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Geomagnetic repeat station survey in Hungary during 1994–1995 and the secular variation of the field between 1950 and 1995

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A geomagnetic repeat station survey was carried out in Hungary during the period 1994–95. The magnetic declination, inclination, and the total field were directly observed by proton-precession and DI-flux magnetometers. The network consisted of 195 sites. In most cases, the geographic coordinates of the stations and the azimuths of the reference marks were determined by a pair of GPS receivers. The direct observations were reduced to the epoch of 1995.0 using the continuous geomagnetic records of Hungary's Tihany Geomagnetic Observatory. The normal reference field in Hungary is expressed traditionally by a second-order polynomial of the geographic coordinates. In the course of the last campaign, the polynomial coefficients were computed by the method of adjustment according to the most frequent value. The normal distributions of the secular variations of the field elements were determined by second-order polynomials of latitude and longitude for the period 1950–95.

Keywords: magnetic survey maps, secular variations, magnetometers, Hungary, GPS

1. Introduction

The Earth's magnetic field is composed of several components having different origins and time variations. While the fast fluctuations are known

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to be connected mainly with magnetospheric, ionospheric phenomena (currents of charged particles), it is suggested that the long-term, so-called secular variations are caused by slow movements of magnetized materials inside the Earth's core [DE SANTIS et al. 1997]. In order to model the internal processes, one must separate the magnetic effects of several origins from the total, observable magnetic field. The part of the field that is thought to be generated mainly by sources from the Earth's interior is termed normal field.

For a great many years the temporal variation of this field has been carefully investigated at some points of the Earth, primarily at the locations of geomagnetic observatories. However, the observatory network is rather sparse and uneven for effectively mapping the spatial distribution of the field, as well as its temporal variations. The fundamental purpose of repeat station surveys is to map the geomagnetic field over a relatively dense and even network of an area of limited size and to compile normal maps of the surveyed region and date (epoch). A knowledge of the normal magnetic distribution is of great importance from two aspects: viz. (as was already mentioned) comparison between fields of different epochs can yield information about mass-flow processes of internal origin; on the other hand, because the normal map demonstrates the global behaviour of the field, it can serve as a reference for investigating local magnetic anomalies.

The results of the field measurements performed at different dates and different stations are reduced to the same epoch by eliminating the fast temporal variation of the field of mainly external origin. Corrections are carried out with the aid of the continuous magnetic records of observatories. The time-corrected field reflects the effects both of the internal magnetic sources and of the Earth's crust. To obtain the normal reference field, the anomalies caused by the surface magnetic rocks must be eliminated. For limited-size regions of the Earth (with no significant curvature), the geomagnetic field can be modelled by polynomials of latitude and longitude. The spatial wavelengths of the crust-generated magnetic changes are much smaller than those of the variation of the core-field. For this reason, the analytical magnetic model of the Earth's interior can be obtained by truncation of the polynomial at the first or second order. For determining the normal map for larger, continent-size areas, regional harmonic analyses (SCHA, TOSCA, ASHA) can yield reliable results [for a summary of these methods, see DE SANTIS et al. 1997].

The first magnetic network survey in Hungary was carried out between 1847 and 1857 (*Table I*). The most extensive geomagnetic research was led by Loránd Eötvös, who performed gravity and geomagnetic observations simultaneously, between 1902 and 1917 at 1600 stations located at several regions of the former territory of Hungary [FEKETE et al. 1918].

1847-57 (1850.0)	K. Kreil J. Liznár	52	D, I, H	Magn. theodolite, Earth-Inductor
1864-79 (1875.0)	G. Schenzl	117	D, I, H	Magn. theodolite, Earth-Inductor
1892-94 (1890.0)	I. Kurländer	38	D, I, H	Magn. theodolite, Earth-Inductor
1902-17 (1903.0, 1906.0)	L. Eötvös	1600	D, I, H	Magn. theodolite, Earth-Inductor
1934-36 (1936.0)	J. Hofhauser	26	D	Magn. theodolite
1949-50 (1950.0)	Gy. Barta	290	D, I, H, Z	Magn. theodolite, Earth-Inductor, QHM, BMZ
1964-65 (1965.0)	E. Aczél, R. Stomfai	300	D, H, Z	BMZ, QHM
1979-82 (1980.0)	T. Lomniczi, P. Tóth	299	D, H, F	QHM, Proton-magn.

Table I. Summary of the Hungarian geomagnetic surveys carried out between 1847 and 1982. The columns show: the observational period and the date of the data reduction (in brackets); the names of the persons who directed the measurements and data processing; the number of surveyed stations; the measured magnetic components; and the equipment used. The networks of the surveys carried out before 1917 covered the former territory of Hungary

I. táblázat. A Magyarország területén 1847 és 1982 között elvégzett geomágneses hálózati mérések összefoglalása. Az egyes oszlopok az alábbi adatokat tartalmazzák: az észlelések időszaka, illetve zárójelben a mért adatok vonatkoztatási időpontja; a méréseket és az adatfeldolgozást irányító személyek nevei; a hálózatban résztvevő állomások száma; a mért mágneses komponensek; az alkalmazott műszerek típusai. Az 1917 előtt elvégzett kutatások hálózatai Magyarország korábbi területére vonatkoznak

The first systematic survey within the country's present boundaries was completed in 1950. Later on, detailed mapping of the Hungarian magnetic field was repeated every fifteen years [SZABÓ 1983]. The last campaign was carried out in 1994 and 1995. In this survey the magnetic declination, inclination, and the total field were directly measured by DI fluxgate and proton precession magnetometers. The data were reduced to the epoch of 1995.0. The network consisted of 195 stations located inside Hungary (184 sites), and within the borders of the neighbouring countries (11 sites).

Here, we present the repeat station network and the equipment utilized for our last geomagnetic campaign. Later on, we give a brief overview on the mathematical procedure adopted for computing the magnetic normal field, then we summarize the results obtained. Finally, the normal distribution of the mean secular variation computed for the time interval of 1950–1995 will be presented.

2. The magnetic repeat station network in 1994–95

Most of the stations of our last magnetic campaign were identical with the base points of the 1964–65 survey [ACZÉL, STOMFAI 1968]. In order to curtail expenses, however, the number of original stations was considerably reduced. Because the magnetic sources of the crust do not represent the global trend of the magnetic field, the network was truncated mainly in regions which are characterized by local magnetic anomalies. These areas are very well known in Hungary on the basis of former geomagnetic investigations. Unfortunately, some of the remaining points had to be omitted because of the increased artificial magnetic noise due to the development of civilization in the last three decades. In order to approach the even character of the former network, some new base points were established instead of the artificially disturbed sites, taking into account the following basic requirements:

— not close to local magnetic anomalies,

— absence of artificial disturbances,

— proximity to the original network station.

To ensure the connection between the magnetic charts of Hungary and the neighbouring countries, some of the border-area repeat stations of our neighbours were also surveyed during the last campaign.

The final form of the network consisted of 195 base points, their locations are shown in *Fig. 1*. The names of the stations and their coordinates are listed in Appendix I.

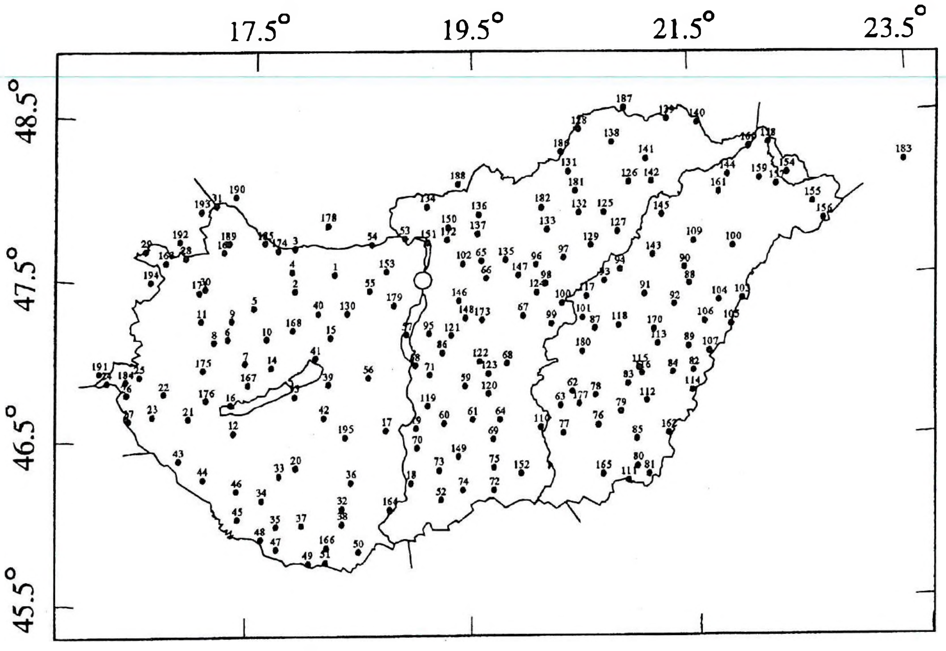

Figure 1. The Hungarian geomagnetic repeat station network in 1994–95. The site names are listed in the Appendix

1. ábra. A magyarországi geomágneses alaphálózat 1994–95-ben. Az állomások nevei a mellékletben találhatóak

3. Equipment and method of observations

The geomagnetic field, as a vectorial field, can be unambiguously determined at a certain point by the measurements of its three independent space components. During the course of our survey, the absolute value of the field vector, the declination (azimuth of the geomagnetic North direction with respect to the geographic North), and the inclination (the angle by which the total field vector is inclined from the horizontal plane) were observed at every site. The total value of the field (F) was measured by G856 type Proton or GSM19 type Proton Overhauser magnetometers having a resolution of 0.1 nT, and 0.01 nT, respectively.

The measurements of declination (D) and inclination (I) were carried out by the use of DIM100 or UFG1 type fluxgate magnetometers and a Zeiss Theo 020B steel-free theodolite using the conventional zero-field method [JANKOWSKI, SUCKSDORFF 1996]. The fluxgate magnetometer consists of an electronic unit and a cylindrical sensor. The equipment measures the magnetic field in the direction of the axis of the sensor. In the course of the observations, the probe is mounted on the telescope of the theodolite so that the axes of the two units should roughly coincide with each other. The azimuth of the magnetic meridian and the value of the inclination can be determined by positioning the sensor in the directions which are characterized by zero magnetic field value. Then, the magnetic line of force is just perpendicular to the axes of the sensor and the telescope at the site of observation. The resolution of the fluxgate magnetometer is 0.1 nT. The scale division of the theodolite is 1 minute of arc, but because one tenth of the scale division can be estimated, the real resolution of the theodolite is about 6–12 second of arc. Since the resolution of our theodolite is less than that of our magnetometer, the overall resolution of D and I observations falls within the specified interval of 6–12 second of arc.

The azimuth of the magnetic meridian can be read on the horizontal scale of the theodolite. This value, however, depends on the actual orientation of the zero point of the scale. In order to be able to give an absolute meaning to the relative observations, we must determine the bearing of the theodolite by making reference measurements to one or more field objects with known geographic azimuths. At some stations, we could use the reference directions that were established during the 1964–65 geomagnetic campaign. In other cases, however, where the environmental changes of the last decades had obliterated the former reference marks, a pair of ASHTECH XII type GPS receivers was utilized to mark new lines for orientation. The possibility of using GPS for determining true geodetic azimuths was checked at several sites before surveying the network. A comparison was carried out between azimuths obtained by GPS observations and other methods, i.e. observations of the Sun and measurements performed with a gyro-theodolite. As a result of the experiments the application of the GPS technique turned out to be a very powerful method in terms of accuracy and reliability of azimuth determinations [HEGYMEGI at al. 1996].

Generally, four sets of observations of the field elements were carried out at the network stations. Each measurement was corrected in time (see next section). The standard deviations of the averages of the time-corrected D, I, or F observations were considered as the determination error of the given component at a certain station. In order to evaluate the determination errors relating to the whole network, we computed the average of the standard deviations calculated for the individual sites. As a result, we obtained errors of 0.37 min., 0.15 min, and 1.26 nT for the determination of the D, I, and F magnetic components, respectively. These values represent the errors both of the field measurements and the time corrections.

4. Processing of measured data

The construction of geomagnetic normal maps for a given region is the primary aim of repeat station surveys. Because the normal charts must be referred to a certain date (epoch) and to a certain topographic level, the measured data must be reduced both in time and space before computing the normal parameters of the field. However, in Hungary, being a flat country, the differences between the levels of the sites are so small that the topographic corrections can be regarded as negligible.

4.1 Correction in time

The aim of the time-correction of the observations is to eliminate the time-variations of the geomagnetic field taking place during the whole period of the survey. The procedure was carried out using the continuous records of the Tihany Geomagnetic Observatory (THY). We considered the 1994–95 biannual means of the individual geomagnetic components at Tihany as the reference levels for the measurements. The field data were corrected by the difference between the reference levels and the Tihany observations using the following formula:

$$B^i(1995.0,P_j) = B^i(t_j,P_j) - [B^i(t_j,THY) - B^i(1995.0,THY)] \quad , \quad (1)$$

where $B^i(1995.0, P_j)$ is the value of the i-th magnetic component at the j-th station (P_j) after time-correction, and t_j is the time of the field measurement at the j-th site. The accuracy of the corrections depends on the extent of the deviations between the magnetic time variations at the observatory and at the base point to be corrected. Fortunately, in the case of quiet daily magnetic variations, due to the relatively small size of Hungary the correction error is negligible. The time-reduced field elements at the network stations are indicated in Appendix I.

4.2 Determination of the magnetic normal field

In Hungary, the magnetic normal field is expressed traditionally by a second order polynomial of the geomagnetic coordinates. One of the normal components of the field (denoted by $\overline{B^i}$) at the points having coordinates of (ϕ, λ) can then be computed as:

$$\begin{aligned}\overline{B^i(\varphi,\lambda,\underline{p})} = p_0 + p_1(\varphi-\varphi_0) + p_2(\lambda-\lambda_0) + p_3(\varphi-\varphi_0)^2 \quad , \quad (2)\\ + p_4(\varphi-\varphi_0)(\lambda-\lambda_0) + p_5(\lambda-\lambda_0)^2\end{aligned}$$

where the coordinates of the reference site are φ_0=45.5°, λ_0=16.0°. The latitude and longitude differences are expressed in minutes. The parameters p_i are the coefficients of the fitted surface.

The parameter vector can be obtained by minimizing a merit function that measures the fitting between the observed data and a given model. The applied adjusting method depends on the statistical distribution of the input data. It means that different merit functions must be minimized in order to achieve the best model of the real physical field.

In our case, adjustment according to the most frequent value [STEINER 1988] was applied for computing the Hungarian reference field. This method requires the fulfilment of the following minimum condition from the adopted parameter vector:

$$\sum_{j=1}^{N} \varepsilon^2 \ln(\varepsilon^2 + \overline{(B_j^i(\varphi_j, \lambda_j) - B^i(\varphi_j, \lambda_j, \underline{p}))}) = \min. \quad , \quad (3)$$

where N is the total number of network stations, φ_j, λ_j are the coordinates of the j-th station, and B^i_j is the value of the i-th magnetic component at the j-th base point. The quantity ε is termed dihesion; this quantity characterizes the scattering of the measured data around the actually computed reference field. In the algorithm, the dihesion determines a weight function according to which the individual observations are weighted with respect to their residuals from the computed model field. Because of the two unknown parameters (ε and $\underline{p}$) in Eq. 3, adjustment according to the most frequent value can be solved only by an iterative procedure.

The coefficients of the normal fields of the measured D, I, F, and the computed H, and Z magnetic components obtained by the specified adjustment are collected in *Table II*, the constructed iso-line maps are demonstrated in *Figs. 2-6*.

	p_0	p_1	p_2	p_3	p_4	p_5
D (')	99.04	0.00469	0.21906	0.00027	0.00010	-0.00001
I (')	3711.44	0.94267	0.07941	-0.00022	-0.00009	-0.00004
F (nT)	47134.28	5.32541	1.05978	-0.00573	0.00105	0.00012
H (nT)	22240.08	-9.09192	-0.46631	-0.00177	0.00169	0.00042
Z (nT)	41575.65	10.84261	1.28384	-0.00839	0.00093	0.00012

Table II. Coefficients of the Hungarian magnetic normal fields for the epoch 1995.0 for the D, I, F, H, and Z components. The normal values of the field elements at a given site can be computed by Eq. 2 (see text). D and I are obtained in minutes, while F, H, and Z in nT

II. táblázat. A geomágneses tér D, I, F, H, és Z komponenseinek 1995.0 epochára vonatkozó magyarországi normál tereit reprezentáló polinom együtthatók. Az egyes tér-elemek normál értékei egy adott ponton az együtthatók 2. egyenletbe való behelyettesítésével számolhatóak. D és I valamint F, H, és Z normál értékei percben, illetve nT-ban adódnak

Of course, different adjustment methods lead to a different second-order model of the magnetic field. In order to have a picture of the dimension of the possible deviations, we computed the normal field using algorithms of both simple and weighted least squares fittings. In the second

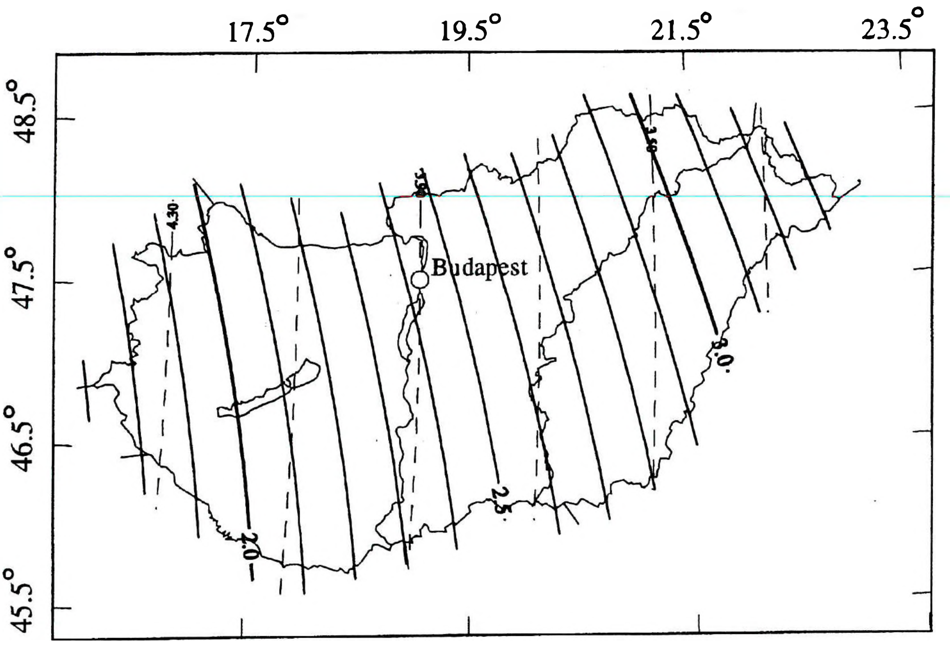

Fig. 2. Declination chart of the normal geomagnetic field in degrees for the epoch 1995.0 (continuous curves) and the mean yearly variation of the declination for the period 1950-95 expressed in minutes/year (dashed lines). The contour intervals are 0.1 degree and 0.2 minute/year for the isolines and the isoporic lines, respectively

2. ábra. A deklináció normálértékének izogon görbéi az 1995.0 epochára vonatkozóan fokokban kifejezve (folytonos vonalak), illetve a deklináció átlagos éves változási ütemének normál eloszlása 1950 és 1995 között perc/év egységekben (szaggatott vonalak). A szomszédos izovonalak közötti különbség 0,1 fok, illetve 0,2 perc/év

case, the weighting was carried out — in accordance with the Chauvenet criterion [see WORTHING and JEFFNER 1943 or MELONI et al. 1994] — using an iterative algorithm. After computing a normal field, its standard uncertainty (σ) was expressed in the following way:

$$\sigma = \sqrt{v/(N-6)} \quad , \tag{4}$$

where v is the sum of the squares of the differences between observed and normal values of the field, and N is the number of network stations that participate in the inversion. The weight was 0 for the sites where the residual

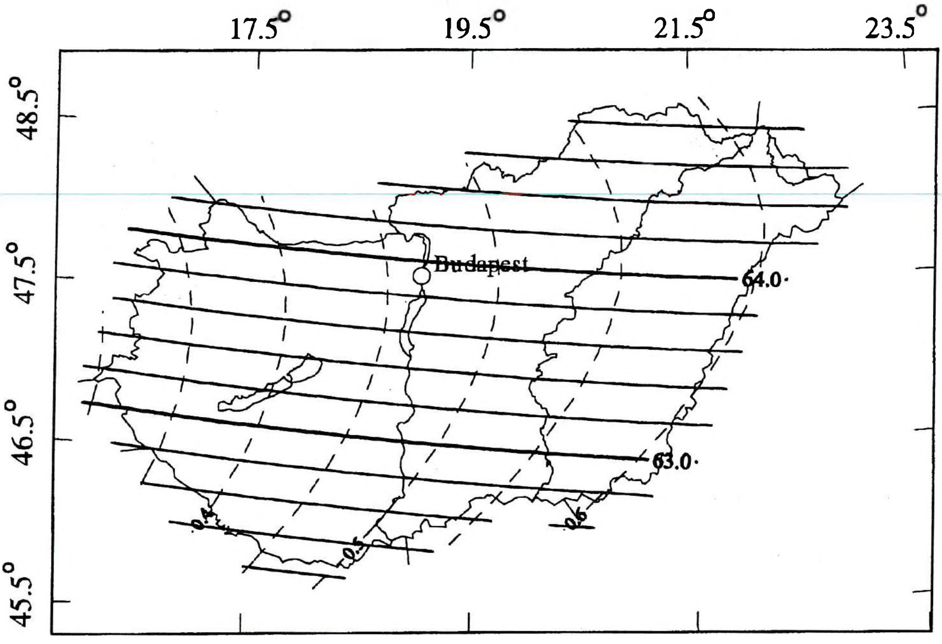

Fig. 3. Inclination chart of the normal geomagnetic field in degrees for the epoch 1995.0 (continuous curves) and the mean yearly variation of the inclination for the period 1950–95 expressed in minutes/year (dashed lines). The contour intervals are 0.2 degree and 0.05 minute/year for the isolines and the isoporic lines, respectively

3. ábra. Az inklináció normálértékének izoklin görbéi az 1995.0 epochára vonatkozóan fokokban kifejezve (folytonos vonalak), illetve az inklináció átlagos éves változási ütemének normál eloszlása 1950 és 1995 között perc/év egységekben (szaggatott vonalak). A szomszédos izovonalak közötti különbség 0,2 fok, illetve 0,05 perc/év

exceeded 2σ, and 1 otherwise. Every rejection of data was followed by the computation of a new normal field and σ until the residuals of all input data remained in the 2σ interval of the model field.

