic fields. This integrated broad scale field is useful in the interpretation of large and
33 deep structures. Therefore in order to make a sectional interpretation of Western Europe and
34 in detail the Pannonian Basin we employed higher altitude measurements.

35 The Geoforschungszentrum (GFZ) satellite *CHAMP* observed the gravity and magnetic
36 fields of the Earth with high accuracy between July 15, 2000 and September 19, 2010. The

37 total magnetic field of the Earth was measured by a scalar Overhauser magnetometer with the
38 accuracy of ± 0.5 nT.

39 We have previously interpreted *CHAMP* magnetic anomalies over several different
40 areas (Taylor et al. 2003, 2005 and 2008, Kis et al. 2011).

41 Our data for this study were measured between January 1 and December 31, 2008. At
42 this time the *CHAMP* had its elevation of 319–340 km. In our report the total magnetic
43 anomaly field over a part of central Europe and the Pannonian Basin will be interpreted.

44 Only data whose Kp index was less than or equal to 1. were selected for processing.

45 After the satellite data were reduced and plotted (Kis et al., 2011) we made a
46 quantitative interpretation using method of Kis et al. (2011) with some modifications. Some
47 parts of the above mentioned phases have been published by Kis et al. (2011). The location of
48 the *CHAMP* total magnetic measurements is determined by latitude, longitude and radius. The
49 total magnetic anomaly data are derived from the 3D interpolation of the Gaussian weight
50 function. The details of the interpolation are given by Véges (1971) and Kis and Wittmann
51 (1998, 2002).

52 For the sake of completeness phases 1 – 3 will be summarized while the others will be
53 discussed in more detail.

54 Our analysis is:

- 55 1) The data for the forward problem of the inversion are in a spherical polar coordinate
56 system. These total magnetic anomaly data are then transformed from the spherical
57 polar coordinate system into an *xyz* Cartesian coordinate system;
- 58 2) We determined an appropriate forward model for the inversion;
- 59 3) A decision on an inversion procedure and the probability distribution of the model
60 parameters was made;
- 61 4) Regularization of these reduced data was then completed;
- 62 5) Finally an interpretation of these results was carried out using our inversion method.

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64 **A review of satellite altitude geomagnetic anomaly interpretations of the tectonics a** 65 **section of Central Europe.**

66

67 The mapped anomalies shown in Fig. 1a reflect the large-scale general tectonic pattern
68 of this region, one of the most complex structural areas on Earth.

69 The region covered by our *CHAMP* satellite altitude magnetic anomaly study of central
70 Europe is given in Fig. 1a. This area extends from 0° to 45° East Longitude and 40° to 65°

71 North Latitude. This sector is centered on central Europe. Satellite altitude magnetic data are
72 only capable of mapping large scale (generally assumed to be equal to the altitude of the
73 satellite) and deep structures. The mapped anomalies, given in Fig. 1a, reflect the large-scale
74 general tectonic pattern of this region.

75 We will briefly discuss a regional interpretation of the major magnetic anomalies and a
76 more detailed one for the anomalies over the Pannonian Basin. There are several major
77 structures in our study area. The northwest-southeast trending Tornquist-Tessyre Zone
78 (TTZ), a suture, dominates central Europe revealing the collision zone between the West
79 European Craton (Avalonia) and the Baltic Shield (Baltica). Therefore, the TTZ is a structural
80 boundary between the Paleozoic or western part of Europe and the Proterozoic or eastern
81 sector. The magnetic signature of this large suture is mapped by the satellite altitude data as
82 two northwest-southeast trending anomalies with the negative to the southeast and the
83 positive to the northeast (Fig. 1a) (Taylor and Ravat, 1995).