To demonstrate the deviations between the normal charts resulting from the applied methods, we calculated the differences of the normal fields at each observation point and characterized the deviations by their averages. For the directly observed declination, inclination, and total field, the mean differences fell within the order of the observational errors of the given components [KOVÁCS et al. in press]. This means — from the practi-

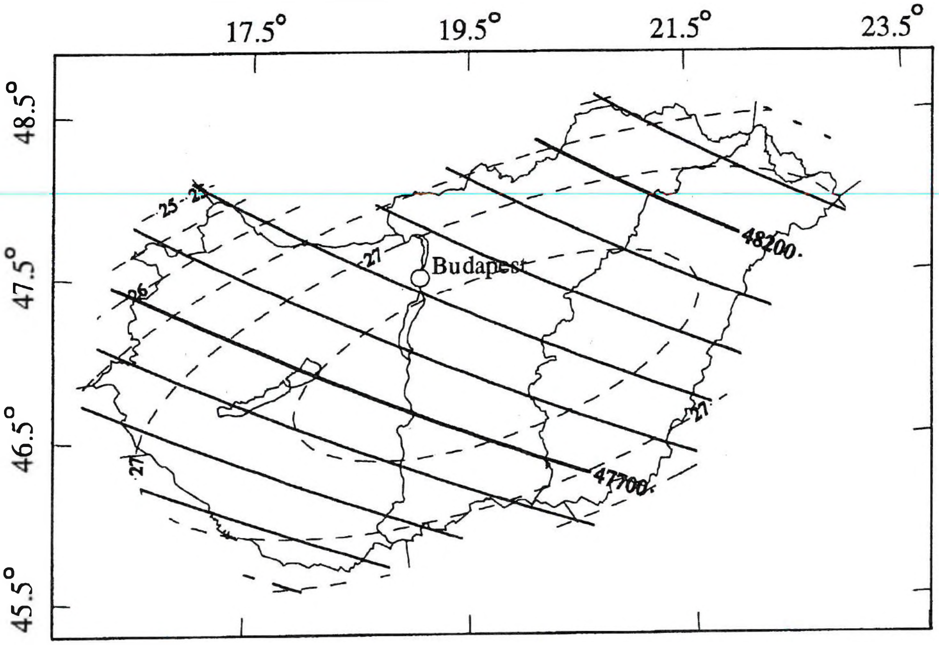

Fig 4. Total intensity chart of the normal geomagnetic field in nT for the epoch 1995.0 (continuous curves) and the mean yearly variation of the total magnetic intensity for the period 1950–95 expressed in nT/year (dashed lines). The contour intervals are 100 nT and 0.5 nT/year for the isolines and the isoporic lines, respectively

4. ábra. A totális mágneses térerősség normálértékének izodinám görbéi az 1995.0 epochára vonatkozóan nT-ban kifejezve (folytonos vonalak), illetve a totális tér átlagos éves változási ütemének normál eloszlása 1950 és 1995 között nT/év egységekben (szaggatott vonalak). A szomszédos izovonalak közötti különbség 100 nT, illetve 0,5 nT/év

cal point of view — that any set of normal coefficients obtained by the specified adjusting methods could be adopted to define the normal field for Hungary on the basis of the last geomagnetic survey.

5. Secular variation

At any point of the Earth, the annual mean values of the geomagnetic field elements show a successive variation which can be characterized by

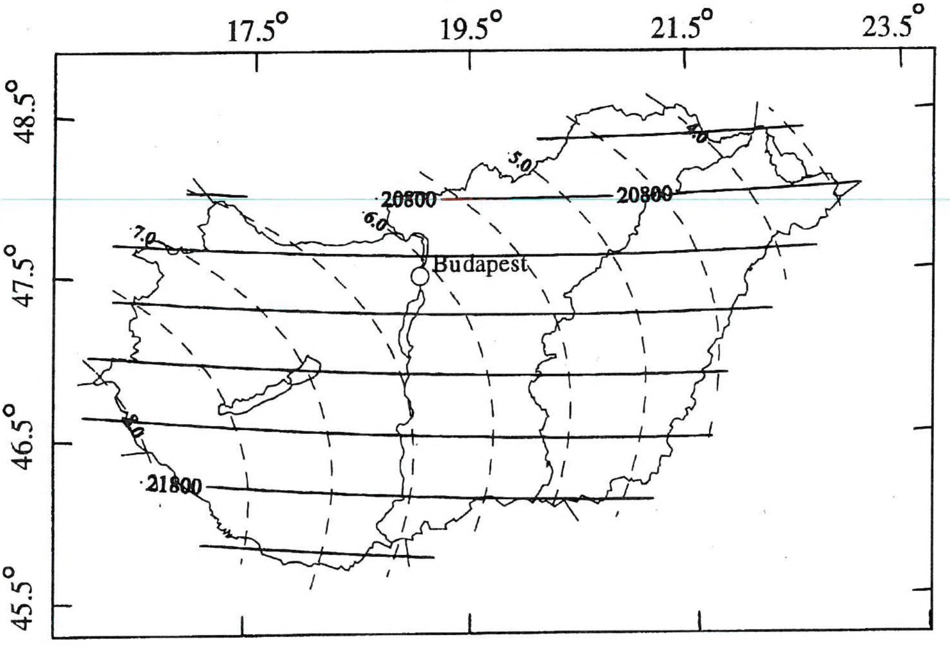

Fig. 5. Horizontal intensity chart of the normal geomagnetic filed in nT for the epoch 1995.0 (continuous curves) and the mean yearly variation of the horizontal intensity for the period 1950–95 expressed in nT/year (dashed lines). The contour intervals are 200 nT and 0.5 nT/year for the isolines and the isoporic lines, respectively

5. ábra. A horizontális intenzitás normálértékének izodinám görbéi az 1995.0 epochára vonatkozóan nT-ban kifejezve (folytonos vonalak), illetve a totális tér átlagos éves változási ütemének normál eloszlása 1950 és 1995 között nT/év egységekben (szaggatott vonalak). A szomszédos izovonalak közötti különbség 200 nT, illetve 0,5 nT/év

nearly the same trend over some decades. Because the characteristic period of these changes can be measured in hundreds of years, this type of magnetic course is called secular variation. It is suggested that this phenomenon arises from flows of magnetized materials within the Earth's core. It follows that the rate and the trend of the secular changes must vary in space over the surface. The contours of equal rate and trend of changes are termed isopor. The spatial distribution of the isopors over an area of limited size can be determined by adjusting the differences obtained between the observations of geomagnetic surveys of different epochs.

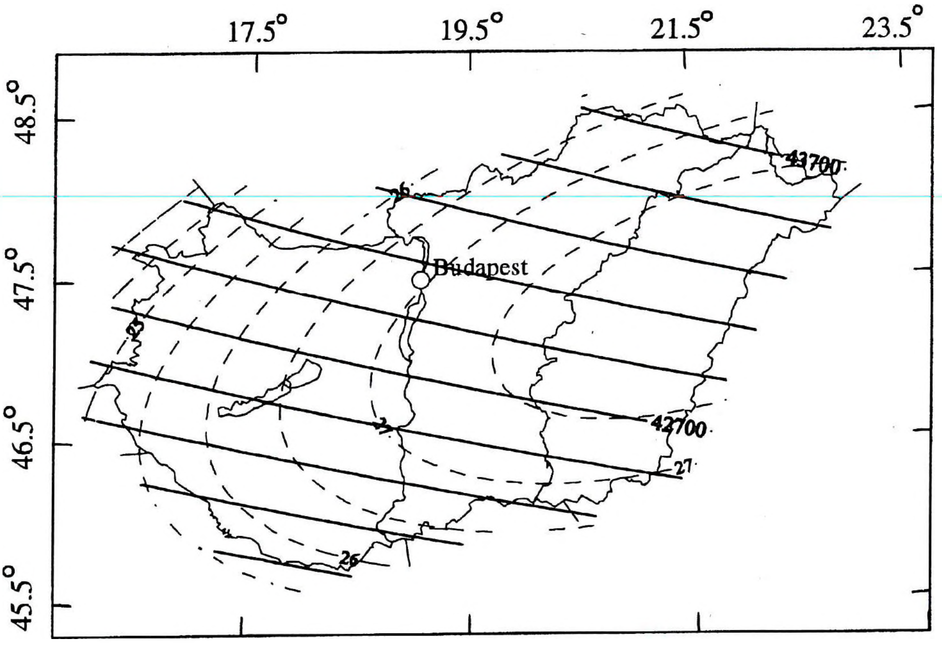

Fig. 6. Vertical intensity chart of the normal geomagnetic field in nT for the epoch 1995.0 (continuous curves) and the mean yearly variation of the vertical intensity for the period 1950–95 expressed in nT/year (dashed lines). The contour intervals are 200 nT and 0.5 nT/year for the isolines and the isoporic lines, respectively

6. ábra A vertikális intenzitás normálértékének izodinám görbéi az 1995.0 epochára vonatkozóan nT-ban kifejezve (folytonos vonalak), illetve a totális tér átlagos éves változási ütemének normál eloszlása 1950 és 1995 között nT/év egységekben (szaggatott vonalak). A szomszédos izovonalak közötti különbség 200 nT, illetve 0,5 nT/év

Figure 7A and *B* show the relative changes of the annual means of the geomagnetic elements at Tihany Observatory between 1955 and 96. It can be seen that the curves of the time variations of declination, vertical and total magnetic intensities continuously increase and are nearly linear. With the inclination and the horizontal intensity, however, the courses are not so evident, and the variations here are much smaller than in the other components.

As was already pointed out, detailed geomagnetic surveys were carried out in Hungary on four occasions during the period 1950–95. This means that we could compare the measured data of our last survey with that

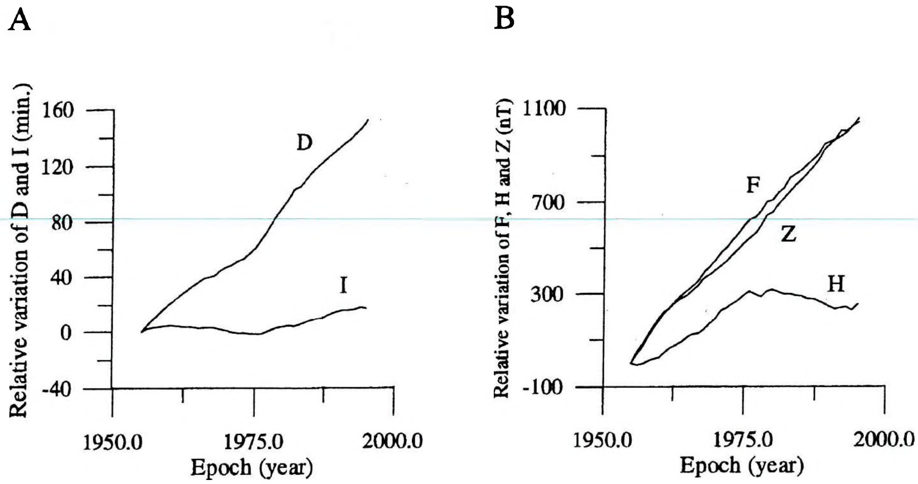

Fig. 7. Variations of the annual means of the D, I (*A*), and H, Z, F (*B*) magnetic field components at Tihany between 1955 and 96. To facilitate the representation, the initial values of the curves were translated to zero

7. ábra. A D, I (*A*), illetve a H, Z, és F (*B*) mágneses komponensek átlagos éves változási üteme Tihanyban 1955 és 1996 között. Az ábrázolás megkönnyítése érdekében a görbéket egységesen nulláról indítottuk

of three earlier ones in order to get a picture of the spatial distribution of the geomagnetic secular variations over the last 45 years. Judging by the records of Tihany Observatory the trends of the changes of the magnetic D, F, and Z components were nearly linear; the dimensions of the H and I variations were negligible in comparison with the changes of the other components over the last 45 years. For this reason, we decided to compute the secular variations for the time interval 1950.0–1995.0.

The stations of the networks in 1949–50 and 1994–95 were not identical. For this reason, we constructed a grid of 20x20 km over the surveyed area, and interpolated the measurements of the real networks to the points of this grid. Then we computed the mean annual variations of the geomagnetic field elements along the regular grid. Similarly to the normal field, the spatial distribution of the secular variation for Hungary is generally defined by the second-order polynomial specified by Eq. 2. Therefore, we adjusted the mean annual variations obtained for the constructed grid by the method of adjustment according to the most frequent value. The polynomial coefficients characterizing the secular variations of the field elements are reported in *Table III*, the adjusted isopors are presented on the maps of the normal fields (Figs. 2–6). As was expected on the basis of the magnetic records of Tihany Observatory: every field component in Hungary increased, on average, over the last 45 years. The dimensions of the annual variations in the country range between about 3.2–4.4 min., 0.3–0.65 min., 25–28 nT, 3.5-8 nT, 24-28 nT for the magnetic D, I, F, H, and Z components, respectively.

	p_0	p_1	p_2	p_3	p_4	p_5
D ('/year)	4.41	0.00033	−0.00276	0.00000	0.00000	0.00000
I ('/year)	0.36	−0.00148	0.00126	0.00001	0.00000	0.00000
F (nT/year)	25.69	0.02334	0.00399	−0.00025	0.00010	−0.00003
H (nT/year)	8.46	0.00314	−0.01112	−0.00009	0.00004	−0.00001
Z (nT/year)	24.24	0.02610	0.01228	−0.00023	0.00008	−0.00003

Table III. Coefficients of the annual variation normal fields of the magnetic components for the time-span 1950–1995. The normal value of the mean annual variation at a given site can be computed by Eq. 2 (see text). D, and I are obtained in minutes/year, F, H, and Z in nT/year

III. táblázat. A geomágneses normál tér 1950 és 1995 közötti átlagos éves változását jellemző polinom-együtthatók értékei. Az átlagos éves változás normál értéke egy adott ponton az együtthatók 2. egyenletbe való behelyettesítésével számolhatóak. D, és I, valamint F, H, és Z változásainak normál értékei perc/év, illetve nT/év egységekben adódnak

6. Summary and conclusions

The spectrum of the geomagnetic field is complex both in time and space. During the course of the geomagnetic surveys, the investigations were mainly concerned with the slow spatial and temporal variations of the field.

In the preparatory phase of the last campaign we decided to complete the measurements along the network of the 1964–65 survey. After checking the quality and condition of some former points, however, it was realised that very many of the original sites had become unsuited to magnetic measurements over the last decades because of the increased artificial noise or the obliteration of the base or reference points. For this reason we had to work out a measuring procedure by which the unsuitable base points or reference marks could be substituted by new ones in the vicinity of the original ones without significant loss of time. The solution was provided by a pair of GPS receivers. These were used to determine both of the geographic coordinates of the new sites and the azimuths of new reference marks. Because the GPS and the magnetic measurements could be carried out simultaneously, the observational time was not very much increased.

During the last survey the geomagnetic normal fields that were adopted were computed by adjustment according to the most frequent value. The benefit of using this technique is the automatic weighting of the measurements with respect to their residuals from the normal field. The reference fields obtained were compared with the results of the traditional simple and weighted least squares fitting methods. The mean deviations between the reference fields obtained by the several techniques were comparable with the determination errors of the individual components (see Section 3). It was shown by STEINER [1988] that both the least squares fitting and the adjustment according to the most frequent value give a reliable result if the distribution of the input data set is of Gaussian type. We would again emphasize, that the last magnetic campaign was not extended to stations that are located on areas of local magnetic anomaly. It means — from the statistical point of view — that our set of observations does not include extreme values. It is supposed, therefore, that the probable normal distribution of the measurements around the reference field is due only to this fact.

Hungarian geomagnetic surveys have been repeated every fifteen years since 1950. Following this tradition, the next campaign is expected to be carried out around the year 2010. However, in order to follow the variation of the field during this relatively long period, we are planning to map the geomagnetic field every 5–6 years using the secular station network of Hungary, which includes 20 base points.

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REFERENCES

ACZÉL E., STOMFAI R. 1968: The Hungarian geomagnetic repeat station survey in 1964–65 (in Hungarian with English summary). Geofizikai Közlemények **XVII**, 3, pp. 5–17

DE SANTIS A., CHIAPPINI M., DOMINICI G., MELONI A. 1997: Regional geomagnetic field modelling: the contribution of the Istituto Nazionale di Geofisica. Annali di Geofisica **XL**, 5, pp. 1161–1169

FEKETE J., MIKOLA S., PEKÁR D., RYBÁR I., TANGL K. 1918: Life and scientific activity of Baron Loránd Eötvös (in Hungarian). Mathematikai és Physikai Lapok 6–7, pp. 115–295

HEGYMEGI L., KOVÁCS P., SÁRHIDAI A., KÖRMENDI A., GILBERT D., CHIAPPINI M. 1996: Determination of true azimuth by different methods. VIIth IAGA Workshop on Geomagnetic Observatory Instruments, Data Acquisition and Processing; Scientific Technical Report STR98/21 of Adolf Schmidt-Observatory for Geomagnetism Niemegk pp. 56–64

JANKOWSKI J., SUCKSDORFF C. 1996: Guide for magnetic measurements and observatory practice. IAGA, Warsaw

KOVÁCS P., KÖRMENDI A., HEGYMEGI L., CHIAPPINI M., DOMINICI G. (in press): The Hungarian magnetic network and the processing of the obtained data. Physics and Chemistry of the Earth

MELONI A., BATTELLI O., DE SANTIS A., DOMINICI G. 1994: The 1990.0 magnetic repeat station survey and normal reference fields for Italy. Annali di Geofisica **XXXVII**, 5, pp. 949–967

STEINER F. 1988: Most frequent value procedures. Geophysical Transactions **34**, 2–3, pp. 139–260

SZABÓ Z. 1983: The magnetic declination and its variation in Hungary between 1850–1980 (in Hungarian with English summary). Geodézia és Kartográfia **35**, 6, pp. 436–442

WORTHING A.G., JEFFNER J. 1943: Treatment of experimental data. John Wiley, New York

Appendix

Names, coordinates, and magnetic field element values of the repeat stations of the last Hungarian magnetic survey. The field values are reduced to the epoch 1995.0. D, I, and F are observed, H and Z are computed. The original numbers of the stations included in the 1964–65 survey (see text) are indicated in brackets. A, SK, and UA mean Austrian, Slovakian and Ukrainian sites, respectively. For three stations the magnetic declinations were not determined.

A legutóbbi magyarországi alaphálózatmérés pontjainak nevei, koordinátái, illetve az ott megállapított mágneses tér komponenseinek az értékei. A tér értékei az 1995.0 epochára vonatkoznak. D, I, és F voltak a mért komponensek, H-t és Z-t pedig ezek alapján számoltuk. Az 1964–65-ös alaphálózatban is szereplő állomások eredeti számait zárójelben közöljük. Az A, SK, és UA jelölések osztrák, szlovák, illetve ukrán állomásokat jelentenek. Három pont esetében a mágneses deklinációt nem sikerült meghatároznunk.

	Station	**Latitude** (Degree)	**Longitude** (Degree)	**D** (Deg.)	**I** (Deg.)	**F** (nT)	**H** (nT)	**Z** (nT)
1	Kocs (4)	47.57525	18.26009	2.245	63.922	47850.0	21034.9	42978.5
2	Bakonybánk (5)	47.46667	17.89500	2.112	63.788	47830.6	21126.2	42912.1
3	Gönyü (6)	47.73389	17.88818	-	64.001	47878.2	20987.9	43032.9
4	Mezőörs (7)	47.59002	17.86712	2.133	63.906	47822.1	21034.5	42947.7
5	Nagygyimót (8)	47.36051	17.52812	2.005	63.668	47791.6	21199.2	42832.6
6	Iszkáz (11)	47.16382	17.29309	1.901	63.461	47679.5	21303.2	42655.7

7	Nyírád (13)	47.01713	17.46311	2.020	63.348	47669.8	21383.1	42604.9
8	Kemenespálfa (14)	47.14550	17.17475	1.926	63.436	47697.3	21329.9	42662.3
9	Nyárád (17)	47.27885	17.33143	1.953	63.563	47748.5	21258.1	42755.3
10	Városlőd(18)	47.17048	17.64646	2.051	63.495	47728.0	21299.5	42711.7
11	Nagysimonyi (19)	47.27515	17.05701	1.817	63.572	47695.9	21228.2	42711.4
12	Marcali (23)	46.58208	17.36810	2.020	62.977	47509.2	21585.5	42322.5
13	Köröshegy (26)	46.81112	17.90700	2.134	63.224	47623.4	21454.4	42517.0
14	Nagyvázsony (29)	46.99504	17.70089	2.098	63.348	47675.6	21385.8	42610.0
15	Csór (30)	47.18410	18.22754	2.291	63.577	47802.3	21272.1	42808.4
16	Vonyarcvashegy (31)	46.75150	17.33324	1.959	63.109	47556.3	21509.6	42413.9
17	Györköny (35)	46.60579	18.73529	2.269	63.125	47635.3	21533.7	42490.3
18	Sükösd (37)	46.28203	18.95663	2.263	62.782	47570.1	21757.6	42302.7
19	Dunapataj (41)	46.61384	19.00305	2.363	63.121	47668.1	21551.1	42518.2
20	Taszár (42)	46.37038	17.93152	2.078	62.800	47533.0	21727.5	42276.5
21	Felsőrajk (44)	46.66221	16.96574	1.877	62.983	47526.2	21588.9	42339.8
22	Milejszeg (45)	46.81200	16.74145	1.802	63.088	47544.6	21519.9	42395.5
23	Nova (46)	46.67066	16.64510	1.878	63.047	47517.1	21537.3	42355.9
24	Kétvölgy (47)	46.87621	16.22828	1.833	63.168	47558.6	21466.9	42438.1
25	Felsőmarác (48)	46.92087	16.51591	1.668	63.158	47613.5	21498.9	42483.4
26	Bajánsenye (49)	46.79853	16.40904	1.677	63.112	47553.5	21505.8	42412.7
27	Szíjártóháza (50)	46.63872	16.43234	1.535	62.954	47517.9	21606.7	42321.4
28	Fertőd (52)	47.66483	16.89555	1.952	63.880	47817.9	21051.6	42934.6
29	Ágfalva (53)	47.70015	16.53629	1.871	63.893	47800.8	21034.7	42923.9
30	Beled (56)	47.47395	17.08110	1.997	63.775	47786.3	21116.3	42867.6
31	Rajka (58)	47.98793	17.16121	2.094	64.205	47874.1	20832.5	43103.8
32	Hosszúhetény (66)	46.12535	18.34988	2.173	62.600	47491.5	21855.6	42163.7
33	Töröcske (67)	46.32156	17.78484	2.034	62.769	47519.7	21743.7	42253.2
34	Hencse (68)	46.17035	17.62814	2.116	62.598	47447.0	21836.4	42123.5
35	Hobol (69)	46.00701	17.76003	2.063	62.479	47440.5	21921.1	42072.2
36	Váralja (70)	46.28703	18.42489	2.209	62.804	47546.7	21730.5	42290.3
37	Szentlőrinc (71)	46.01700	17.98485	2.089	62.464	47429.6	21926.8	42056.9
38	Magyarsarlós (72)	46.02866	18.35155	2.173	62.536	47479.4	21896.8	42128.6
39	Enying (75)	46.88865	18.21177	2.205	63.286	47673.3	21431.1	42584.6
40	Bakonycsernye (77)	47.33500	18.10833	2.184	63.670	47809.4	21205.7	42849.2

41	Balatonkenese (78)	47.05361	18.09207	2.180	63.424	47719.1	21348.8	42677.2
42	Iregszemcse (79)	46.68122	18.17818	2.165	63.079	47669.3	21583.0	42503.4
43	Semjénháza (81)	46.40207	16.88804	1.849	62.799	47444.8	21687.8	42197.7
44	Csurgó (83)	46.29555	17.10630	1.959	62.726	47438.1	21738.6	42164.0
45	Csokonyavisonta (86)	46.05033	17.41978	2.026	62.476	47416.7	21912.5	42049.8
46	Lábod (87)	46.22536	17.40819	1.991	62.620	47433.2	21814.4	42119.4
47	Drávafok (88)	45.87031	17.76649	2.019	62.333	47362.6	21992.1	41947.1
48	Potony (89)	45.92699	17.62481	2.024	62.394	47382.0	21956.2	41987.8
49	Kisszentmárton (91)	45.78472	18.04911	2.105	62.270	47349.5	22032.2	41911.3
50	Magyarbóly (93)	45.85864	18.49823	2.204	62.347	47413.1	22004.8	41997.5
51	Drávaszabolcs (94)	45.79447	18.20478	2.119	62.292	47367.5	22024.0	41935.9
52	Mátételke (98)	46.17853	19.22644	2.349	62.711	47563.2	21807.0	42269.5
53	Pilismarót (101)	47.79720	18.89162	2.399	64.068	48010.1	20995.0	43176.1
54	Nyergesújfalu (102)	47.76096	18.59104	2.346	64.069	47932.5	20960.0	43106.9
55	Újbarok (103)	47.47031	18.57520	2.327	63.817	47856.4	21115.9	42945.9
56	Sárszentágota (105)	46.93366	18.57312	2.385	63.355	47734.3	21407.1	42665.0
57	Ráckeve (106)	47.20296	18.91651	2.324	63.598	47812.8	21261.1	42825.6
58	Dunavecse (107)	47.01091	18.99020	2.301	63.409	47797.6	21395.0	42741.8
59	Fülöpháza (108)	46.88140	19.45305	2.517	63.346	47750.0	21421.0	42675.6
60	Kiskőrös (109)	46.64804	19.25338	2.444	63.150	47697.2	21542.6	42555.1
61	Bócsa (111)	46.66802	19.51559	2.500	63.172	47721.2	21537.6	42584.6
62	Öcsöd (112)	46.83709	20.41013	2.602	63.378	47851.3	21442.0	42778.4
63	Kunszentmárton (113)	46.74977	20.29816	2.596	63.261	47822.9	21517.0	42708.9
64	Bugac (114)	46.66612	19.76283	2.528	63.187	47766.0	21546.1	42630.5
65	Galgahévíz (117)	47.65591	19.59295	2.629	64.018	47994.9	21026.0	43144.1
66	Zsámbok (118)	47.54885	19.63840	2.603	63.949	47964.3	21064.3	43091.4
67	Tápiógyörgye (120)	47.31548	19.97342	2.599	63.778	47950.7	21187.0	43016.0
68	Nagykörös (124)	47.02045	19.83006	2.718	63.503	47842.8	21345.3	42817.2
69	Szank (127)	46.54547	19.69839	2.548	63.056	47732.7	21628.6	42551.3
70	Kalocsa (128)	46.49627	19.01394	2.386	62.991	47685.1	21655.1	42484.4
71	Szalkszent-márton (129)	46.94973	19.12535	2.409	63.380	47766.0	21402.4	42702.8
72	Ásotthalom (130)	46.23869	19.70672	2.525	62.829	47618.0	21744.4	42363.4
73	Kéleshalom (131)	46.36038	19.20832	2.384	62.873	47612.5	21709.5	42375.1

74	Mélykút (132)	46.24037	19.43001	2.447	62.787	47639.4	21785.7	42366.2
75	Zsana (134)	46.37340	19.70419	2.535	62.905	47648.8	21702.6	42419.4
76	Orosháza (135)	46.62539	20.63515	2.691	63.187	47777.3	21551.7	42640.3
77	Derekegyháza (136)	46.58040	20.32678	2.582	63.125	47742.8	21582.0	42586.3
78	Csabacsüd (138)	46.80708	20.61848	2.683	63.348	47845.6	21462.0	42762.0
79	Kétsoprony (139)	46.70206	20.84183	2.757	63.268	47816.1	21508.7	42705.4
80	Mezőkovácsháza (144)	46.36680	20.98200	2.804	62.970	47721.6	21687.6	42508.8
81	Battonya (145)	46.31469	21.07999	2.788	62.930	47709.8	21711.4	42483.4
82	Zsadány (146)	46.94876	21.50359	2.933	63.500	47930.1	21386.3	42894.3
83	Csárdaszállás (147)	46.87719	20.90941	2.738	63.416	47884.0	21428.6	42821.6
84	Vésztő (148)	46.93861	21.31405	2.875	63.507	47915.7	21374.5	42884.1
85	Pusztaottlaka (149)	46.53205	20.97851	2.900	63.119	47802.4	21613.6	42637.1
86	Kunpeszér (151)	47.09165	19.23678	2.356	63.517	47889.8	21355.5	42864.6
87	Kenderes (152)	47.22726	20.62191	2.782	63.705	47919.2	21227.7	42960.8
88	Hajdúszoboszló (158)	47.48724	21.48060	2.977	63.991	48096.8	21090.8	43225.9
89	Furta (159)	47.10086	21.46354	2.930	63.632	48000.4	21318.9	43006.3
90	Hajdúböszörmény (160)	47.59209	21.44154	3.063	64.041	48148.9	21076.1	43291.0
91	Nádudvar (162)	47.43417	21.07427	2.875	63.928	48057.5	21121.1	43167.4
92	Kaba (163)	47.36407	21.34246	2.949	63.896	48047.4	21141.3	43146.2
93	Tiszaszöllös (164)	47.52382	20.71352	2.732	64.021	48068.4	21055.9	43211.3
94	Egyek (165)	47.59389	20.85480	2.840	64.089	48076.8	21008.5	43243.8
95	Bugyi (167)	47.20954	19.11324	2.453	63.632	47831.1	21243.4	42854.8
96	Zaránk (168)	47.63051	20.09678	2.736	64.068	48055.3	21014.7	43216.8
97	Tenk (169)	47.66849	20.34180	2.722	64.112	48101.3	21001.5	43274.4
98	Jászapáti (171)	47.51165	20.18266	2.590	63.982	48015.9	21062.5	43149.7
99	Besenyszög (172)	47.26492	20.22448	2.670	63.737	47924.7	21206.5	42977.5
100	Tiszasüly (173)	47.39048	20.33013	2.688	63.873	47964.7	21122.2	43063.5
101	Tiszabő (174)	47.29944	20.51317	2.644	63.799	47968.4	21178.9	43039.8
102	Domony (176)	47.64335	19.43157	2.543	64.014	47958.7	21013.2	43110.1
103	Kókad (178)	47.38828	21.94888	3.039	63.885	48112.5	21177.7	43200.9
104	Hosszúpályi (179)	47.38225	21.74328	3.053	63.888	48099.0	21169.8	43189.7
105	Kismarja (180)	47.23116	21.84392	2.995	63.773	48095.8	21254.7	43144.5

106	Szentpéterszeg (181)	47.25379	21.61193	2.921	63.782	48039.7	21223.4	43097.3
107	Körösszegapáti (182)	47.06627	21.64570	2.977	63.627	47994.2	21319.6	42999.1
100	Nyíradony (190)	47.71683	21.88398	3.100	64.239	48179.2	20939.5	43390.9
109	Hajdúvid (192)	47.75552	21.53028	2.973	64.251	48212.0	20945.0	43424.7
110	Csánytelek (194)	46.61538	20.12651	2.464	63.153	47796.3	21584.9	42644.8
111	Mezőhegyes (197)	46.28324	20.89622	2.741	62.901	47675.6	21717.5	42441.9
112	Békés (199)	46.76374	21.07187	2.838	63.363	47844.1	21450.5	42766.0
113	Füzesgyarmat (200)	47.12232	21.18313	2.857	63.649	48016.6	21313.4	43027.1
114	Újszalonta (201)	46.82520	21.48396	2.777	63.417	47880.3	21426.3	42818.7
115	Dévaványa (203)	46.97874	21.00939	2.736	63.514	47934.6	21378.1	42903.4
116	Körösladány (204)	46.93836	21.03477	2.753	63.476	47905.9	21393.6	42863.6
117	Tiszabura (207)	47.42963	20.54707	2.694	63.862	48022.1	21155.6	43111.1
118	Karcag (208)	47.24506	20.83364	2.829	63.758	47951.1	21202.1	43009.1
119	Dunatetétlen (210)	46.75234	19.10616	2.390	63.216	47714.1	21501.1	42595.0
120	Helvécia (211)	46.82803	19.66105	2.564	63.317	47783.2	21457.2	42694.5
121	Dabas (212)	47.19518	19.32262	2.476	63.635	47859.9	21254.2	42881.6
122	Lajosmizse (213)	47.03712	19.58170	2.588	63.479	47820.8	21353.6	42788.5
123	Kecskemét (214)	46.95900	19.66009	2.589	63.434	47820.1	21386.2	42771.4
124	Jászalsó-szentgyörgy (215)	47.45883	20.09678	2.639	63.847	47981.0	21148.9	43068.6
125	Harsány (219)	47.94197	20.71961	2.874	64.343	48139.8	20844.0	43393.2
126	Gesztely (220)	48.12452	20.94577	2.909	64.489	48216.3	20766.4	43515.2
127	Mezőcsát (224)	47.82553	20.83687	2.962	64.246	48115.7	20906.5	43336.4
128	Aggtelek (225)	48.45559	20.49015	2.823	64.774	48260.2	20567.7	43658.0
129	Egerlövő (226)	47.74362	20.59257	2.852	64.193	48082.4	20932.1	43287.0
130	Csákberény (228)	47.33382	18.37490	2.286	63.705	47805.3	21177.4	42858.7
131	Sáta (231)	48.20057	20.39477	2.776	64.557	48179.0	20698.5	43506.2
132	Noszvaj (232)	47.94387	20.48350	2.812	64.325	48115.1	20846.4	43364.6
133	Verpelét (233)	47.84488	20.19328	2.623	64.181	48098.1	20948.2	43296.6
134	Nagyoroszi (237)	47.99222	19.09332	2.540	64.350	48034.3	20792.6	43300.8
135	Csány (239)	47.66052	19.81675	2.484	64.067	47995.2	20989.5	43162.2
136	Cserhát-szentiván (241)	47.94221	19.57004	2.576	64.277	48016.6	20840.2	43258.3
137	Kisbágyom (242)	47.82554	19.56172	2.572	64.167	48027.9	20928.4	43228.3

138	Szendrőlád (243)	48.37124	20.78910	2.928	64.712	48256.9	20613.9	43632.5
139	Zsujta (246)	48.50727	21.30026	3.338	64.774	48316.3	20591.9	43708.6
140	Vilyvitány (247)	48.47894	21.58196	-	64.902	48150.5	20424.2	43604.2
141	Felsődobsza (248)	48.26662	21.10514	2.945	64.631	48259.9	20676.6	43606.1
142	Szerencs (250)	48.12556	21.14689	3.014	64.504	48222.6	20757.4	43526.4
143	Tiszacsege (255)	47.67559	21.15431	2.912	64.178	48110.4	20955.6	43306.7
144	Beszterec (259)	48.15270	21.84718	3.207	64.566	48289.5	20738.8	43609.4
145	Újtikos (260)	47.91988	21.23637	2.863	64.437	48155.1	20779.1	43441.3
146	Gyömrő (262)	47.41244	19.38765	2.423	63.815	47903.4	21138.1	42987.4
147	Jászberény (263)	47.56550	19.93676	2.731	63.963	47984.3	21062.7	43114.4
148	Csévharaszt (266)	47.30549	19.45337	1.541	63.743	47862.0	21174.3	42923.4
149	Kiskunhalas (268)	46.44160	19.38154	2.428	62.945	47653.8	21675.3	42439.0
150	Legénd (271)	47.86554	19.29001	2.623	64.186	48019.5	20910.5	43227.6
151	Tahitótfalu (274)	47.77472	19.09960	2.448	64.096	47983.2	20962.4	43162.1
152	Zsombó (276)	46.33432	19.94601	2.618	62.913	47654.1	21699.1	42427.1
153	Tök (279)	47.59051	18.72661	2.355	63.962	47911.0	21031.7	43048.0
154	Tákos (280)	48.14890	22.39538	3.302	64.573	48336.2	20753.8	43654.0
155	Nagyszekeres (284)	47.96391	22.61877	3.243	64.516	48295.5	20779.6	43596.6
156	Csenger (285)	47.86013	22.71021	3.211	64.368	48269.6	20880.9	43519.5
157	Vitka (287)	48.08012	22.29701	3.226	64.542	48314.4	20767.7	43623.2
158	Eperjeske (289)	48.34062	22.22705	3.336	64.700	48341.1	20659.1	43704.3
159	Nyirkárász (290)	48.12382	22.13402	3.285	64.549	48292.1	20752.8	43605.6
160	Révleányvár (291)	48.32158	22.04719	3.005	64.706	48331.8	20650.5	43698.1
161	Kótaj (292)	48.04511	21.76159	3.128	64.480	48222.3	20775.1	43517.7
162	Elek (295)	46.56294	21.26092	2.938	63.229	47873.7	21563.7	42742.2
163	Nagycenk (301)	47.63275	16.72106	1.568	63.852	47768.2	21051.0	42879.6
164	Báta	46.11768	18.77142	2.244	62.636	47531.0	21847.5	42212.3
165	Csanádalberti	46.31982	20.67189	2.688	62.920	47678.8	21704.8	42452.0
166	Csarnóta	45.88371	18.21726	2.135	62.349	47392.0	21993.8	41979.5
167	Diszel	46.88368	17.49135	2.014	63.242	47620.5	21439.8	42521.1
168	Eplény	47.22528	17.88528	2.150	63.542	47769.7	21283.1	42766.5
169	Bősárkány	47.70280	17.24286	2.024	63.942	47886.4	21035.4	43018.8
170	Szerep	47.21718	21.15017	2.890	63.791	48043.1	21218.0	43103.8
171	Cirák	47.45077	17.02713	2.002	63.800	47756.5	21085.1	42849.8

172	Penc	47.78873	19.28266	2.475	64.147	48006.2	20933.9	43201.5
173	Pilis	47.28994	19.60027	2.619	63.796	47917.1	21158.8	42992.5
174	Győrszentiván	47.72040	17.74154	2.138	63.727	47886.8	21196.7	42940.0
175	Türje	46.96969	17.08262	1.894	63.284	47635.3	21415.6	42549.9
176	Bókaháza	46.77920	17.11744	1.925	63.111	47566.3	21512.5	42423.6
177	Cserebökény	46.75559	20.47291	2.620	63.292	47830.1	21497.1	42727.0
178	Hurbanovo – SK	47.87417	18.19000	2.196	64.082	47950.6	20958.2	43127.9
179	Pusztazámor	47.38362	18.79921	2.428	63.784	47852.3	21139.1	42930.0
180	Kétpó	47.08810	20.50586	2.825	63.608	47884.9	21285.5	42893.9
181	Miskolc	48.07496	20.45545	2.767	64.427	48156.5	20787.3	43438.9
182	Pétervására	47.98117	20.14853	2.682	64.314	48106.9	20851.7	43353.0
183	Nizsnye Szeliscse – UA	48.19608	23.45697	3.563	64.626	48385.7	20734.6	43717.9
184	Kondorfa	46.88461	16.39443	1.664	63.129	47606.0	21516.8	42466.0
185	Vámosszabadi	47.76388	17.61075	-	64.101	47919.0	20930.0	43106.4
186	Lenartovce - SK	48.31615	20.32553	2.726	64.653	48182.1	20626.8	43543.6
187	Janik - SK	48.57818	20.91086	2.960	64.884	48300.2	20501.4	43733.3
188	Zselovce - SK	48.12898	19.37348	2.586	64.462	48051.5	20715.2	43357.0
189	Novy Straz - SK	47.75888	17.27491	2.192	64.043	47897.8	20964.6	43066.0
190	Samorin - SK	48.04080	17.33922	2.122	64.305	47903.4	20770.2	43166.4
191	Jennersdorf - A	46.93565	16.15975	1.851	63.202	47535.0	21431.3	42429.6
192	Apetlon - A	47.76298	16.83944	1.955	64.024	47823.3	20946.1	42992.2
193	Zurndorf - A	47.94840	17.02607	1.968	64.159	47862.1	20861.6	43076.4
194	Oberpullendorf - A	47.50774	16.58313	1.911	63.845	47675.0	21015.0	42793.4
195	Regöly	46.56030	18.36881	2.220	63.069	47665.7	21588.4	42496.6

Geomágneses alaphálózat mérés Magyarországon 1994–95 folyamán valamint a tér szekuláris változása 1950 és 1995 között

KOVÁCS Péter és KÖRMENDI Alpár

A legutóbbi országos alaphálózat-mérésünkre 1994 és 1995 folyamán került sor. Hálózatunk 195 pontot tartalmazott, amelyeken közvetlenül a mágneses deklinációt, inklinációt, valamint a tér abszolút értékét mértük DI fluxgate, valamint protonprecessziós magnetométerek segítségével. Az állomások földrajzi koordinátáit, illetve a referencia pontok irányait a legtöbb esetben GPS vevők segítségével állapítottuk meg. Az eredményeket a tihanyi geomágneses obszervatórium regisztrátumainak a felhasználásával az 1995.0 epochára redukáltuk. A tér komponenseinek normáltereit a földrajzi koordináták másodrendű polinomjaiként határoztuk meg. A polinomok együtthatóit a leggyakoribb érték szerinti kiegyenlítés felhasználásával számoltuk. A tér szekuláris változásának normál eloszlását a legutóbbi és az 1949-50-es országos alaphálózat-mérés eredményei alapján ugyancsak a földrajzi koordináták másodrendű polinomjaiként adtuk meg.

ABOUT THE AUTHORS

Péter Kovács was born in Budapest, in 1969. He graduated as geophysicist in the Eötvös Loránd University, in 1994 and then joined Eötvös Loránd Geophysical Institute of Hungary. His main research interest is geomagnetism and he played a part in the last Hungarian geomagnetic repeat station survey, which was carried out in 1994 and 1995. In addition he is working towards his Ph.D. The subject of this Ph.D. research is the numerical investigation of the dynamics of the magnetosphere and solar wind using the time series of the geomagnetic field.

Alpár Köremendi (1944) geophysicist. Graduated from Eötvös Loránd University (ELTE), Budapest in 1968. Experienced in exploration geophysics, geoelectrical resistivity and shallow seismic measurements (Research Institute for Water Management VITUKI), seam-wave seismic and seismoacoustic research (Tatabánya Coal Mines) and in observatory practice: recording and processing the variations of the Earth's magnetic field, ionospheric phenomena, testing and developing magnetic instruments (ELGI).

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Magnetic sources from vertical magnetic anomalies

Károly I. KIS*, William B. AGOCS**, Arthur A. MEYERHOFF***

Four vertical magnetic anomaly profiles (along a total length of 1124 km) across the Pannonian basin of Hungary were digitized for this study using 1 km spacing. The profile data were sampled in 31 km and 127 km sections for determining the depths to magnetic sources, using power density spectra at intervals of 5 km for the shorter sections and 10 km for the longer. All profiles show a shallow layer bracketed by a horizon about 2 km deep and another about 4 to 5 km deep for the 31 km sections. For the 127 km sections a second layer was found with an upper surface or horizon between 6 and 16 km deep — but rising as high as 4 km — and a lower horizon which locally is as deep as 25 km. The greatest depth probably represents the depth of the Curie point temperature. The lower layer is offset where major tectonic lines (generally deep faults) intersect the magnetic profiles, a fact indicated by magnetic techniques showing that the tectonic lines extend through the upper crust in Hungary.

The depths obtained using current spectral analysis are compared with results of other studies using related techniques such as areal depth averaging, depth determinations using magnetic anomaly slopes, and magnetotelluric methods. The results for the shallow horizons coincided with the results of the other studies, a fact that lends considerable confidence to the findings with the deeper horizons.

Keywords: Curie point, magnetic anomalies, Hungary, power spectrum, upper crust

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1. Introduction

Hungary, an east-central European nation of 93,030 km^2, is surrounded by Austria, Slovakia, Ukraine, Romania, Yugoslavia, Croatia, and Slovenia (*Fig. 1*). The geology of Hungary has been summarized by KŐRÖSSY [1964], WEIN [1969], BALOGH and KŐRÖSSY [1974], BÉRCZI et al. [1981], and FÖLDVÁRY [1988]. A brief résumé of the geology is presented and summarized in *Figures 2, 3* and *4*. These three figures also show the probable sources of the magnetic anomalies that are the principal theme of this paper.