84 Avalonia is a mélange of Caledonian, Hercynian (Variscan) and Alpine terrains;
85 while Baltica is essentially a complex of Pre-Cambrian structures. Three major tectonic plates
86 converge to form the TTZ. The northwest sector of Avalonia is comprised of Caledonian and
87 Hercynian terranes. Initially this feature collided with Baltica in the late Ordovician
88 (Trench and Torsvik, 1992). Subsequently, the combined Caledonian (Hercynian) Baltica
89 block merged with the Alpine/Carpathian plate. The Alpine/Carpathian block came from the
90 south and abuts the Rhenohercynian and Saxothuringian Zones which acted as a buffer
91 between these two joined plates. This Alpine/Carpathian segment was added during the major
92 collision between the Eurasian and the African plates in the Tertiary. A complex pattern of
93 compression and extension resulted from this merger. See Aubouin (1980) and Blundell et al.
94 (1992) for a general description and Pharaoh (1999) and Guterch et al. (1986) for a more
95 detailed interpretation.

96 There have been several magnetic studies of the TTZ using both ground based and
97 satellite data. Ground based magnetic interpretations of this region are given by Banka et al.
98 (2002) and Grabowska and Bojdys (2004), they emphasized the distinct border of this feature.
99 While satellite altitude data reveal a broader structural pattern (Taylor and Ravat, 1995 and
100 1996; Pucher and Wonik, 1996, and 1998). Taylor and Ravat (1995) found that this suture
101 represented the juxtaposition of two different plates the Avalonia section with a younger and
102 thinner crust and higher than average heat flow had a negative anomaly while the older,
103 Baltica plate has a thicker and lower than average heat flow and a positive anomaly. This
104 region was modeled by two bodies with Avalonia having a reverse magnetization on the

105 Baltica a normal magnetization. However, Pucher and Wonik (1996, 1998) models are
106 significant different in the number and shape of these magnetized bodies while having a
107 somewhat different direction of the magnetization. However, that both agree the Avalonia and
108 Baltic blocks have a reverse magnetization for the former and a positive for the latter.

109 The two remaining large circular satellite magnetic anomalies circular and (Fig. 1a) were
110 interpreted to be the result of varying crustal thickness, one negative (< -20 nT) over the
111 southern part of the Finnish Svecofennian shield (Taylor et al., 2005, 44 km crustal thickness)
112 and the other positive (> 22 nT) with a greater than 50 km thick crust is the Kursk Magnetic
113 Anomaly (KMA, Taylor and Frawley, 1987, Taylor et al. 2003).

114 Figure. 1b shows a subsection of the anomaly field (Fig. 1a) and is centered on the
115 Pannonian Basin. The data processing for the Pannonian Basin is the same as the regional
116 field. *CHAMP* anomaly data are transformed from the spherical polar coordinate system to the
117 Cartesian coordinate system. The steps of transformation are summarized in the published
118 paper of Kis et al. (2011). Only those anomaly data which cover the Pannonian Basin are
119 transformed. We will quantitatively invert and interpret these data in more detail.

120 The Pannonian Basin formed in the Miocene when elements of the African plate
121 collided with the Eurasian plate this initiated a complex series of tectonic interactions. From
122 the northeast thin European continental crust was subducted beneath the Dinarides plate.
123 North-south directed forces produced both compression and east-west extension. The
124 subducting East Carpathian slab then rolled back allowing asthenospheric material to rise
125 under the lower crust producing a back arc extension and thermal up lift of the Carpathian
126 crust. Subsequently this produced extensional collapse in these terraines causing crustal
127 thinning, local compression, rifting, northeast-southwest shear faulting and basin formation.
128 This is description is oversimplified and serves to give some indication of the complexity of
129 this region, see; Horvath (1993), Morley (1993), Huisman et al. (2002) and Lorinczi and
130 Houseman (2010) and references therein.