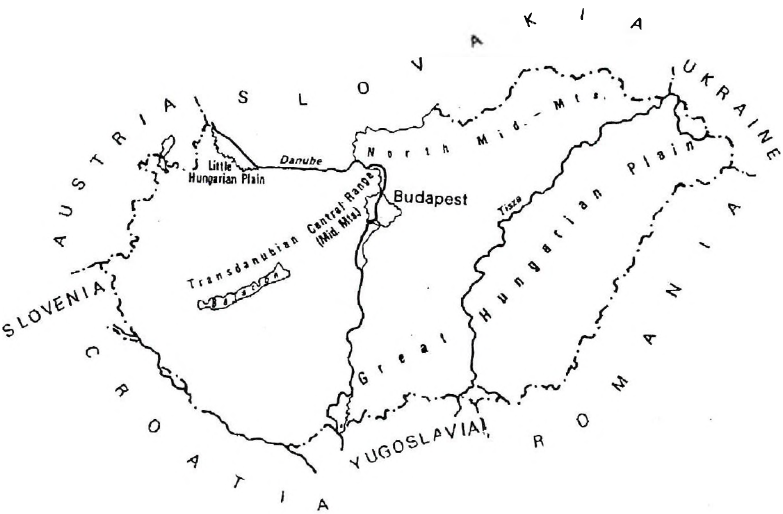


Fig. 1. Index map
1. ábra. Magyarország és a környező országok

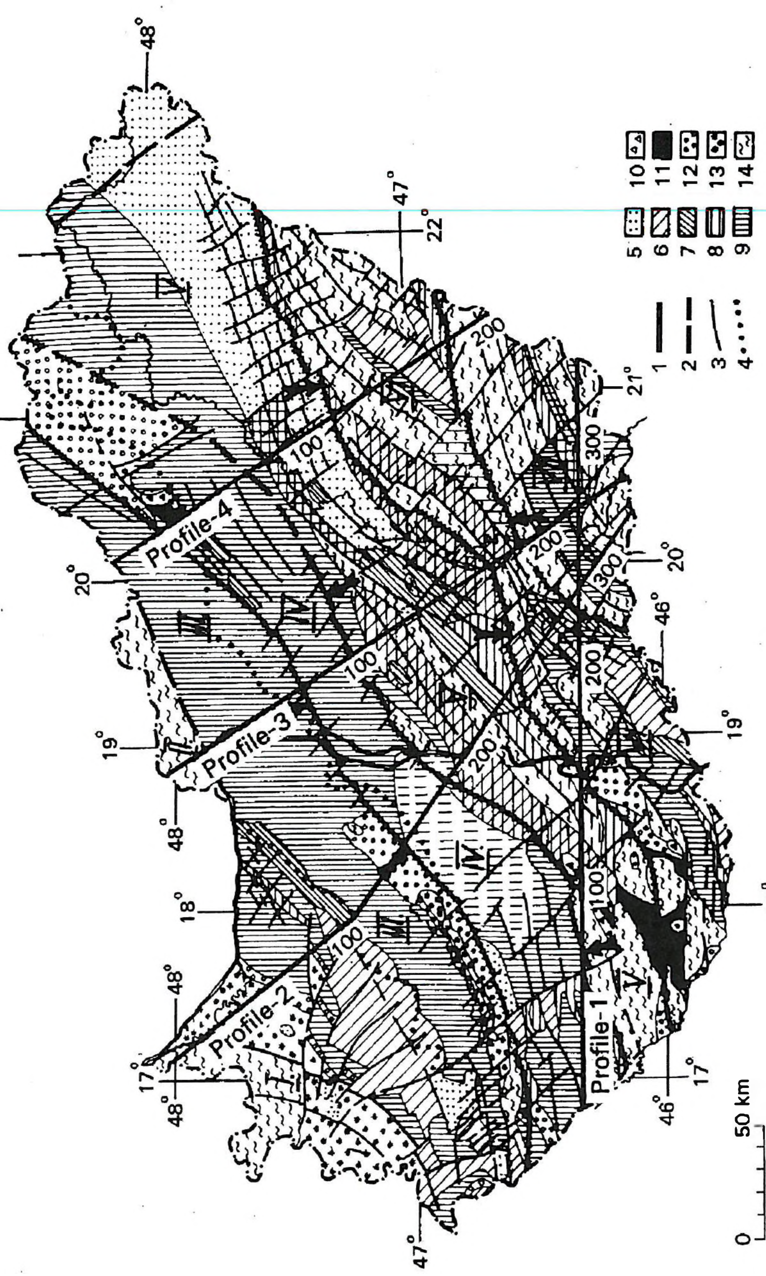
Geologically, Hungary lies in the centre of the Pannonian basin, which is enclosed in the north, east, and southeast by the arc of the Carpathian Mountains, in the northwest by the Eastern Alps, and in the southwest by the Dinaric Alps. Within Hungary itself, three main tectonic phases can be distinguished. These are (1) the pre-Neogene phase which includes all pre-Miocene rocks, (2) the early and middle Miocene phase, and (3) the late Miocene and younger phase.

Figure 2 illustrates the tectonic pattern of the pre-Tertiary (mainly pre-Neogene) rocks of the oldest tectonic phase. These rocks, which range in age from Proterozoic to Early Cretaceous, lie in zones or belts that acquired their present form during the Austrian (mid-Cretaceous) and Savian (mid-Tertiary) phases of Alpine tectogenesis. Nearly all of the pre-Tertiary belts strike east-northeast–west–southwest or northeast–southwest. KŐRÖSSY [1964] grouped them into seven major structural blocks or zones (units I-VII, Figure 2). Each of the structural units has a unique geological history. The boundaries separating them are major (first-order) tectonic lines, many of them fault zones. Less important (second- and third-order) tectonic lines are within the blocks and separate the various subdivisions of each block. RUMPLER and HORVÁTH [1988] described the nature of the various tectonic lines.

Figure 3 is an isopach map of the early and middle Miocene sediments of the Hungarian part of the Pannonian basin. Several northeast–southwest depressions are present. These depressions developed in an extensive tectonic regime, and reflect the northeast–southwest structural grain in the pre-Miocene rocks underneath. Sedimentation rates during early to middle Miocene times were high, and reached approximately 5.3 m/1000 yr by the end of middle Miocene times.

Also shown in Figure 3 is the extent of the early Miocene volcanism. In general, volcanism took place in the fault-bounded depressions where the thickest sedimentary sections lie. During early Miocene (Burdigalian) times, rhyolitic tuffs accumulated. These comprise the 'lower rhyolite tuff', or Gyulakeszi Volcanic Formation, of the literature. During the latter part of early Miocene and middle Miocene times (Langhian-Serravallian), the 'middle rhyolite tuff' or Mátra Volcanic Formation accumulated. This volcanic unit includes widespread rhyodacite tuff and local extrusions of andesite, dacite, and rhyodacite. During late middle Miocene and early late Miocene times (late Serravallian–early Tortonian), the 'upper rhyolite formation' formed; this also is known as the Tokaj Volcanic Formation, a unit consisting of andesite and rhyolite.

Figure 4 is an isopach map of the post-middle Miocene rocks in the Hungarian part of the Pannonian basin. These rocks were originally called 'Pannonian' (sensu lato) in the literature. The thickness values indicate that


Profile-1
Profile-2
Profile-3
Profile-4
0
50 km
1
2
3
4
5
6
7
8
9
10
11
12
13
14

the sedimentation rate tended to increase. The volcanic products are almost entirely basalt, and include the Kecel Basalt (late Miocene), the Tapolca Basalt Formation (late Miocene-Pliocene), and the Bár and Nógrád Basalts (Pliocene; NAGYMAROSY and MÜLLER [1988]). These basalts have been found in boreholes drilled on the Great Hungarian Plain (Figure 1). Volcanic cones north of Lake Balaton are well known, they are found in holes drilled on the Little Hungarian Plain and they outcrop in northeastern Hungary. The basalts are found where the greatest subsidence took place and where the thickest sedimentary sections are located. They are a further manifestation of the dominant extensional tectonic regime.

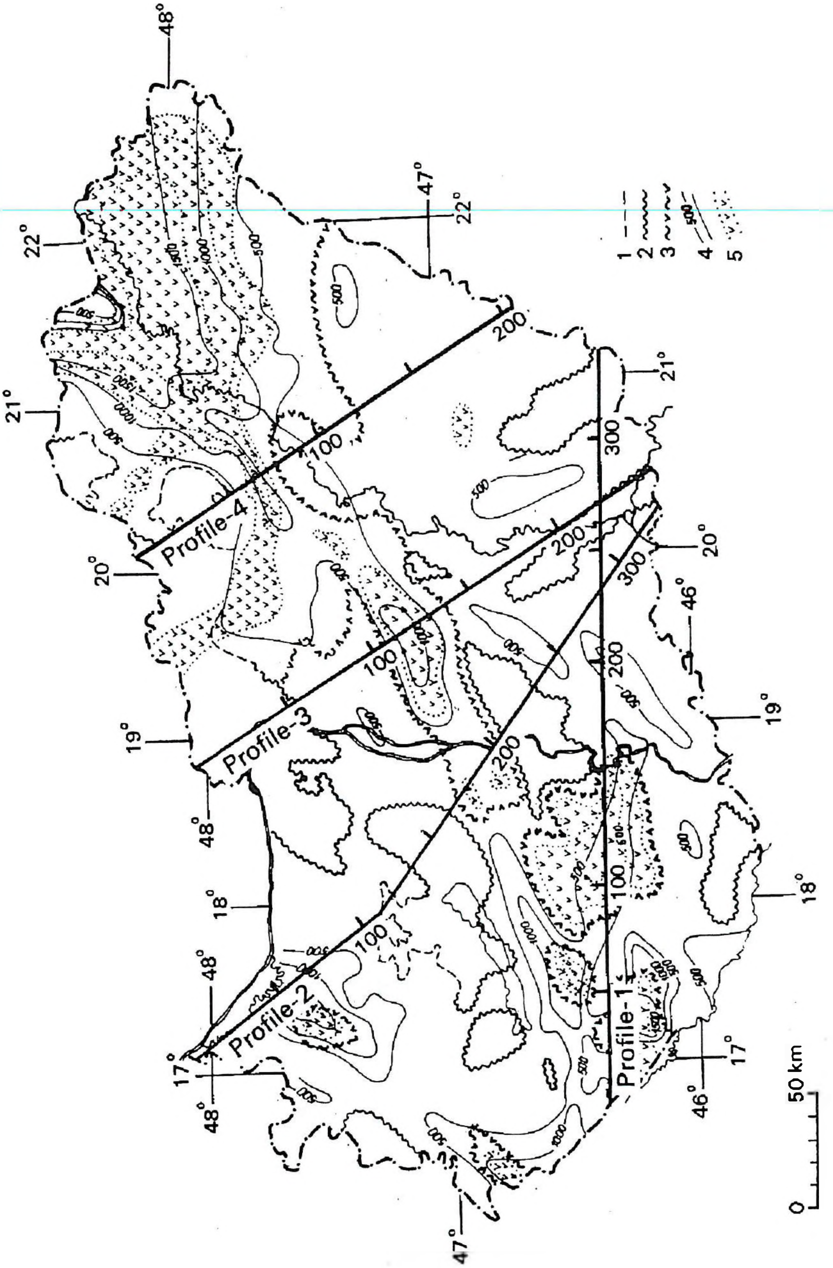
The Vertical Magnetic Anomaly Map of Hungary, published by the Eötvös Loránd Geophysical Institute of Hungary in 1967 and compiled by HAÁZ and KOMÁROMY [1967] on a 1:200,000 scale, is the source for all the depth determinations presented here. The values contoured are accurate to $\pm$(5–10) nT. *Figure 5* is a simplified version of the HAÁZ and KOMÁROMY map.

Vertical magnetic field intensity in Hungary ranges from about 41,200 to 43,000 nT; the inclination ranges from 62° to 64.5°, and the declination from 0° to 2° E.

This study presents the determinations of spectral energy density depth made on four profiles digitized from the vertical magnetic data along

Fig. 2. Tectonic sketch map of the Tertiary basement complex of Hungary. *Keys:* I—Kőszeg-Mihályi zone; II—Diósjenő-Salgótarján zone; III—Mid-Mountain zone; IV—Igal-Bükk zone; V—Mecsek-Central Plain zone; VI—Villány-Bihar zone; VII—Szeged-Békés zone. 1—First order tectonic lines; 2—Second order tectonic lines; 3—Third order tectonic lines; 4—Outcrops; 5—Upper Cretaceous to Paleogene; 6—Upper Cretaceous; 7—Lower Cretaceous; 8—Jurassic; 9—Triassic; 10—Permian; 11—Carboniferous; 12—Devonian; 13—Silurian; 14—Proterozoic to Early Paleozoic. [From BÉRCZI et al. 1981]. The locations are shown of Profiles-1, -2, -3, and -4, respectively

2. ábra. A magyarországi harmadidőszaki medencék tektonikai vázlata. *Jelmagyarázat:* I—Kőszeg-Mihályi zóna; II—Diósjenő-Salgótarján zóna; III—Középhegységi zóna; IV—Igal-Bükk zóna; V—Mecsek-Alföld zóna; VI—Villány-Bihar zóna; VII—Szeged-Békés zóna. 1—elsőrendű tektonikai vonal; 2—másodrendű tektonikai vonal; 3—harmadrendű tektonikai vonal; 4—kibukkanás; 5—felső krétától paleogénig; 6—felső-kréta; 7—alsó-kréta; 8—jura; 9—triász; 10—perm; 11—karbon; 12—devon; 13—szilur; 14—proterozóikumtól korai paleozóikumig, [BÉRCZI et al. 1981]. Az ábra feltünteti az 1-, 2-, 3- és 4-szelvény helyzetét


Profile-1
Profile-2
Profile-3
Profile-4
50 km
0
1
2
3
4
5

a total profile length of 1,124 km. The east-west Profile-1 located in southern Hungary is 347 km long; the northwest–southeast bearing Profiles-2, -3, and -4 are respectively 330, 240, and 207 km long. The locations of the four are shown in Figures 2 through 5; the vertical magnetic anomaly profiles are presented in Figures 8 through 11.

2. Curie isotherm depth

The depth of the Curie isotherm is defined as the greatest depth at which the rocks are nonparamagnetic; that is, they contribute to the production of the magnetic anomalies. The Curie temperature — which varies in the interval -150 °C – 578 °C [NAGATA and OZIMA 1967] — is a function of mineral composition of the rocks. The titanomagnetites are the most common such minerals.

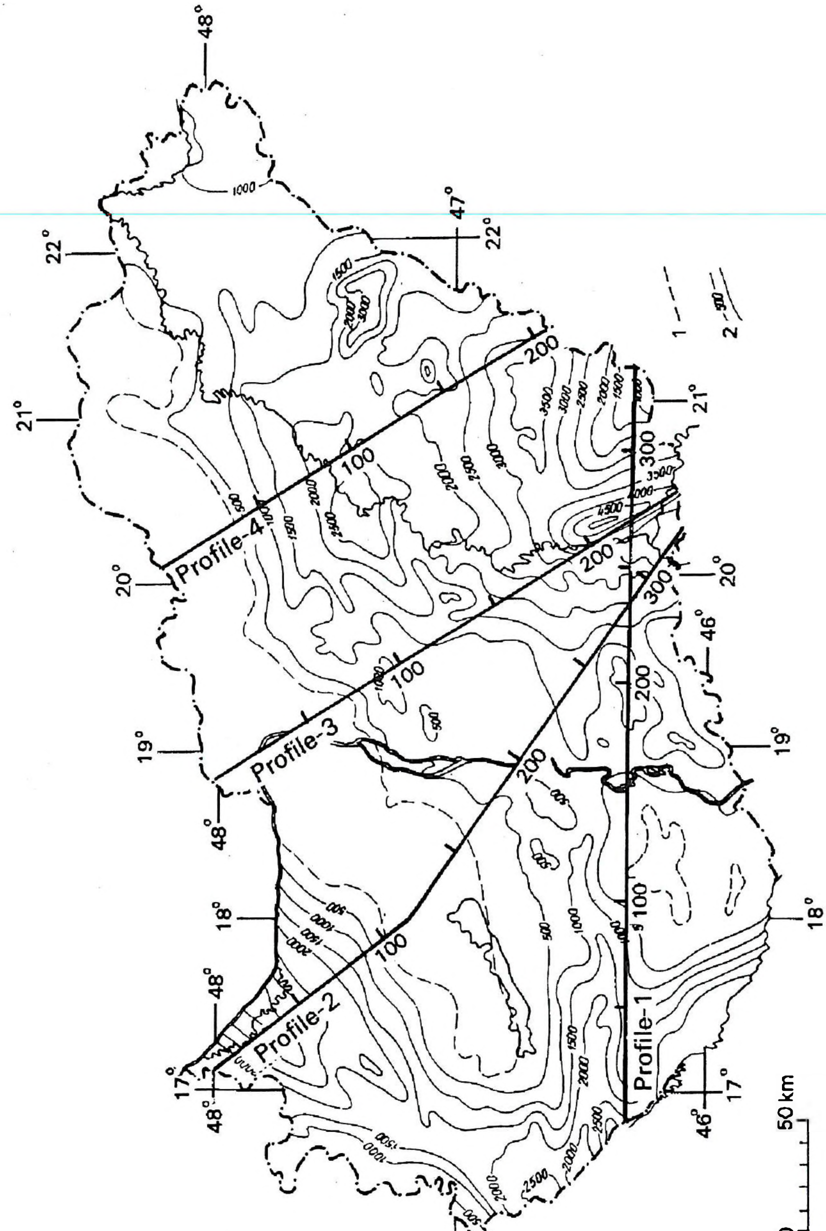
Different temperatures have been suggested as the value of the upper limit of the Curie isotherm: 560 °C by BHATTACHARYYA and LEU [1975b]; 500 °C by BYERLY and STOLT [1977] based on seismic velocity, thermal, and magnetic properties of the rocks; between 520 and 560 °C by SHUEY et al. [1977]; from 500 – 600 °C by OKUBO et al. [1985].

If the average geothermal gradient of 30 to 50 °C/km determined in continental areas is assumed, then the depth of the Curie isotherm can be expected in the depth range of 10 to 20 km. Such depth determinations must be based on the consideration of only the largest magnetic anomalies. This requirement was emphasized by SPECTOR and GRANT [1970] and SHUEY et al. [1977]. From data published by DÖVÉNYI et al. [1983], the

Fig. 3. Isopach map of Miocene sediments. *Key:* 1—pre-Miocene outcrops; 2—Pinchout of Miocene strata; 3—Boundary of Miocene volcanites; 4—Isopach contours of the Miocene formations; 5—Miocene volcanic rocks (mainly tuffs) of considerable thickness. [From BÉRCZI et al. 1981]. The locations are shown of Profiles-1, -2, -3, and -4, respectively

⇦

3. ábra. Miocén rétegek vastagság térképe. *Jelmagyarázat:* 1—pre-miocén kibukkanások; 2—kiékelődő miocén rétegek; 3—a miocén vulkanitok határa; 4—a miocén rétegek vastagságának izovonalai; 5—nagyobb vastagságú miocén vulkáni kőzetek (elsősorban tufák) [BÉRCZI et al. 1981]. Az ábra feltünteti az 1-, 2-, 3- és 4-szelvény helyzetét


Profile-1
Profile-2
Profile-3
Profile-4
100
200
300
1
2
500
0
50 km
17°
18°
19°
20°
21°
22°
46°
47°
48°

average geothermal gradient in Hungary is 43 °C/km between the depths of 1 and 3 km, and 33 °C/km between 3 and 5 km. If one uses the latter value, the Curie temperature beneath Hungary should be at about 18 km. By extrapolation, then, the Curie temperature beneath Hungary cannot be higher than the values given above.

3. Profile spectrum

Determination of the parameters of magnetic sources based on the estimate of the power spectrum has been discussed by SPECTOR and GRANT [1970], TREITEL et al. [1971], GREEN [1972], BHATTACHARYYA and LEU [1975a], CURTIS and JAIN [1975], HAHN et al. [1976], BHATTACHARYYA and LEU [1977], KIS and MESKÓ [1978], and AGOCS [1983].

Application of the spectral method in the case of isolated 2-D structures was discussed by BHATTACHARYYA and LEU [1975a]. If the magnetic anomalies may be produced by several sources, a statistical approach is required, and the method and equations suggested by SPECTOR and GRANT [1970], and GREEN [1972] can be applied. In the statistical approach, the power density spectrum of the vertical magnetic anomalies on a profile can be produced by an ensemble of 2-D rectangular, vertical-sided parallelepipeds. The results of this kind of computations are the expectations of parameters of the magnetic sources.

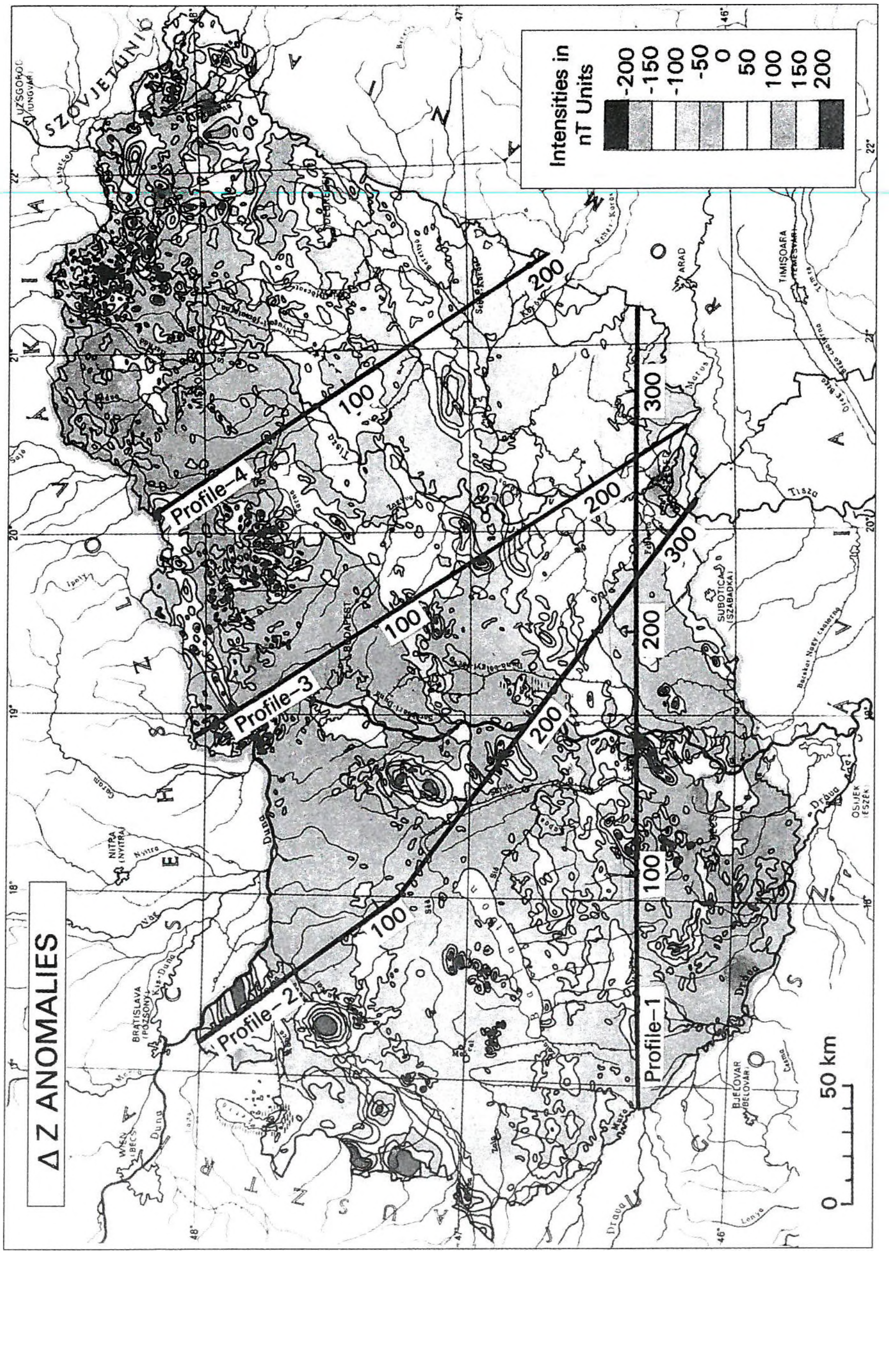
Each of the above-mentioned methods requires numerical computation of the power density spectrum. OTNES and ENOCHSON [1978] summarized the application of the different numerical methods.

In the present study, the profiles were digitized using equidistant 1 km spacing. In the computations, the profiles were divided into sections of 32 and 128 data points of 31 km and 127 km length. The central point of each sampled section is considered the reference point of the calculations. The

Fig. 4. Isopach map of the Pannonian sediments. *Key:* 1—Boundaries of pre-Pannonian outcrops; 2—Isopach contours of the Pannonian sediments. [From BÉRCZI et al. 1981]. The locations are shown of Profiles-1, -2, -3, and -4, respectively

⇦

4. ábra. Pannon üledékek vastagság térképe. *Jelmagyarázat:* 1—pre-pannon kibukkanások határa; 2—pannon üledékek vastagságának izovonalai [BÉRCZI et al. 1981]. Az ábra feltünteti az 1-, 2-, 3- és 4-szelvény helyzetét


Δ Z ANOMALIES
Intensities in
nT Units
-200
-150
-100
-50
0
50
100
150
200
Profile-1
Profile-2
Profile-3
Profile-4
100
200
300
0
50 km
BUDAPEST
BRATISLAVA
NITRA
SUBOTICA
OSIJEK
BJELOVAR
TIMIŞOARA
ARAD
WIEN
SZOVJETUNIÓ

increased sampling length is required to determine the maximum depth obtainable, and to correlate depths with the Curie isotherm. The power density spectrum of the vertical magnetic anomalies is calculated by the FFT algorithm summarized by BRIGHAM [1974]. The spatial frequency increments of the numerical calculated power density spectra are 1/32 and 1/128 cycles/km. When determining the depths the uniform distribution of the parameters as suggested by SPECTOR and GRANT [1970], and GREEN [1972] was accepted.

Depth determinations were obtained from the slope of the straight lines fitted to the logarithmic power density spectra. The straight lines were fitted to the power density spectra by the least squares method by selecting parts of the spectra for the least squares fitting. It is assumed that the uncertainties are caused by the fluctuations of the power spectra. The depth expectation (see Figures 8–11) is indicated by vertical bars specifying the standard error of the mean.

4. Interpretation

Previous interpretations

POSGAY [1962, 1967] made comprehensive depth determinations from the vertical magnetic anomalies deviating 30–40 nT from the surroundings. These show a broad central arch-like feature across the Pannonian basin with a depth range of 2–4 km. This central high zone is flanked on both the southeast, and on the west to northwest, by zones more than 8 km deep. POSGAY's depth determinations for the magnetic sources are illustrated in *Figure 6*. As a consequence of the graphical depth determination method which he used, the depths were considered to be approxi-

Fig. 5. Simplified version of the Vertical Magnetic Anomaly Map of Hungary. From HAÁZ and KOMÁROMY [1967]. The locations are shown of Profiles-1, -2, -3, and -4, respectively.

⇦ *5. ábra.* A magyarországi vertikális mágneses anomália térkép egyszerűsített változata [HAÁZ és KOMÁROMY 1967]. Az ábra feltünteti az 1-, 2-, 3- és 4-szelvény helyzetét mate. In his general summary concerning the magnetic sources, POSGAY [1967] observed:

(1) The sources producing large-scale magnetic anomalies are in the Mesozoic –Paleozoic –Proterozoic metamorphic granitogenic crystalline basement; they lie in the depth range 3 to 7 km;

(2) Most magnetic anomalies are caused by Cenozoic eruptive volcanic rock;

(3) Early to middle Miocene volcanic rocks have been found beneath younger sediments in many place so that the area of early to middle Miocene volcanics is much greater than indicated on the basis of surface outcrops; and

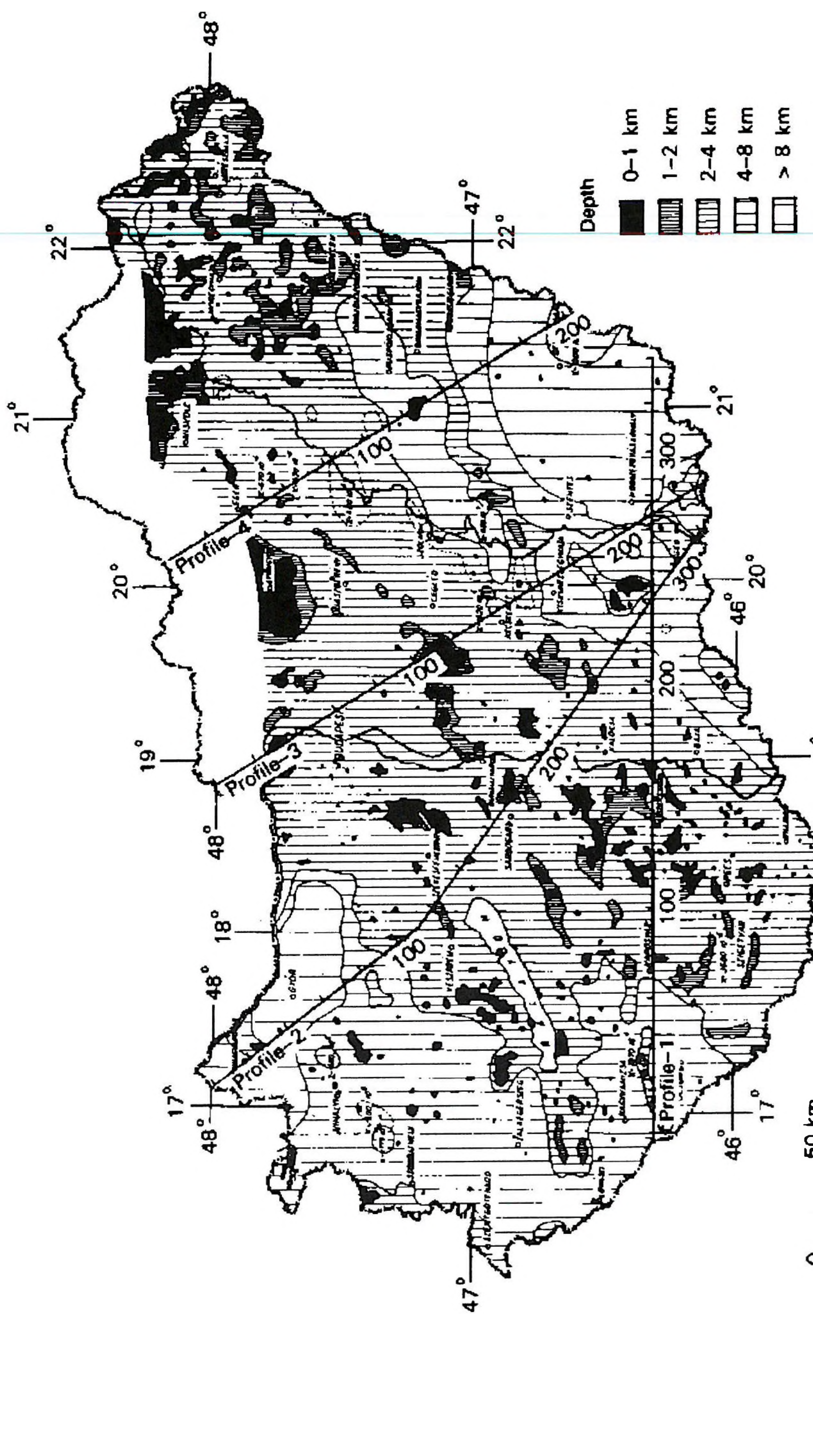
(4) Belts of Pliocene–Pleistocene volcanics are quite widely distributed.

In another study KIS and MESKÓ [1978] used the power spectra on the Vertical Magnetic Anomaly Map of Hungary for depth determinations. They used a modification of the depth procedure discussed by SPECTOR and GRANT [1970]. This modification involves the radial spectral power density control which is determined by the average radial values and radial extent. The 2-D power spectral density was used to determine depths in 40 cells, each 31 × 31 km, covering a large part of Hungary. *Figure 7* shows the cell locations and the depths to the shallow and deep horizons. They show a maximum depth of slightly more than 4 km and a minimum of less than 2 km. The base shows a fairly wide range of depth, with deep values in the northwest (5.2 km), centre (4.2–4.9 km), and southeast (4.3–4.8 km).

Depth determinations of a conductive layer in the middle to the lower crust, based on magnetotelluric measurements, were presented by ÁDÁM et al. [1989]. Their depth determination is located near km 103 of Profile-4, their depth value is 17.4±5.1 km, and the temperature is approximately 500 °C.

Fig. 6. Depth of the isolated magnetic sources [from POSGAY 1967]. The locations are shown of Profiles-1, -2, -3, and -4, respectively.

6. ábra. Izolált mágneses hatók mélysége [POSGAY 1967]. Az ábra feltünteti az 1-, 2-, 3- és 4-szelvény helyzetét


Depth
0–1 km
1–2 km
2–4 km
4–8 km
> 8 km
Profile-1
Profile-2
Profile-3
Profile-4
BUDAPEST
0
50 km

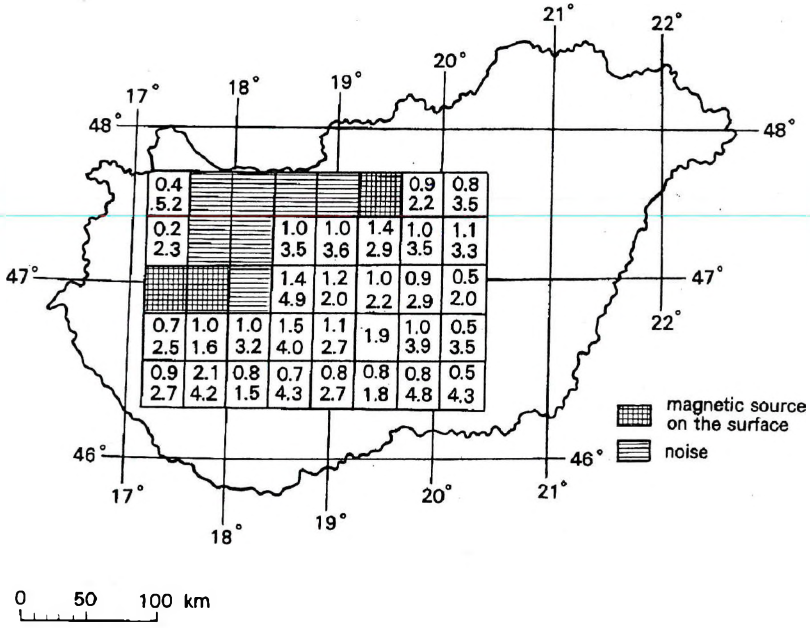


Fig. 7. Average depths of the magnetic sources in 31 31 km cells determined from the logarithmic power density spectra. The upper numbers refer to the shallower, the lower numbers to the deeper sources. Cells where sources are on the surface and cells where the fields due to sources buried in noise are indicated. [From KIS and MESKÓ 1978]

7. ábra. 31x31 km blokkok adatainak logaritmikus teljesítmény spektrumából meghatározott mágneses hatók átlagmélysége. A blokkokban lévő felső számok a sekély, míg az alsó számok a mélyebben elhelyezkedő hatók mélységét jelöli km egységekben. Ahol a ható a felszínen található vagy zaj következtében a mélység nem határozható meg vonalkázás jelöli [KIS és MESKÓ 1978]

Present interpretation

This study made use of two magnetic anomaly sampling sections of lengths, 31 and 127 km, respectively. All profiles using the section length of 31 km reveal the presence of a shallow source layer whose top is about 2 km deep and whose base is as deep as 5 km or slightly more. These results agree with those obtained by KIS and MESKÓ [1978]. These horizons detect basement depths. In Hungary the Proterozoic–Paleozoic crystalline rocks are generally considered the basement of the young basins which are filled with Miocene and younger layers. Some Tertiary sediments are commonly found at the top of the basement together with Miocene tuff.

For the magnetic anomaly sampling section length of 127 km the spectral power reveals the presence at greater depths of an additional possible magnetic anomaly source. The depths of both the shallow and deep magnetic anomaly source layers are plotted with vertical depth variation bars in Figures 8 through 11. At the right-hand side of each figure is a temperature –depth scale extrapolated from the 33 °C/km geothermal gradient published by DÖVÉNYI et al. [1983] for the Hungarian subsurface.

A significant result of the present investigations is that the known tectonic lines of Figure 2 extend downward into the upper crust. Heavy lines and dashed heavy lines in Figures 8–11 show the position of the principal tectonic lines and the interpretation of their downward continuations. The principal tectonic lines separate the major structural zones of the Pannonian basin; the thin lines are locations for second- and third-order tectonic lines. According to RUMPLER and HORVÁTH [1988], who characterized these lines, the Rába, Balaton, and Kapos tectonic lines have the characteristics of strike-slip faults whose magnitude of displacement is unconstrained. This is also true of the Békési tectonic line. In contrast, the Mecsekalja and Darnó tectonic lines are strike-slip zones where the amount of the displacement is well constrained. Beneath the Great Hungarian Plain, the tectonic lines are crossed by normal faults, thrust faults, and folds.

Discussion of individual profiles

Profile-1 (*Figure 8*) crosses three principal tectonic lines: the Kapos line (at km 95), the Mecsekalja line (at km 160), and the Békési line (at km 220). The Transdanubian section (0–160 km) of this profile crosses several local basins as indicated by the depth oscillations (highs and lows) of the upper tier of vertical bars. Thus at km 80–90 the profile crosses the southeast–southwest elongated deep Nak trough, which is part of the Bükk–Igal zone (Figure 2). Between km 170 and km 200, the profile crosses the Kiskunhalas basin whose Mesozoic basement is cut by listric normal

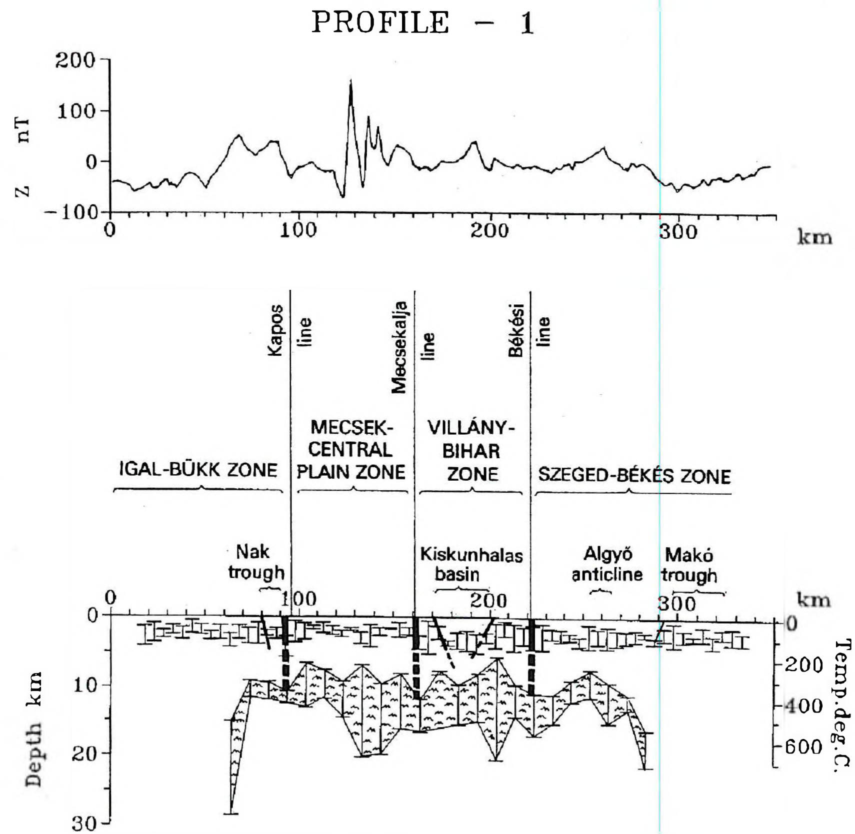


Fig. 8. Vertical magnetic anomaly Profile–1; the local names of the structural zones and the tectonic lines; the depth of shallow sources is indicated by vertical bars; and the depth of deep sources is indicated by vertical bars and zigzags. The positions of the principal tectonic lines and their downward continuations are indicated by heavy lines; the second- and third-order tectonic lines are marked with thin lines; the extrapolated temperature–depth scale is also shown.

8. ábra. Profile–1 vertikális mágneses szelvény. Az ábra feltünteti a szerkezeti zónákat és a tektonikai vonalakat, a sekélyebb helyzetű hatók meghatározott mélységét hibaintervallum, a mélyebb helyzetű hatók meghatározott mélységét hibaintervallum és hullámos vonalak jelölik. Vastag vonal jelöli az elsőrendű tektonikai vonalakat míg vékony vonal jelöli a másod és harmadrendű tektonikai vonalakat. Az ábra jobb oldalán az extrapolált hőmérséklet–mélység skála látható faults. The basin is filled with middle Miocene sediments that are overlain by late Miocene, Pannonian, and younger sediments [DANK 1988]. At km 260 the profile crosses the Algyő anticline and, at 290 km, the Makó trough.

Profile-2 (*Figure 9*) crosses five major tectonic lines, the Rába at km 60, the Balaton at km 140, the Kapos at km 180, the Mecsekalja at km 250, and the Békési at km 285. The profile shows the great depth to basement beneath the Little Hungarian Plain between km 2.5 and km 4.5. The profile located a pronounced high in the deeper section between km 80 and km 110. This high coincides with the central part of the Transdanubian Central Range. This deep horizon high does not correlate with the depth to the Mohorovičić discontinuity given by POSGAY et al. [1981]. The Transdanubian Central Range is a zone of complex structure whose origin is beyond the scope of the present paper; the Central Range is bounded by the Rába (at km 60) and Balaton (at km 140) tectonic lines. The low between km 240 and km 250 is the southwestern part of the Kiskunhalas basin. Southeast of km 310, the basement dips toward the Újszentiván–Gyula basin.

At the northwest end of Profile-3 (*Figure 10*) the magnetic sources outcrop as indicated by the high amplitudes of the vertical magnetic profile. The profile crosses four principal tectonic lines: the Balaton line at km 80, the Kapos line at km 110, the Mecsekalja line at km 180, and the Békési line at km 200. The position of the Paleogene basin is indicated between km 60 and km 80. The Örkény depression is present in the 110–130 km interval, and the Kiskun depression in the 145–180 km interval. At the southeastern end, the basement dips into the Makó basin.

Profile-4 (*Figure 11*) also crosses four main tectonic lines: the Darnó line at km 20, the Kapos line at km 75, the Mecsekalja line at km 115, and the Békési line at km 170. The Vatta–Maklár trough is in the 50–55 km interval. The eastern part of the Jászság basin is in the 85–120 km interval. The basement at the southern end of the profile dips into the Békés basin, which is part of the Szeged–Békés zone (Figure 2).

The upper crust beneath the Pannonian basin consists of pre-Alpine metamorphic and sedimentary rocks. It is very probable that where the vertical depth bars extend below a depth of 18–19 km, the Curie isotherm is

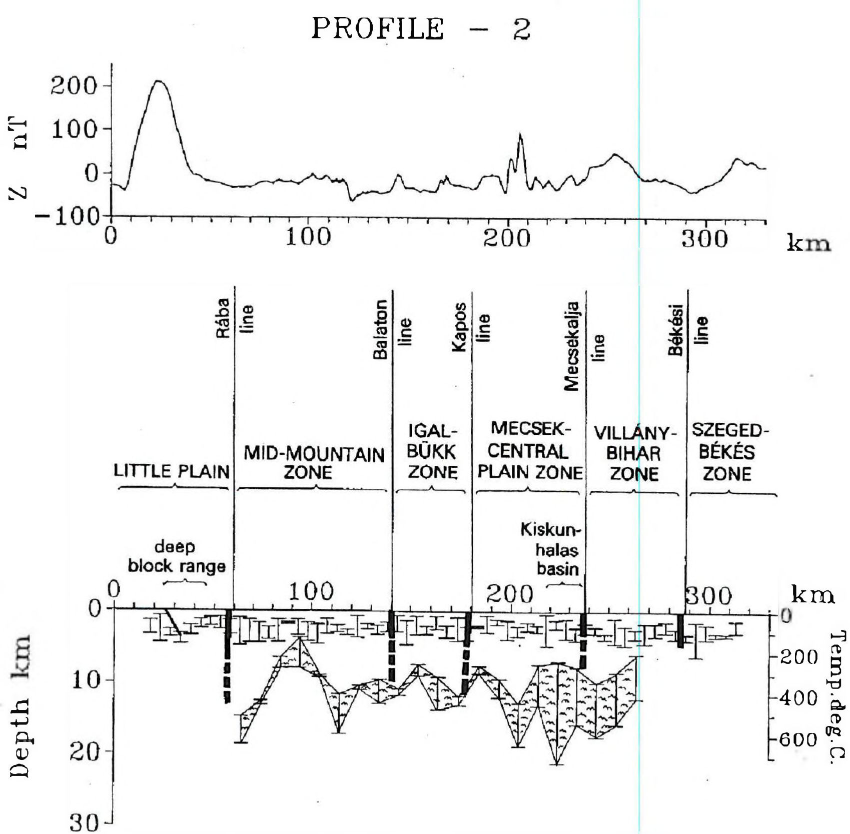


Fig. 9. Vertical magnetic anomaly Profile 2; the local names of the structural zones and the tectonic lines; the depth of shallow sources is indicated by vertical bars; and the depth of deep sources is indicated by vertical bars and zigzags. The positions of the principal tectonic lines and their downward continuations are indicated by heavy lines; the second- and third-order tectonic lines are marked with thin lines; the extrapolated temperature depth scale is also shown

9. ábra. Profile 2 vertikális mágneses szelvény, az ábra feltünteti a szerkezeti zónákat és a tektonikai vonalakat, a sekélyebb helyzetű hatók meghatározott mélységét hibaintervallum, a mélyebb helyzetű hatók meghatározott mélységét hibaintervallum és hullámos vonalak jelölik. Vastag vonal jelöli az elsőrendű tektonikai vonalakat míg vékony vonal jelöli a másod és harmadrendű tektonikai vonalakat. Az ábra jobb oldalán az extrapolált hőmérséklet mélység skála látható

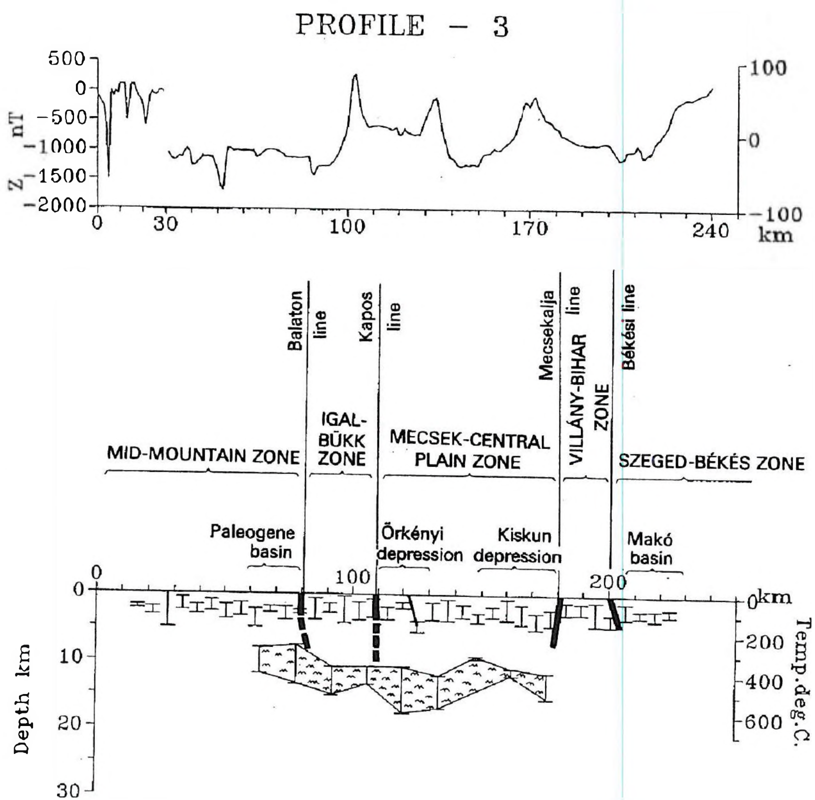


Fig. 10. Vertical magnetic anomaly Profile 3; the local names of the structural zones and the tectonic lines, the depth of shallow sources is indicated by vertical bars; and the depth of deep sources is indicated by vertical bars and zigzags. The positions of the principal tectonic lines and their downward continuations are indicated by heavy lines; the second- and third-order tectonic lines are marked with thin lines; the extrapolated temperature depth scale is also shown. The scale of vertical magnetic anomalies changes at 30 km (the scale for 0 30 km is given in the left, for 30 240 km on the right).