131 The magnetic anomaly map at an altitude of 324 km (Fig. 1b) shows a large NW–SE
132 oriented negative anomaly in the middle of the Pannonian Basin. To model this anomaly in
133 our inversion we used a triangular polygonal prism. The inversion model is shown by Fig. 2.
134 Plouff's (1976) method was used to compute the field of this model. The selection of this
135 model was based on our interpretation of the vertical gradient map of the *CHAMP* total
136 magnetic anomaly field (Kis et al. 2011). The forward model has a reverse magnetization of
137 minus 1.5 A/m, with an inclination and declination of -60° and 60° , respectively. These values
138 were determined by Taylor et al. (2005) and applied by Kis et al. (2011).

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Results summarized in the phase 1 – 3

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Multivariate Gaussian and Laplacian probability distribution have been investigated in inversion procedures. The Bayesian inference procedure has been applied which is expressed by the following equation

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$$p(\mathbf{m}|\mathbf{d}) \propto p(\mathbf{d}|\mathbf{m})p(\mathbf{m}) \quad (1)$$

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where $p(\mathbf{m}|\mathbf{d})$ is the *a posteriori* conditional probability density, $p(\mathbf{d}|\mathbf{m})$ is the likelihood probability density, and $p(\mathbf{m})$ is the *a priori* probability density. The Bayesian inversion is widely used in the inversion procedures and is summarized by Duijndam (1988a, 1988b), Menke (1989) and Sen and Stoffa (1995). In the above equation vector \mathbf{m} indicates the determined model parameters $[(x_1, y_1), (x_2, y_2), (x_3, y_3), \text{ and top and base depths are } Z_T \text{ and } Z_B, \text{ respectively}]$, vector \mathbf{d} indicates the measured data.

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The multivariate Gaussian *a posteriori* probability can be expressed as the multiplication of *a priori* and likelihood probability densities. Disregarding the constant multipliers the *a posteriori* probability is given as:

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$$p^{a \text{ posteriori}} \propto \exp\left(-\frac{1}{2} (\mathbf{m} - \mathbf{m}^{a \text{ priori}})^T \mathbf{C}_m^{-1} (\mathbf{m} - \mathbf{m}^{a \text{ priori}})\right).$$

158

$$\cdot \exp\left(-\frac{1}{2} (\mathbf{d}^{\text{measured}}(\mathbf{c}, y) - T^{\text{calculated}}(\mathbf{c}, y, \mathbf{m}))^T \mathbf{C}_D^{-1} (\mathbf{d}^{\text{measured}}(\mathbf{c}, y) - T^{\text{calculated}}(\mathbf{c}, y, \mathbf{m}))\right). \quad (2)$$

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The multivariate Laplace *a posteriori* probability density distribution is given in the following form:

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$$p^{a \text{ posteriori}} \propto \exp\left(-\frac{|\mathbf{m} - \mathbf{m}^{a \text{ priori}}|}{\mathbf{C}_m^{1/2}}\right) \cdot \exp\left(-\frac{|\mathbf{d}^{\text{measured}}(\mathbf{c}, y) - T^{\text{calculated}}(\mathbf{c}, y, \mathbf{m})|}{\mathbf{C}_D^{1/2}}\right), \quad (3)$$

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in which the *a posteriori* probability can be expressed as the multiplication of the *a priori* and the likelihood functions. We disregard the constant multipliers. The superscript indicate the measured and calculated (forward model) data.

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Two objective functions are

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$$E(\mathbf{m}) = \left(\mathbf{m} - \mathbf{m}^{a\ priori} \right)^T \mathbf{C}_m^{-1} \left(\mathbf{m} - \mathbf{m}^{a\ priori} \right) + \left(\mathbf{d}^{measured}(\mathbf{c}, y) - T^{calculated}(\mathbf{c}, y, \mathbf{m}) \right)^T \mathbf{C}_D^{-1} \left(\mathbf{d}^{measured}(\mathbf{c}, y) - T^{calculated}(\mathbf{c}, y, \mathbf{m}) \right) \quad (2)$$

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171 which is for the multivariate Gaussian function and

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$$E(\mathbf{m}) = \left(\frac{|\mathbf{m} - \mathbf{m}^{a\ priori}|}{\mathbf{C}_m^{1/2}} \right) + \left(\frac{|\mathbf{d}^{measured}(\mathbf{c}, y) - T^{calculated}(\mathbf{c}, y, \mathbf{m})|}{\mathbf{C}_D^{1/2}} \right). \quad (3)$$

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175 which is for the multivariate Laplacian function. In the objective functions \mathbf{C}_m and \mathbf{C}_D are the
176 *a priori* and the data covariance matrices, respectively.

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Regularization

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181 The minimum problem generally appears in various fields of science and engineering.
182 The solution of the minimum problem is often approximated by numerical methods. The aim
183 of regularization is to construct the $\Omega(\mathbf{m})$ or $\lambda\Omega(\mathbf{m})$ functions which help the determination of
184 the minimum of the $E(\mathbf{m})$ function, where λ is the regularization parameter. Regularization is
185 discussed in details by Tikhonov and Arsenin (1977).

186 Let us suppose there is an element \mathbf{m}_0 of the F set, where $E(\mathbf{m})$ has its smallest value,
187 that is

188

$$\inf E(\mathbf{m}) = E(\mathbf{m}_0) = E_0 \quad \text{where } \mathbf{m} \in F. \quad (4)$$

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191 The minimizing sequence $\{\mathbf{m}_n\}$ converges to the element \mathbf{m}_0 . In this case $E(\mathbf{m})$ is regularized.

192 The function $\Omega(\mathbf{m}_n)$ is often referred to as a stabilizing function. It has the property of

193

$$\Omega(\mathbf{m}_n) \geq \Omega(\mathbf{m}_{n-1}) \geq \dots \geq \Omega(\mathbf{m}_1) \quad (5)$$

195

196 $\Omega(\mathbf{m})$ is a continuous non-negative function.

197 There are several possibilities of finding the appropriate stabilizing function. In our

198 present paper the $\Omega(\mathbf{m}) = \lambda(\mathbf{m}_{i-1} - \mathbf{m}_i)^2$ and $\Omega(\mathbf{m}) = \lambda |\mathbf{m}_{i-1} - \mathbf{m}_i|$ functions are selected as

199 stabilizing functions for the case of the Gaussian distribution and Laplacian distribution
 200 model parameters, respectively. The regularized objective functions can be expressed in the
 201 forms of

$$\begin{aligned}
 & E(\mathbf{m}) = \left(\mathbf{m} - \mathbf{m}^{a\ priori} \right)^T \mathbf{C}_m^{-1} \left(\mathbf{m} - \mathbf{m}^{a\ priori} \right) \\
 & + \left(\mathbf{d}^{measured}(\mathbf{e}, y) - T^{calculated}(\mathbf{e}, y, \mathbf{m}) \right)^T \mathbf{C}_D^{-1} \left(\mathbf{d}^{measured}(\mathbf{e}, y) - T^{calculated}(\mathbf{e}, y, \mathbf{m}) \right) + \lambda \|\mathbf{m}_{i-1} - \mathbf{m}_i\|^2 \quad (6)
 \end{aligned}$$

204 and

$$E(\mathbf{m}) = \left(\frac{\|\mathbf{m} - \mathbf{m}^{a\ priori}\|}{\mathbf{C}_m^{1/2}} \right) + \left(\frac{\|\mathbf{d}^{measured}(\mathbf{e}, y) - T^{calculated}(\mathbf{e}, y, \mathbf{m})\|}{\mathbf{C}_D^{1/2}} \right) + \lambda \|\mathbf{m}_{i-1} - \mathbf{m}_i\|, \quad (7)$$

208 respectively.

209 The regularized minimum problem was solved by a numerical method: the Simplex
 210 method summarized by Walsh (1975) and the Simulated Annealing procedure by Kirkpatrick
 211 et al. (1983) and Sen and Stoffa (1995).