10. ábra. Profile 3 vertikális mágneses szelvény, az ábra feltünteti a szerkezeti zónákat és a tektonikai vonalakat. A sekélyebb helyzetű hatók meghatározott mélységét hibaintervallum, a mélyebb helyzetű hatók meghatározott mélységét hibaintervallum és hullámos vonalak jelölik. Vastag vonal jelöli az elsőrendű tektonikai vonalakat míg vékony vonal jelöli a másod és harmadrendű tektonikai vonalakat. Az ábra jobb oldalán az extrapolált hőmérséklet mélység skála látható. A mágneses anomáliát megadó skála változik 30 km értéknél (0 30 km intervallumra a bal oldali skála vonatkozik míg 30 240 km intervallumra a jobb oldali skála vonatkozik)

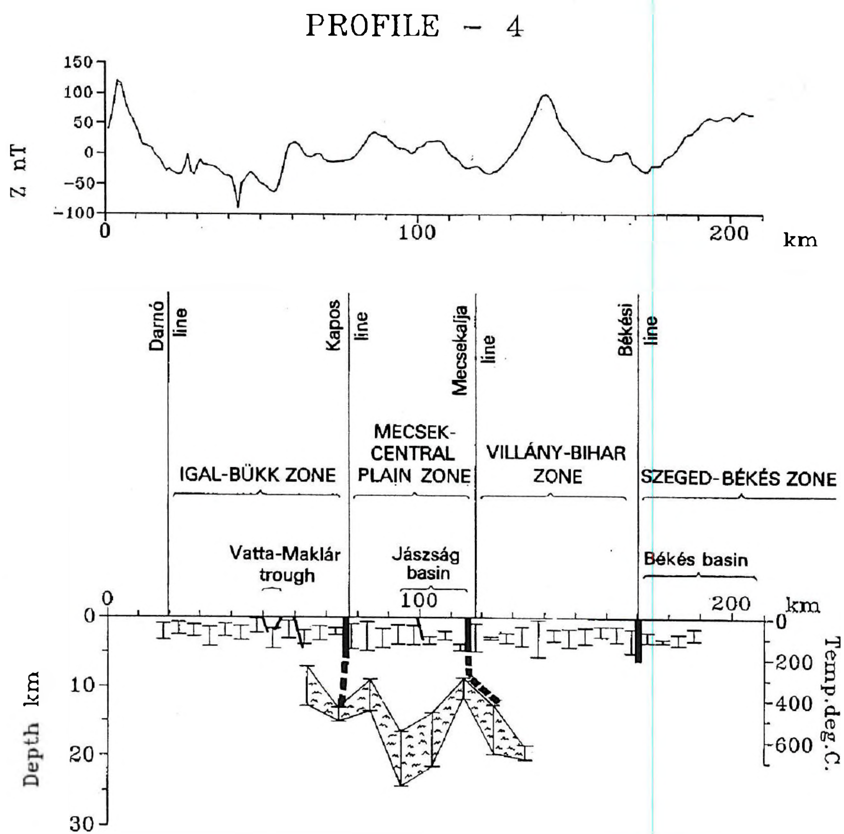


Fig. 11. Vertical magnetic anomaly Profile 4; the local names of the structural zones and the tectonic lines; the depth of shallow sources is indicated by vertical bars; the depth of deep sources is indicated by vertical bars and zigzags. The positions of the principal tectonic lines and their downward continuations are indicated by heavy lines; the second- and third-order tectonic lines are marked with thin lines; the extrapolated temperature depth scale is also shown

11. ábra. Profile 4 vertikális mágneses szelvény. Az ábra feltünteti a szerkezeti zónákat és a tektonikai vonalakat, a sekélyebb helyzetű hatók meghatározott mélységét hibaintervallum, a mélyebb helyzetű hatók meghatározott mélységét hibaintervallum és hullámos vonalak jelölik. Vastag vonal jelöli az elsőrendű tektonikai vonalakat míg vékony vonal jelöli a másod és harmadrendű tektonikai vonalakat. Az ábra jobb oldalán az extrapolált hőmérséklet mélység skála látható present. If, following OKUBO et al. [1985], the Curie temperature ranges from 500 to 600 °C, the geothermal gradient can be calculated. Between depths of 18–24 km, the calculated low and high geothermal gradients are respectively 20 °C/km and 35 °C/km. These estimates thus support the observation that the geothermal gradient of the Pannonian basin decreases with increasing depth.

4. Conclusions

In this study of magnetic profiles across the Hungarian Pannonian basin, three approximately northwest–southeast profiles, and one east–west profile of the vertical magnetic anomaly were digitized at equidistant 1 km intervals. Two magnetic anomaly sampling lengths — 31 and 127 km — were used in order to study not just the shallow magnetic sources already known from the region but possible deeper sources to the Curie point isotherm. This study located a shallow magnetic source layer between horizons at 2 km and 4 to 5 km depths and a deeper layer between horizons that are as shallow as 4 km and as deep as 24 km. The greatest depths are believed to be the Curie point. Offsets and/or abrupt changes at depths where the magnetic profiles cross Hungary's principal tectonic lines prove, for the first time by magnetic methods, that these tectonic lines penetrate the full thickness of the upper crust. It is envisaged that the future use of this method, utilizing two magnetic anomaly lengths, will be helpful in tectonic studies of Hungary and elsewhere.

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REFERENCES

AGOCS W. B. 1983: Gravity and magnetic anomaly for model E-W thrust zones and spectral energy depths. Unpublished manuscript

ÁDÁM A., LANDY K., NAGY Z. 1989: New evidences for distribution of the electric conductivity in the Earth's crust and upper mantle in the Pannonian basin as a 'hot spot'. Tectonophysics **164**, pp. 361–368

BALOGH K., KŐRÖSSY L. 1974: Hungarian Mid-Mountains and adjacent areas. *In* MACHEL M., *ed.*, Tectonics of the Carpathian Balkan region. Geological Institute of Dionyz Štúr, Bratislava, pp. 391–402

BÉRCZI I., KÓKAI J., DANK V., SOMFAI A. 1981: Some new results for petroleum geology obtained by hydrocarbon exploration wells drilled in the Hungarian part of the Pannonian basin. Earth Evolution Sciences **1–3**, pp. 301–306

BHATTACHARYYA B. K., LEU L.-K. 1975a: Spectral analysis of gravity and magnetic anomalies due to two-dimensional structures. Geophysics **40**, pp. 993–1013

BHATTACHARYYA B. K., LEU L.-K. 1975b: Analysis of magnetic anomalies over Yellowstone National Park; mapping of Curie point isothermal surface for geothermal reconnaissance. J. Geophys. Res. **80**, pp. 4461–4465

BHATTACHARYYA B. K., LEU L.-K. 1977: Spectral analysis of gravity and magnetic anomalies due to rectangular prismatic bodies. Geophysics **42**, pp. 41–50

BRIGHAM E. O. 1974: The fast Fourier transform. Prentice-Hall, Inc., New Jersey

BYERLY P. E., STOLT R. H. 1977: An attempt to define the Curie point isotherm in northern and central Arizona. Geophysics **42**, pp. 1394–1400

CURTIS C. E., JAIN S. 1975: Determination of volcanic thickness and underlying structures from aeromagnetic maps in the Silet area of Algeria. Geophysics **40**, pp. 79–90

DANK V. 1988: Petroleum geology of the Pannonian basin, Hungary; an overview. *In* ROYDEN L. H., F. HORVÁTH, (*eds.*): The Pannonian basin: a study in basin evolution. Am. Assn. Petr. Geol. Mem. **45**, pp. 319–331

DÖVÉNYI P., HORVÁTH F., LIEBE P., GÁLFI J., ERKI I. 1983: Geothermal conditions in Hungary. Geophysical Transactions 29, pp. 3–144

FÖLDVÁRY G. Z. 1988: Geology of the Carpathian region. World Scientific, Singapore.

HAÁZ I., KOMÁROMY I. 1967: Vertical magnetic anomaly map of Hungary (in Hungarian). Geofizikai Közlemények **16**, 4, enclosure

GREEN A. G. 1972: Magnetic profile analysis. Geophys. J. Roy. Astr. Soc. **30**, pp. 393–403

HAHN A., KIND E. G., MISHRA D. C. 1976: Depth estimation of magnetic sources by means of Fourier amplitude spectra. Geophys. Prosp. **24**, pp. 287–308

KIS K., MESKÓ A. 1978: Application of the logarithmic power spectrum in the interpretation of magnetic data. Proceedings II of XXIInd International Geophysical Symposium Prague, pp. 51–65

KÖRÖSSY L. 1964: Tectonics of the basin areas of Hungary. Acta Geol. Acad. Sci. Hung. **8**, pp. 377–394

NAGATA T., OZIMA M. 1967: Palaeomagnetism. *In* MATSUSHITA S., CAMPBELL W. H. *eds*., Physics of Geomagnetic Phenomena. Academic Press Inc. **1**, pp. 103–180

NAGYMAROSY A., MÜLLER P. 1988: Some aspects of Neogene biostratigraphy in the Pannonian basin. *In* ROYDEN L.H., F. HORVÁTH (*eds*.): The Pannonian basin: a study in basin evolution. Am. Assn. Petr. Geol. Mem. **45**, pp. 69–77

OKUBO Y., GRAF R. J., HANSEN R. O., OGAWA K., TSU H. 1985: Curie point depth of the island of Kynshu and surrounding areas, Japan. Geophysics **50**, pp. 481–494

OTNES R. K., ENOCHSON L. 1978: Digital Time Series Analysis. Vol I. John Wiley & Sons. Inc., New York, London, Sydney, Toronto

POSGAY K. 1962: Reconnaissance map of the magnetic bodies in Hungary and its interpretation (in Hungarian). Geofizikai Közlemények **11**, pp. 78–99

POSGAY K. 1967: A comprehensive survey of geomagnetic masses in Hungary (in Hungarian). Geofizikai Közlemények **16**, pp. 5–118

POSGAY K., ALBU I., PETROVICS I., RÁNER G. 1981: Character of the Earth's crust and upper mantle on the basis of the seismic reflection measurements in Hungary. Earth Evolution Sciences **3–4**, pp. 272–279

RUMPLER J., HORVÁTH F. 1988: Some representative seismic reflection lines from the Pannonian basin and their structural interpretation. *In* ROYDEN L.H., F. HORVÁTH (*eds*.): The Pannonian basin a study in basin evolution. Am. Assn. Petr. Geol. Mem. **45**, pp. 153–169

SHUEY R. T., SCHELLINGER D. K., TRIPP A. C., ALLEY L. B. 1977: Curie depth determination from aeromagnetic spectra. Geophys. J. Roy. Astr. Soc. **50**, pp. 75–101

SPECTOR A., GRANT F. S. 1970: Statistical models for interpreting aeromagnetic data. Geophysics **35**, pp. 293–302

TREITEL S., CLEMENT W. G., KAUL R.. 1971: The spectral determination of depth to buried magnetic rocks. Geophys. J. Roy. Astr. Soc. **24**, pp. 415–428

WEIN Gy. 1969: Tectonic review of the Neogene covered areas of Hungary. Acta Geol. Acad. Sci. Hung. **13**, pp. 399–436

Magyarországi mágneses hatók mélységének eloszlása négy vertikális mágneses szelvény mentén

KIS Károly, William B. AGOCS, Arthur A. MEYERHOFF

A Pannon-medencének Magyarország területére eső, négy, 1 km távolsággal mintavételezett, vertikális mágneses szelvénye, összesen 1124 km hosszúságban került feldolgozásra. A feldolgozás célja a mágneses hatók mélységének meghatározása spektrális analízissel. A számítások során 31 km-es illetve 127 km-es átfedő szelvényrészletek kerültek feldolgozásra. A mélységbecslés a rövidebb szelvényrészletek esetében 5 km-ként, míg a hosszabb szelvényrészletek esetében 10 km-ként történt. A meghatározott mélységek mind a négy szelvény esetében 2 km és 4–5 km körüli mélységeket mutattak, míg a hosszabb szelvényrészletekből meghatározott mélységek 6–16 km-es intervallumban jelentkeztek. A hatók alsó mélysége néhány helyen eléri a 25 km-t. Ez valószínűleg a Curie izoterma mélysége.

A tektonikai vonalak, általában mély vetőzónák, nagyobb mélységbe (a felső kéregbe) történő folytatása a jelen módszerrel kimutatható. A spektrális módszerrel meghatározott mélységek összehasonlíthatók a más tanulmányokban megjelent eredményekkel. Ez az összehasonlítás támasztja alá a nagyobb mélységekre vonatkozó meghatározások hatékonyságát.

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Károly I. Kis received his M. Sc.(1969) and Ph. D. (1972) in geophysics from the Eötvös Loránd University. In 1969 he joined the Geophysics Department of his Alma Mater. Since 1974 he has been a member of the Geophysical Research Group of the Hungarian Academy of Sciences. He became a Senior Research Associate in 1984; in 1985 he was awarded the title Honorary Associate Professor of Geophysics. His main interests are in the processing and interpretation of gravity and magnetic anomalies.

William B. Agocs received his B. Sc. (mining, with subsidiary geophysics) in 1934, and his M. Sc. and Ph. D. in 1946—all from Lehigh University. He is a registered professional engineer in petroleum gas and mining engineering; he is also a licensed blaster. In 1935 he joined a research and development company, and directed and interpreted reflection seismic, gravity and magnetic surveys in Venezuela. The years 1946 to 1950 saw him organizing an exploration development programme. He became Head of the Geophysical Department at Oklahoma University from 1950 to 1955. In many parts of the world he directed field operations and interpretation of magnetic data, and at one time he headed an airborne geophysics department. He was a United Nations consultant on mineral exploration surveys carried out in Bolivia, Mexico, the Ivory Coast, and Saudi Arabia. Dr. Agocs was Chairman of the Department of Physical Sciences at Kutztown State College from 1964 to 1978; in addition to holding advanced courses in physics and geophysics, he set up the Astronomy, Geology, and Chemistry departments, and the Seismic Station. He has authored numerous scientific papers on various aspects of geophysics and computer computation. He is a member of SEG, EAEG, AIP, IEEE, and of GSA.

Arthur A. Meyerhoff, photograph and biography not available at the time of publication.

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Tectonic aspects of a palaeomagnetic study on the Neogene of the Mecsek Mountains

Emő MÁRTON* and Péter MÁRTON**

Despite the general lack of unweathered Neogene outcrops in the Mecsek Mts., renewed efforts enabled palaeomagnetic sampling to be carried out at 29 localities of which 15 gave, after laboratory treatment, useful palaeomagnetic directions for the Ottnangian through Upper Pannonian.

Our results fall into four groups: (i) this group comprises the ignimbrites aligned with the northern margin of the Neogene sedimentary trough which exhibit counterclockwise rotated declinations averaging 60°; (ii) the younger sediments of the same trough with no rotation; (iii) Tertiary localities from the main Palaeozoic–Mesozoic body of the Mecsek Mts, where the Cretaceous alkali basalts and related rocks are characterized by declinations rotated to the east, exhibit similar easterly declinations; (iv) the declination of two Upper Pannonian localities from the surroundings of the Mecsek Mts. do not deviate significantly from the present north.

These results together with those from the Apuseni Mts. and the South Carpathians on one hand, and from the Slavonian Mts. on the other — all parts of the Tisza megatectonic unit — strongly suggest that this megatectonic unit was not yet a rigid body during the Tertiary as some tectonic models suggest.

Keywords: palaeomagnetism, tectonics, Mecsek, Hungary

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1. Introduction

In the Pannonian Basin the most important tectonic belt is the Mid-Hungarian zone, which separates the North Pannonian and the South Pannonian (or Tisza) megatectonic units. Different sets of data, palaeomagnetic ones among them [e.g. MÁRTON and MÁRTON 1978; MÁRTON 1986; MÁRTON 1990], suggest that these megatectonic units must have been situated far from each other in the Mesozoic, and their present arrangement was brought about as late as the Upper Miocene.

The North Pannonian unit is characterized by counterclockwise (CCW) rotations, and the angle of rotation varies both in space and time [e.g. MÁRTON and MÁRTON 1983, 1995; MÁRTON et al. 1996]. From the western part of the Tisza unit the Carboniferous through Hauterivian palaeomagnetic results are characterized by declinations which cluster around the present north, while the younger Cretaceous ones, which are derived from dykes and small intrusions related to the alkali basalt volcanism, are characterized by large clockwise (CW) rotations. From these observations one can infer that the area, essentially the Mecsek Mts., underwent first a CCW rotation (after the Hauterivian) and a second, CW rotation after the Cretaceous. Cretaceous igneous rocks from the Apuseni Mts. and the Southern Carpathians [PĂTRAŞCU et al. 1990, 1992] also exhibit large CW rotation.

We started a palaeomagnetic study on the Tertiary of the Mecsek Mts. (*Fig. 1*) with the aim of constraining the timing of the post-Cretaceous CW rotation. It has turned out, however, that the area is more complex than was previously thought and the palaeomagnetic results we present in this paper call for a redefinition of the Tisza megatectonic unit.

2. Tertiary geology of the Mecsek Mts.

According to HÁMOR [1970] the Mesozoic sedimentation cycle in the Mecsek Mountains was followed by uplift and erosion during the Palaeogene which resulted in peneplainization of the area. The beginning of the Neogene sedimentation was related to the relatively large height differ-

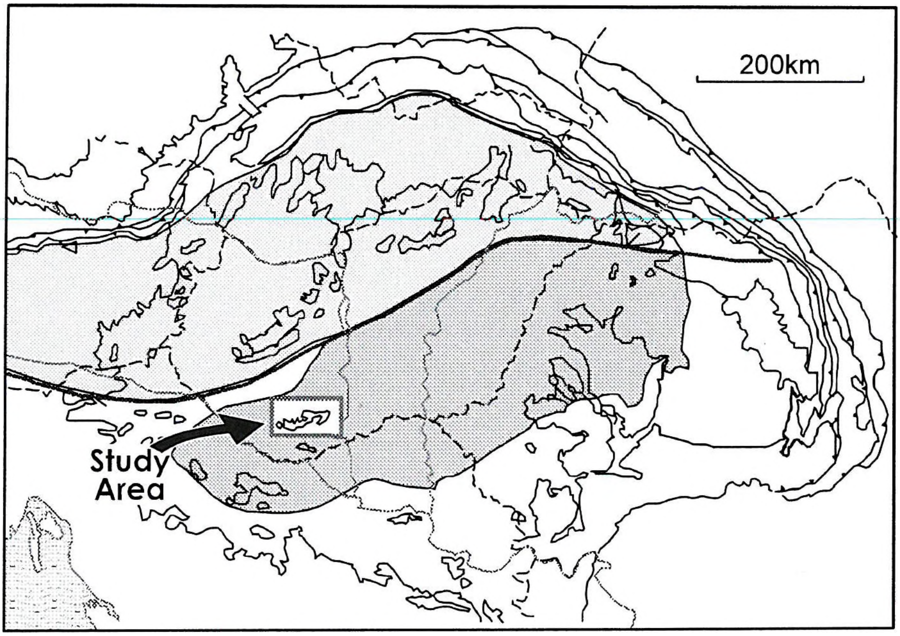


Fig. 1. Study area in relation to the North Pannonian (*light grey*) and South Pannonian (*dark grey*) megatectonic units

1. ábra. A vizsgált terület elhelyezkedése az Észak-Pannon (világos szürke) és a Dél-Pannon (sötét szürke) nagytektonikai egységekhez képest

ences which had been brought about by the Savian orogene. The area south of the Mecsekalja line was uplifted and became the provenance area for sediment accumulation in a slowly subsiding basin, north of the intervening flat mountain range along the Jakabhegy–Misina–Zengő strip.

The stratigraphical developments of the Neogene of the eastern and western Mecsek Mts. are somewhat different. Nevertheless, their distant and rather variable complexes are correlatable with each other [HÁMOR, JÁMBOR 1964; CHIKÁN 1991]. Thus, the following description of the Neogene stratigraphy is based on data from the eastern Mecsek Mts., where three sedimentation cycles can be distinguished in the Miocene.

The first cycle, which is wholly terrestric, started with the deposition of a fluviatile complex with pebbly and sandy beds, often with rhyolite tuff occurrences ('Lower Rhyolite Tuff' with K/Ar ages of 19.6 ±1.5 Ma.) and was followed by a variegated clay complex which resulted from less intensive sedimentation in a variable dryland environment (*Terrestric complex*). The closing member of the first cycle is the *Limnic complex* with grey clay, brown coal and sand layers. The limnic complex contains an andesite intrusion at Komló with a K/Ar age of 19.0–19.5 Ma.

During the next cycle, introduced by the old-Styrian orogene, the sedimentation becomes gradually more and more marine. Transgression first affects the deeper parts, where sandstones and limestones with Congeria are formed (*Congerian complex*). Fluviatile transport is still intensive in the west but is of only local significance in the east. Elsewhere, lacustrine and brackish water claymarl with fishscales and sand are deposited. Dacitic tuff occurs all over the area ('Middle Rhyolitic Tuff' with K/Ar ages of 16.4 ± 0.8 Ma.) of which the material is traceable both in the claymarl and the schlier complex. The latter is an open marine, always shallow water sedimentary complex, contemporaneous with the maximum of the Miocene transgression. The most characteristic sediment of the schlier is clay–claymarl with micaceous sand and fine sand (schlier), and sandstone, pebble and conglomerate in the nearshore environment (*Schlier complex*). The end of the second cycle is marked by uplift with no sedimentation in most areas, while fluviatile pebble, sand, brown coal, clay, etc. are deposited in the remaining basins (*Regression complex*).