212 The minimum problem was solved by the L_1 norm in the case of the Laplace
 213 distribution of the model parameters and L_2 norm in the case of the Gaussian distribution of
 214 the model parameters.

215 Figs. 3 and 4 show the regularized objective functions and the regularization functions
 216 *versus* the iterative step in a logarithmic scale. In the cases we show the regularized minimum
 217 problem was solved by the Simulated Annealing method where the regularization parameter
 218 was $\lambda=0, 1, 10$ and 100 . It can be deduced that the appropriate choice for the parameter λ is in
 219 the interval $1-10$. This was determined after some trial and error calculation of several
 220 synthetic examples. The decrease of the objective and regularization functions is not
 221 appropriate for the case of $\lambda=100$. In the case of the Gaussian parameter distribution the
 222 regularization function shows some oscillations.

223 Similar results can be obtained from the regulated inversion procedure calculated by the
 224 Simplex method.

225 Interpretation

229 At an elevation of 324 km a relatively large total magnetic field anomaly lies along the
230 central part of the Pannonian Basin (Fig. 1b). The magnitude of this NW–SE trending
231 negative anomaly is -13 nT. A subsection of Fig. 1b, extending between 45°–49° latitude and
232 15°–24° longitude contains the main section of this anomaly and it is qualitative interpreted.

233 The values of the model parameter we determined are summarized in the Table 1.

234 The source of this anomaly is in the upper crust according to these derived depths. We
235 propose that the anomaly is probably caused by a metamorphic complex situated in the
236 upper crust.

237 Similar large magnitude negative anomalies were discovered over the Mid-Proterozoic
238 granulites in southwestern Sweden (McEnroe et al. 2001), Proterozoic Åna Sira anorthosite in
239 Rogaland Norway (McEnroe et al. 2004, 2005 and Robinson et al. 2002) and in the Modum
240 district of Southern Norway (Fabian et al. 2008). These results suggest that the stable
241 remanent magnetization is produced by the exsolution of the hematite–ilmenite minerals. The
242 contact zones around these minerals can produce a strong ferromagnetic effect.

243 The Hungarian Balaton Highlands xenolites carry some indications on the probable
244 rocks of the upper crust (Dégi et al. 2009, Embey–Isztin et al. 2001, 2003; Dobosi et al.
245 2002). We propose that the exsolution of the hematite–ilmenite minerals also is found in the
246 upper crust of the Pannonian Basin.

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310 Captions

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312 Fig.1. (a) Total magnetic field anomaly map at 324 km elevation over a part of Europe,
313 plotted in an Albers' equal area projection, anomalies are given in nT with a range of 24 grey
314 levels and a 2 nT contour interval; (b) total magnetic field anomaly over the Pannonian Basin,
315 plotted in an Albers' equal area projection at 324 km elevation, anomalies are given in nT
316 with a range of 16 grey levels and a 1 nT the contour interval, inner frame outlines the region
317 of our inversion study.

318
319 Fig. 2. Three dimensional triangular model of the magnetic source body which was used as
320 the forward model of the inversion procedure; upper and lower depths are indicated by Z_T and
321 Z_U , respectively, the triangular base is given by three coordinate pairs: (x_1, y_1) , (x_2, y_2) , (x_3, y_3) .

322
323 Fig. 3. The objective and regularization functions *versus* the iterative step for the parameter
324 $\lambda=0, 1, 10$ and 100 , the functions are plotted with the same logarithmic scale; the minimum
325 problem was solved by the Simulated Annealing method and the model parameters have a
326 Laplacian distribution.

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329 Fig. 4. The objective and regularization functions *versus* the iterative step for the parameter
330 $\lambda=0, 1, 10$ and 100 , the functions are plotted with the same logarithmic scale; the minimum
331 problem was solved by the Simulated Annealing method and the model parameters have
332 Gaussian distribution.

333

334 Table 1. Determined model parameters by Simplex and Simulated Annealing methods in the
335 case of the Gaussian and Laplace distributions

336