The third sedimentary cycle is associated with subsidence followed by vertical oscillations due to the young-Styrian movements. The first beds (*Leitha complex*) were deposited transgressively with an abrasion unconformity onto the different, older Miocene members. The Leitha limestone complex reflects a nearshore environment with abrasion conglomerate and breccia, lithotamnic limestone, calcareous sandstone, etc. From the complexes that follow the Leitha complex the *Brown coal complex* is related to uplift and the *Turritellan-corbulan claymarl complex* to renewed subsidence affecting the NE, S and NW foreground of the Mecsek. The end member of the cycle is the *Sarmatian complex* with predominantly shallow marine deposits, with frequent transitions towards freshwater sedimentation. Characteristic is the coarse Miliolidean limestone, but there are pebbly layers as well, and Molluscan claymarl in the basins. Traces of altered rhyolite tuff ('Upper Rhyolite Tuff', 13.7± 0.8 Ma.) occur both in the eastern and western Mecsek Mts.

The general regression during the Sarmatian continued into the Lower Pannonian. There are several occurrences of pebbles, conglomerates and calcareous sandstones deposited under shallow water, paralic conditions (nearshore facies), and calcareous claymarl, marl, calcareous marl (basinal facies). In the Upper Pannonian (Pontian) — as a result of the Rhodanian movements — the Mecsek Mts. and its surrounding area, apart from the highest parts of the mountains, was again inundated. On the slopes extensive abrasion took place and gigantic boulders, stone blocks, pebbles and coarse sandstone were deposited along the shore. The open water areas are characterized by silt and silty claymarl.

The present morphology of the Mecsek Mts. and their environs was brought about by the Rhodanian movements which caused local folds in the pre-Pontian Miocene formations as well as imbrications (Palaeozoic and Mesozoic formations were thrust over Pannonian formations in the southern Mecsek Mts.).

3. Palaeomagnetic sampling

Sampling for palaeomagnetic measurements in the Mecsek Mts. is difficult owing to the scarcity of good outcrops; this situation is especially true for soft rocks such as those constituting the majority of the suitable Neogene sites. Artifical outcrops which were made in the sixties for mapping purposes are no longer accessible due to intensive weathering and thick vegetation cover. Despite this situation, we were able to sample several outcrops that seemed promising for palaeomagnetic studies thanks to L. Benkovics, who recently carried out a microtectonic survey of the area, to Z. Máté and Gy. Konrád who guided us several times to outcrops that were not easily accessible, and to G. Hámor for showing us some of the still existing key outcrops of the sixties.

The palaeomagnetic sampling localities in relation to the stratigraphical description above are listed as follows.

Terrestric complex:

1. Árpádtető, red and grey coloured sandy clay, Eggenburgian–Ottnangian
2. Máza–Vörösvölgy, siltstone, Eggenburgian–Ottnangian

Lower rhyolite tuff, Ottnangian:
3. Balinca graben, I. and II., ignimbrite
4. Horváthertelend, ignimbrite
5. Nyárádi vadászház, ignimbrite
6. Máza–Vörösvölgy, ignimbrite
7. Mázaszászvár, ignimbrite

Andesite, Ottnangian:
8. Komló, multiple sampling

Schlier complex:
9. Feked, basal clastic sediment, Karpathian
10. Komló, schlier, Karpathian
11. Budafa, silt, Karpathian
12. Magyaregregy, fishscale marl, Karpathian
13. Mecsekjánosi, schlier, lower Badenian
14. 'Orfű', schlier, lower Badenian
15. Nagymátépuszta, grey and yellowish clay, lower Badenian
16. Husztót, tuffaceous schlier, lower Badenian
17. Pécsvárad, limestone, lower Leitha limestone, lower Badenian

Middle rhyolite tuff, lowermost Badenian:
18. Komló–Kökönyös, sandy tuffite
19. Erdősmecske, tuffite
20. Pécs–Vasas, tuff
21. Hetvehely, tuff
22. Kisbeszterce, tuff (ignimbrite?)

Sarmatian complex:
23. Hermann Ottó lake, porous white limestone

Lower Pannonian:
24. Danitzpuszta, white marl
25. Geresdlak, marl
26. Kishajmás, ceramic clay

Upper Pannonian:
27. Bátaszék, dark grey claymarl
28. Kakasd, claymarl
29. Boda–Füzi erdő, white and grey clay.

1, 4, 11, 13, 14, 15, 16, 21, 22, 23, 26, 29 are from the western Mecsek Mts., mainly north of the Mesozoic sequence. 2, 3, 5, 6, 7, 8, 10, 12, 17, 18, 20, 24, 25 are from the eastern Mecsek Mts. 9 and 19 are outcrops in the Mórágy area, and 27 and 28 are in the surroundings of the Mecsek Mts.

The palaeomagnetic samples were collected by using a portable hand-held drill. The samples were oriented in situ with a magnetic compass; the igneous rocks were also oriented with a sun compass. The total number of samples collected from the Neogene is 337. In addition, one site (9 samples) was drilled at Szentkút near Pécs for samples from a Cretaceous dyke. This latter provided a palaeomagnetic site mean direction of D=78° I=51° (with rather poor statistics K=15, α_{95}=21°) similar to the palaeomagnetic directions observed earlier for the alkali basalts and related rocks in the Mecsek Mts. (cf. Introduction).

4. Laboratory processing and results

The samples, cut into standard size specimens, were subjected to laboratory analysis in the palaeomagnetic laboratory of the Eötvös Loránd Geophysical Institute of Hungary and in the Geophysics Department of Eötvös Loránd University in the following way. Both remanent magnetization and the susceptibility of each specimen were measured in the initial state. Demagnetization of selected specimens from each igneous site or sedimentary locality took place in several steps either by alternating field (AF) or thermally, or by combination of the two methods. Often, one sister specimen was demagnetized using AF, the other by using the thermal method. Then, based on the behaviour of the pilot samples, the remaining samples of each group were also demagnetized stepwise in several incremental steps until the magnetic signal was practically lost or became unstable. After each step of heating the susceptibility was remeasured to monitor possible mineralogical changes. In most cases, the magnetic fabric of the rocks was also studied by measuring the low-field magnetic susceptibility anisotropy.

Identification of the carriers of the magnetic signal, i.e. the magnetic minerals, took place either by measuring Curie temperatures or by the behaviour of their saturation remanence, i.e. IRM acquisition plus stepwise thermal demagnetization of their three-component IRM [LOWRIE 1990]. In the latter case the IRM was successively imposed along the X, Y, and Z axes of the sample: first in a field of 1.0T (Z), then in a field of 0.36T (Y), and finally in a field of 0.2T (X). This method allows one to study the components of different hardness often residing in the different magnetic minerals.

The results of the stepwise demagnetization were subjected to component analysis [KENT et al. 1983] whereby the components of the magnetization were separated and palaeomagnetic mean directions were calculated from the appropriate (stable) components (*Tables I* and *II*).

As expected, the different rock types responded to laboratory processing in widely different ways. Several sedimentary localities failed to yield any meaningful palaeomagnetic signal, mainly owing to the unstable behaviour of the remanence on demagnetization. Those with well-defined remanence are again quite diverse: some are very weakly magnetic and the signal is only moderately stable though the remanence is carried by magnetite (*Fig. 2*: Danitzpuszta (24)). These localities are marked with b in Table II. The carrier of the remanence at Mecsekjánosi (13) and Orfű (14) is also magnetite, but the remanence is stable up to 500°C or AF 0.5 mT

Table I. Palaeomagnetic results for the igneous sites from the Mecsek Mts.
Explanation of symbols: Left column: identifying numbers (cf. text). n/n_0: useful collected number of samples. D and I: palaeomagnetic declination ($D°$) and inclination ($I°$) before tilt correction. k and $\alpha°_{95}$: statistical parameters after FISHER [1953]. k: precision, $\alpha°_{95}$: semi-angle of cone of confidence at the 95% confidence level. $D°_c$, $I°_c$: palaeomagnetic declination ($D°_c$) and inclination ($I°_c$) after tilt correction. *Dip*: bedding attitude, azimuth/magnitude of dip of bedding plane. *Remark*: a: result obtained by linearity analysis, b: result obtained from stable end points. Three results are shown for the Komló andesite (8). The first is from MÁRTON and MÁRTON [1969], the second is from MÁRTON [1986] and the third is from the present study. The last row shows an earlier result for an ignimbrite body from the Mid-Hungarian Zone [MÁRTON and MÁRTON 1989]. ⇨

I. táblázat. A mecseki magmás kőzetek paleomágneses irányai.
Jelmagyarázat: bal oldali oszlop: azonosító számok (lásd szöveg), n/n_0: hasznos/gyűjtött minták száma, $D°$és $I°$: paeleomágneses deklináció és inklináció dőléskorrekció előtt; k és $\alpha°$: FISHER-féle [1953] statisztikai paraméterek; k: pontosság, $\alpha°_{95}$: a 95%-os megbizhatósági szintű konfidencia szög fele; $D°_c$, $I°_c$: paleomágneses deklináció és inklináció a dőléskorrekció után; *dip*: a tektonikai dőlés azimutja/a dőlés nagysága; *Remark*: a: linearitás analízissel kapott eredmény, b: stabil végpontokból kapott eredmény

	locality	n/no	$D°$	$I°$	k	$\alpha°_{95}$	$D°_C$	$I°_C$	k	$\alpha°_{95}$	dip	Remark
	Mecsek Mts. igneous rocks											
	Komló andesite* 1	10	82	+62	112	4						a
	Komló andesite* 2	5	71	+64	179	6						a
	Komló andesite* 3 7702 713	12/12	56	+59	164	3						a
8	Komló andesite mean	3	69	+62	143	10						
22	Kisbesztece ign. 7299 314	11/16	7	67	67	6	105	52	67	6	315/49	a
4	Horváthertelend ign. 7663 679	16/17	124	53	33	7	84	33	33	7	(220/40)	a
6	Vörösvölgy ign.	8/10	139	33	15	15	99	80	15	15	146/50	a
3	Balinca ign. 7417 425	9/9	67	61	491	2	111	59	491	2	351/26	a
7	Máza-Szászvár ign 6372 381	10/10	118	57	35	8	118	57	35	8	horizontal	a
	Mecsek ignimbrites overall mean	5	108	62	8	28	113	60	45	12		
	Mid-Hungarian Zone											
	Sárszentmiklós ignimbrite*	12/	315	+55	47	7						

	locality	n/n_0	$D°$	$I°$	k	$\alpha°_{95}$	$D°_c$	$I°_c$	k	$\alpha°$	dip	Remark
9	Feked 7973 983	6/11	59	+55	22	17	62	+6	22	17	220/6	b
13	Mecsekjánosi 7602 611	5/10	191	+11	23	16	5	+79	23	11	10/89	a
12	Magyaregregy 7591-601, 7880 891	15/23	59	+74	120	3	355	+47	120	3	330/40	a
14	Orfű 7345 362	16/18	36	+58	43	6	19	+57	43	6	304/11	a
18	Komló-Kökönyös 7330 41	7/12	357	+53	126	5	350	+54	126	5	252/5	b
16	Husztót 7426 37	7/12	355	+63	25	12	4	+68	36	7	82/5 168/14	a
24	Danitzpuszta 7573 590	9/18	90	+60	19	12	118	+25	60	19	145/35	b
27	Bátaszék 7950 972	10/11	187	61	136	4	201	60	136	4	100/8	a
28	Kakasd 7892 901	5/10	193	41	75	9	201	46	75	9	135/10	a
	13, 12, 14, 18, 16 overall mean	5/5	24	+79	3	50	1	+61	34	13		

Table II. Palaeomagnetic results for sedimentary localities from the Mecsek Mts. *Explanation of symbols:* as for Table I.
II. táblázat. A mecseki üledékes kőzetek paleomágneses irányai. *Jelmagyarázat:* l. I táblázat alatt.

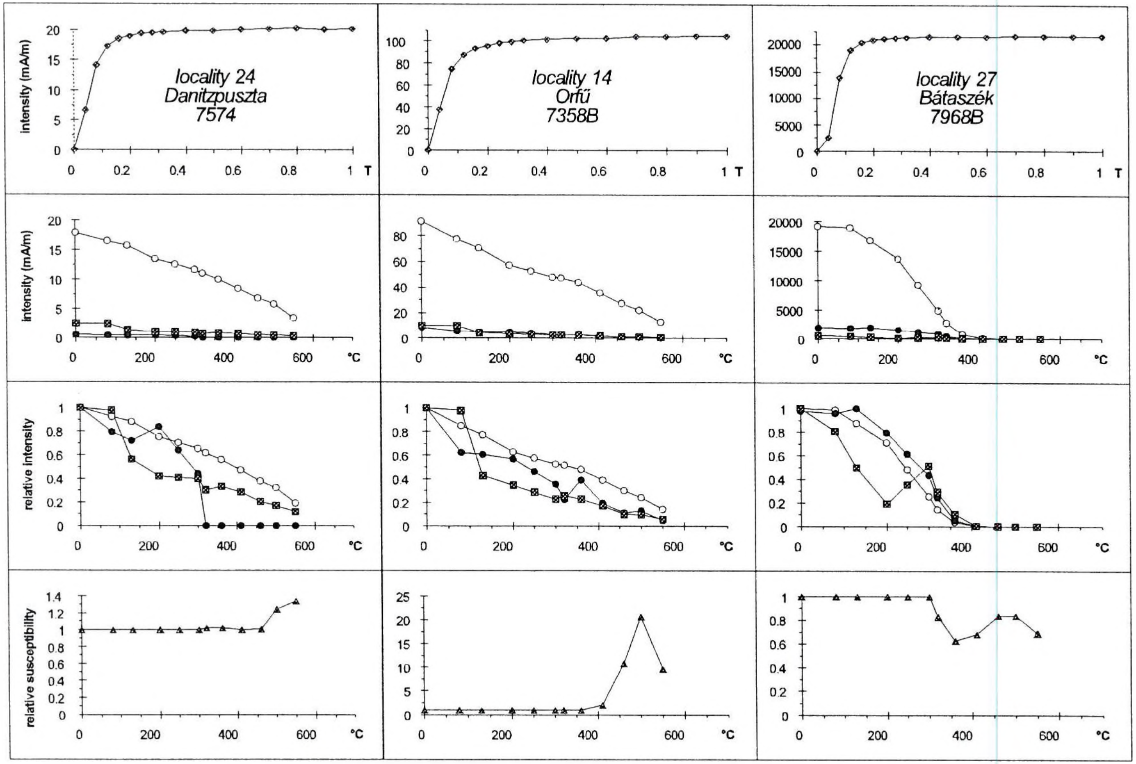


Fig. 2. Identification of magnetic minerals

From top to bottom: IRM acquisition curve, decay of the soft (*circles*), medium (*dots*) and hard (*squares*) components versus temperature; same normalized to the initial values; susceptibility versus temperature curve

2. ábra. Mágneses ásványok azonosítása

Felülről lefelé: IRM görbe, a lágy (*körök*), közepes (*pontok*) és kemény (*négyzetek*) komponensek a hőmérséklet függvényében; ugyanez a kezdeti értékekre normálva; szuszceptibilitás a hőmérséklet függvényében

(*Figs.* 2. and 3). Yet another type is characterized by the presence of magnetic iron sulphide which seems to be the only carrier of the magnetic signal (Fig. 2: Bátaszék (27), Fig. 3: Magyaregregy (12)).

The igneous rocks of the Lower Rhyolite Tuff horizon (except for one subsite, Nyárádi Vadászház (6)) gave excellent palaeomagnetic results.

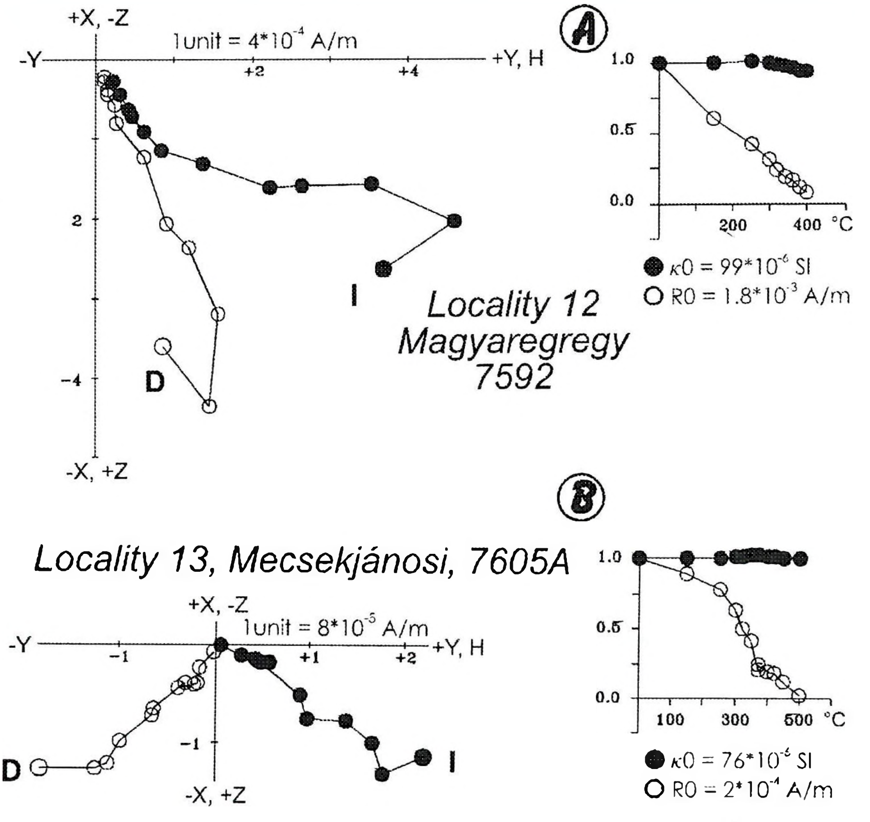


Fig. 3. Typical demagnetization curves
A: M 7592: Magyaregregy, Karpathian fishscale marl (12), *B*: M 7605: Mecsekjánosi, Karpathian schlier (13). *Left side*: modified Zijderveld diagrams, *Right side*: susceptibility (*dots*) and NRM intensity (*circles*) versus temperature

3. ábra. Tipikus lemágnesezési görbék
A: M 7592: Magyaregregy, Kárpáti halpikkelyes márga (12), *B*: M 7605: Mecsekjánosi, Kárpáti slír (13). *Bal oldal*: módosított Zijderveld diagrammok, *Jobb oldal*: szuszceptibilitás (*pontok*) és NRM intenzitás (*körök*) a hőmérséklet függvényében

The carrier of the remanence is magnetite. The dominant magnetic mineral in the Komló andesite (8) is hematite, probably accompanied by a minor amount of magnetite (*Fig. 4*).

The 'primary' magnetic signal for all the above sites is well-defined on thermal or on combined AF and thermal demagnetization. Complete un-

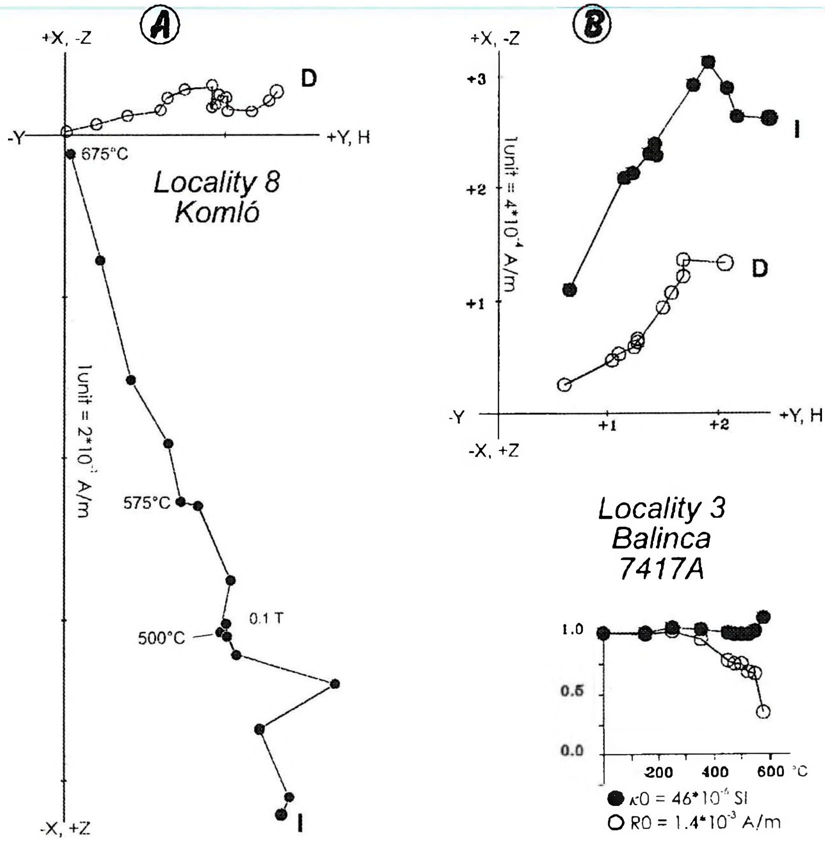


Fig. 4. Typical demagnetization curves: Komló, andesite (8) and Balinca, ignimbrite (3).
A: Modified Zijderveld diagram, combined AF and thermal demagnetization,
B: Upper-right: Modified Zijderveld diagram, thermal demagnetization.
Lower-right: susceptibility (*dotes*) and NRM intensity (*circles*) versus temperature

4. ábra. Tipikus lemágnesezési görbék: komlói andezit (8) és balinkai ignimbrit (3)
A: módosított Zijderveld diagramm, kombinált AF és termál lemágnesezés,
B: jobbra fent: módosított Zijderveld diagramm, termál lemágnesezés. *Jobbra lent* : szuszceptibilitás (*pontok*) és NRM intenzitás (*körök*) a hőmérséklet függvényében

blocking of the remanence occurs at the Curie temperature of the carrier minerals (Fig. 4: Balinca (3)).

The palaeomagnetic directions in Tables I and II are shown before and after tilt correction with the exception of the Komló andesite (8), where tectonic tilting is not estimable (see below). Elsewhere, the bedding attitude, i.e. the azimuth and tilt angles, was either measured directly (sediments) or estimated by the tilt of the nearby sediments. In the latter case, the directions of the magnetic fabric of the rocks were also computed before and after tilt correction in order to decide whether or not the igneous body was tilted with the sediments.

The magnetic fabric of rocks reflects the degree of orientation of the magnetic domains. At some sites and localities in the Mecsek Mts. the fabric is weakly oriented (*Fig. 5*: Kisbeszterce (22)). More often, however, the fabric is foliated, i.e. the minima cluster and their values are significantly lower than those of the maximum and intermediate susceptibilities (Fig. 5: Balinca (3), Bátaszék (27)). Such fabric is due to compaction, and the minima are assumed to be perpendicular to the bedding or foliation. This is the characteristic fabric for the Tertiary sediments of the Mecsek Mts. When the fabric is viewed before and after tilt correction, the most striking difference is that the minima are off-centred before tilt correction and become vertical (or close to it) in the tectonic system. However, there are magnetic fabrics that are of post-tilting age, i.e. the minima are vertical before and move away from the centre on tilt correction. This is the situation at Horváthertelend (4) and that is why the palaeomagnetic direction is considered here before tilt correction for tectonic interpretation.

The magnetic properties of the Kisbeszterce site (22) (*Fig. 6*), which is thought to belong to the Middle Rhyolite Tuff horizon, are similar to those of the Lower Rhyolite Tuffs. The others that are also classified as Middle Rhyolites (19, 20, 21) are completely different: they are probably not sufficiently welded or consolidated for none of them yielded any palaeomagnetic result. In view of this, Kisbeszterce (22) will hereinafter be treated as a Lower Rhyolite Tuff occurrence.

The magnetic fabric of the Komló andesite (8) (Fig. 6) is of more than a little interest. Here the fabric is very strong for an igneous rock and it is unrelated to a compaction-type texture but could be the consequence of

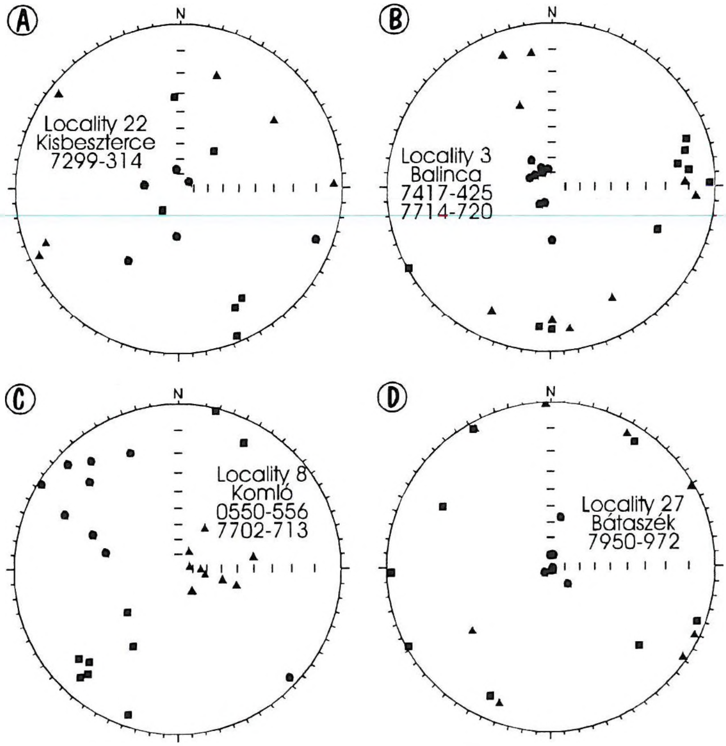


Fig. 5. Typical magnetic fabrics from the Neogene of the Mecsek Mts. Stereographic projections

Key: dots — minimum susceptibilities; *triangles* — intermediate susceptibilities; *squares* — maximum susceptibilities. Ignimbrites (*A*: Kisbeszterce (22) : 7299–7314; *B*: Balinca (3): 7414–7425, and 7714–7720); Andesite (*C*: Komló (8): YM 550–7556, and 7702–7713), and Marl (*D*: Bátaszék (27): 7950–7972).

The degree of anisotropy is low for the ignimbrites. On average, it is 1.3% for Kisbeszterce (22) and 3.9% for Balinca (3). The minima tend to cluster about the vertical, lineation is poorly developed in the first, and better developed (0.2–1.2%) in the second case. The degree of anisotropy on average is 10.4% for the Komló andesite (8) and the fabric is dominantly foliated (degree of foliation is 7.0 %). For Bátaszék (27) the degree of anisotropy is 2.5%, and the fabric is foliated

5. ábra. Tipikus mágneses szövetek a Mecsek hegység neogén rétegeiből. Sztereografikus vetületek

Jelmagyarázat: pontok — minimum szuszceptibilitások; *háromszögek* — közepes szuszceptibilitások; *négyzetek* — maximum szuszceptibilitások

Ignimbritek (*A*: Kisbeszterce (22): 7299–77314; *B*: Balinca (3): 7414–7425 és 7714–7720); andeszit (*C*: Komló (8): YM 550–7556 és 7702–7713) és márga (*D*: Bátaszék (27): 7950–7972)

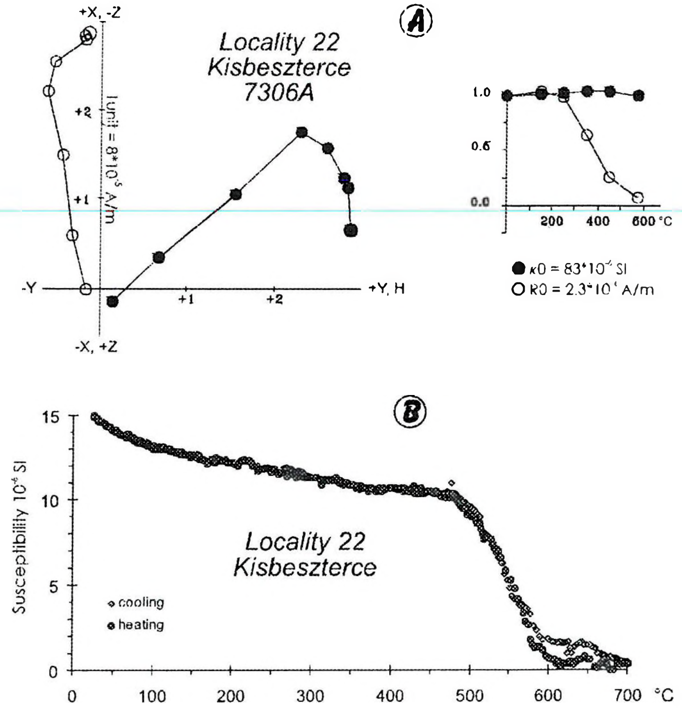


Fig. 6. Kisbeszterce (22) 7306A. *A*: Typical demagnetization curves
Left side: Modified Zijderveld diagram. *Right side*: NRM intensity (*circles*) and susceptibility (*dots*) versus temperature. *B*: lowfield susceptibility versus temperature curves

6. ábra. Kisbeszterce (22) 7306A. *A*: tipikus lemágnesezési görbék
Bal oldal: módosított Zijderveld diagram. *Jobb oldal*: NRM intenzitás (*körök*) és szuszceptibilitás (*pontok*) a hőmérséklet függvényében. *B*: kezdeti szuszceptibilitás a hőmérséklet függvényében

strain during the cooling of the Komló laccolith and not related to the slow setting of the magnetic minerals due to gravity, since it is the intermediate susceptibility directions which are nearly vertical and not the minima. It is very likely that this igneous body is unaffected by tectonic tilt.

5. Discussion and conclusions

The igneous sites that border the Neogene sedimentary basin in the north exhibit large counterclockwise rotated declinations after tilt correction *(Fig. 7)* with definitely improving statistical parameters for the overall mean palaeomagnetic direction in the tectonic system ($D_c = 108°$, $I_c = -57°$, and $k = 19$, $\alpha_{95} = 18°$) compared with those in the geographic system ($D_c = 108°$, $I_c = -62°$, and $k = 8$, $\alpha_{95} = 28°$). However, the tilt correction at Horváthertelend (4), derived from the sediments not far from the ignimbrite that was sampled, does not bring the minima of the susceptibility to the vertical, i.e. the tilt correction is not applicable. If we recalculate the overall mean from the tilt corrected mean directions for sites 22, 6, 3 and 7, on one hand, and from the mean in the geographic system for site 4 on the other, the statistical parameters further improve (Table I). We suggest that this overall mean palaeomagnetic direction be used as one characterizing the rotation of the area covered by our ignimbrite sites. In fact, this is a narrow belt bordering the Neogene trough in the north. However, we found a remarkably similar palaeomagnetic direction for the Sárszentmiklós rhyolite which is located in the mid-Hungarian Zone (Table I). The radiometric age of this rhyolite, originally given as 17 Ma or younger [HÁMOR et al. 1987], is in fact a rejuvenated age [PÉCSKAY, pers. com.], so this volcanic body can be placed among the Lower Rhyolites.

The Komló andesite (8) is of more or less the same age as the Lower Tuff Horizon, yet the declination here on average is 60° (while the inclination matches that of the ignimbrites). Similar clockwise rotated declinations were observed at Feked (9) and Danitzpuszta (24). Localities 8, 9 and 24 are situated in an area which is the source area for the CW rotated Cretaceous alkali basalts and related rocks (*Fig. 8*).

This area, in fact, comprises the western and the eastern Mecsek and the Mórágy Granite massif. Thus, in a way, 8, 9 and 24 date the CW rotation of the main Palaeozoic and Mesozoic complexes of the Mecsek Mts.

The Karpathian–Badenian sediments from the Neogene trough (Table II: 12, 13, 14, 16, 18) exhibit large scatter before, and reasonably good grouping after tilt corrections. The overall mean declination direction is close to the present north (Fig. 7).

The declinations of two of the three Upper Pannonian localities (27 and 28) are exactly the same (21°, if we convert both directions in Table II to normal polarity) with inclinations which are a bit shallow for locality 28, so the 21° declination may not signify rotation. On the other hand, the tendency for CW rotation may be noted (Fig. 8).

The lack of rotation in the Karpathian–Badenian sediments in the Neogene trough as opposed to the large CCW rotation of the ignimbrites at the northern margin of the same trough (Fig. 7) sets a limit to the time of the rotation north of the main Palaeozoic–Mesozoic body of the Mecsek: the rotation must have occurred some time close to the Ottnangian–Karpathian boundary. Though the outcrops of the ignimbrites are aligned with the northern margin of the Neogene trough, the rotation may be of regional character, as suggested by the surprisingly similar palaeomagnetic direction observed for Sárszentmiklós (Table I).

There seems to be no fault boundary between the Neogene trough and the area which rotated clockwise. Thus we suggest that this area was thrust over the Neogene trough (the extent of the thrust cannot be estimated on palaeomagnetic grounds) after the termination of the rotation in the latter, i.e. not before the Karpathian. It is more likely, however, that the rotation (or part of it) is linked with the intra-Pannonian compressional event [BENKOVICS 1997], since the Lower Pannonian Danitzpuszta (24) exhibits large rotation whereas the Upper Pannonian localities (27 and 28) only slight, i.e. negligible, CW rotation.

Very recently two palaeomagnetic studies have dealt with the Tertiary rotation of the Tisza megatectonic unit outside of the Mecsek Mts. In one of them, the authors concluded that a CW rotation of 60° of the Apuseni Mts. took place between 14 and 12 Ma, i.e. during late Badenian–early Sarmatian [PANAIOTU et al. in prep.]. The magnitude of this rotation is quite similar to what we observe on average for localities 8, 9 and 24 in the Mecsek Mts. but the timing may be different. Unless we ascribe the palaeomagnetic direction for 24 (Lower Pannonian in age) to local tectonics, our data suggest an intra-Pannonian rotation. It should be pointed out here that locality 24 is close to the Mecsekalja tectonic zone which is a left-lateral strike-slip [BENKOVICS 1997] requiring CCW rotation. Since the declination we observe here is rotated to the east it is hard to associate it with

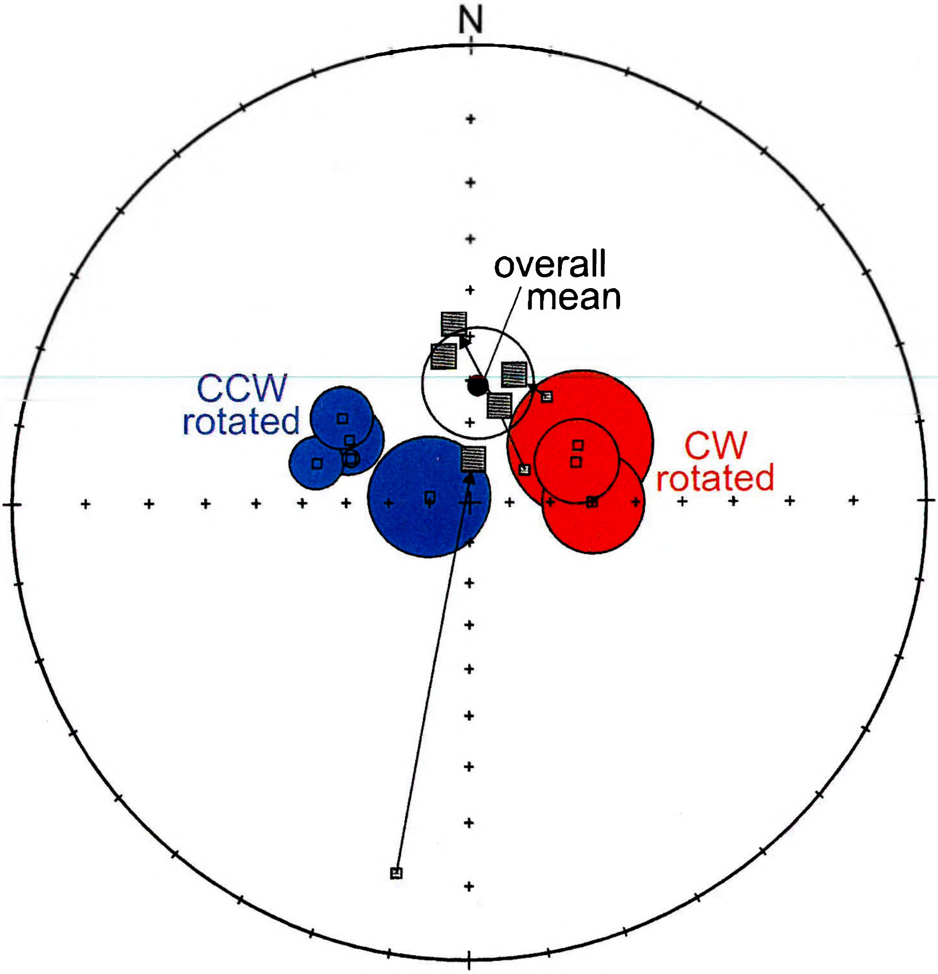


Fig. 7. Palaeomagnetic site and locality mean directions from the Mecsek Mts. Stereographic projection

Black: Karpathian-Badenian sediments (12, 13, 14, 16, 18): *small squares:* before tilt correction, *bigger squares:* after tilt correction. Overall mean with α_{95} is interpreted as indicating no significant rotation of the source area after the Ottnangian.

Blue: site mean directions with α_{95}'s for the sites ignimbrite (3, 4, 6, 7, 22).

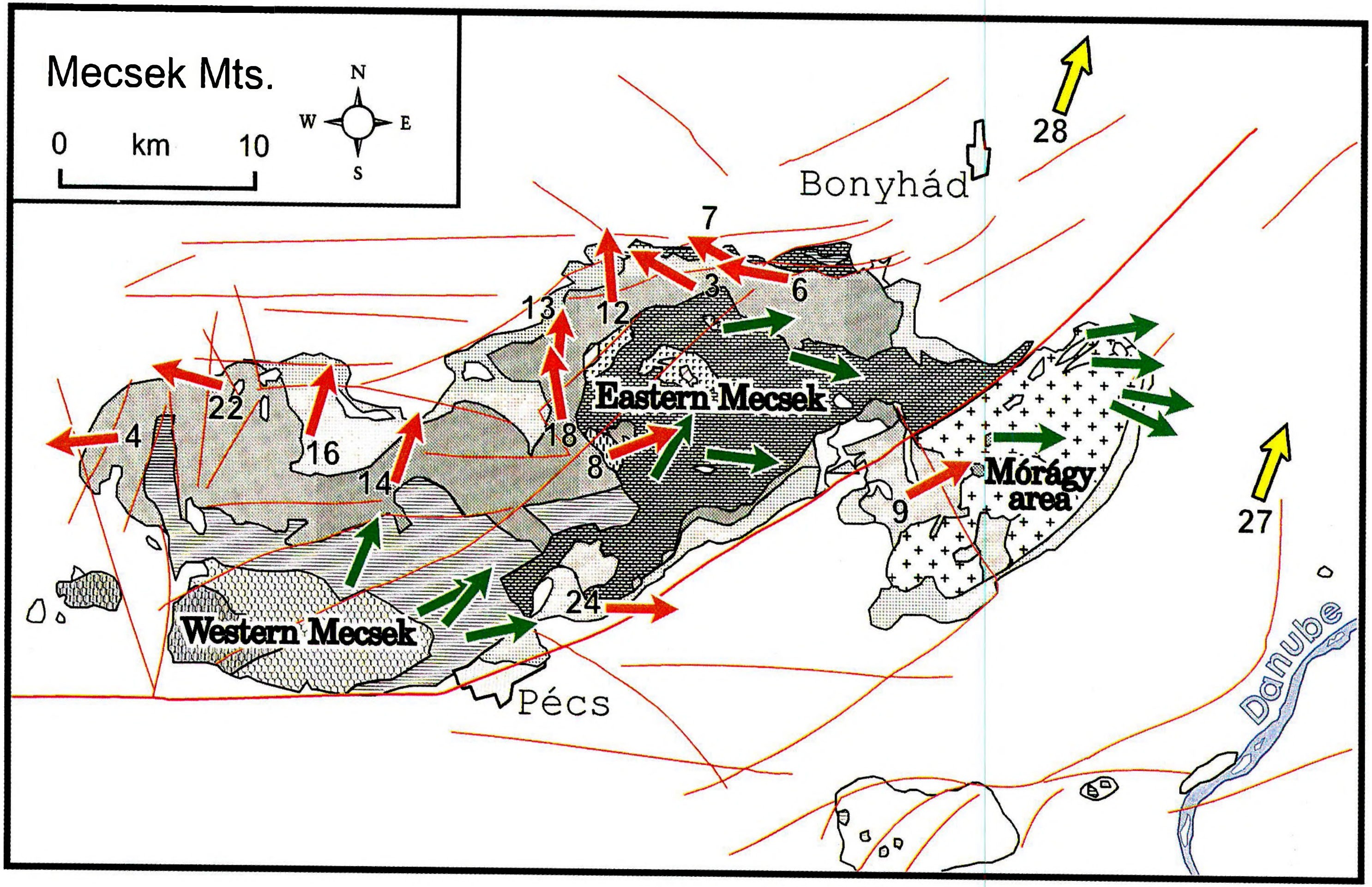
Red: site mean directions with α_{95}'s for sites 8, 9, 24.

7. ábra. Paleomágneses középirányok a Mecsek-hegységből. Sztereografikus projekció.

Fekete: kárpáti-bádeni üledékek (12, 13, 14, 16, 18); *kis négyzetek:* dőléskorrekció előtt, *nagyobb négyzetek:* dőléskorrekció után. Az összesített középirány a konfidenciakörrel azt indikálja, hogy az üledékes terület az ottnangi után nem rotált.

Kék: az ignimbritek (3, 4, 6, 7, 22) középirányai konfidenciakörökkel.

Piros: a 8, 9 és 24 számú mintavételi helyek középirányai


Mecsek Mts.
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km
10
N
W
E
S
Bonyhád
28
27
7
3
6
13
12
22
4
16
18
14
8
9
24
Eastern Mecsek
Western Mecsek
Mórágy area
Pécs
Danube

Fig. 8. Palaeomagnetic declinations for the Mecsek Mts.

Cretaceous: *green arrows*; Ottnangian – Lower Pannonian: *orange arrows*; Upper Pannonian: *yellow arrows*. Numbers refer to Tables I and II.

8. ábra. A Mecsek hegység paleomágneses deklinációi.

Kréta: *zöld nyilak*; ottnangi–alsó pannon: *narancssárga nyilak*; felső pannon: *sárga nyilak*. A számok az I. és II. táblázatokra utalnak movements along the Mecsekalja-zone. The second study concerns the Slavonian Mts. in Croatia. Here Ottnangian through Lower Pannonian rocks exhibit CCW rotations with an average angle of 40° [MÁRTON et al. in press].

Summarizing, it is concluded that the Tisza megatectonic unit cannot be characterized by consistent palaeomagnetic directions in the Tertiary. The palaeomagnetic data suggest that the eastern part (Apuseni Mts. and, along with this, probably the Southern Carpathians) rotated as a rigid area. In the west, the situation is more complicated. The Mecsek Mts. proper must be divided into two differently moving units: north of the Palaeozoic –Mezozoic main body of the Mecsek Mts. the CCW rotations must have been terminated by the Karpathian; the main body of the Mecsek was probably emplaced during the Intra-Pannonian compressional event with a CW rotation — more or less at the same time that the CCW rotations occurred in the Slavonian Mts.

This scenario suggests that the present arrangement of the elements of the Mesozoic–Palaeozoic basement complex of the Tisza megatectonic unit was brought about by Neogene tectonic movements. Consequently, the Tisza megatectonic unit as defined by several authors [BALLA 1984; CSONTOS et al. 1992; KOVÁČ et al. 1994] cannot be reconstructed as a rigid tectonic unit in the Tertiary.

Acknowledgements

Our thanks are due to L. Benkovics, Z. Máthé, Gy. Konrád and G. Hámor for guiding us in the field. This work was partially supported by the Hungarian Science Research Found (OTKA) Project No. T 017008.

REFERENCES

BALLA Z. 1984: The Carpathian loop and the Pannonian Basin: a kinematic analysis. Geophysical Transactions **30**, pp. 5–43

BENKOVICS L. 1997: Etude structurale et géodynamique des Monts Buda, Mecsek et Villány (Hongrie). These l'Universite des Sciences et Technologies de Lille, Docteur de l'Universite en Geologie et Geochimie Sedimentaries. pp. 1–230.

CHIKÁN G. 1991: Die kainozoischen Ablagerungen des westlichen Mecsek-Gebirges. Ann. Ins. Geol. Publ. Hung. **LXXII**. pp. 91–137

CSONTOS L., NAGYMAROSY A., HORVÁTH F., KOVÁČ M. 1992: Tertiary evolution of the Intra-Carpathian area: a model. Tectonophysics **208**, pp. 221–241

FISHER R. A. 1953: Dispersion on a sphere. Proc. R. Soc. London, Ser. A., **217**, pp. 295–305

HÁMOR G. 1970: Das Miozän des Östlichen Mecsek-Gebirges. Ann. Ins. Geol. Publ. Hung. **LIII/1**. pp. 1–483

HÁMOR G. 1984: Paleogeographic reconstruction of Neogene plate movements in the Paratethyan realm. Acta Geologica Hungarica **27**, 1–2. pp. 5–21

HÁMOR G. RAVASZ-BARANYAI L., HALMAI J., BALOGH K., ÁRVA-SÓS É. 1987: Dating of Miocene acid and intermediate volcanic activity in Hungary. Ann. Ins. Geol. Publ. Hung. **LXX**. pp. 149–152

HÁMOR G., JÁMBOR Á. 1964: Correlation of the Miocene formations from the Eastern and Western Mecsek respectively. Földtani Közlöny **94**, pp. 53–64

KENT J. T., BRIDEN J. C., MARDIA K. V. 1983: Linear and planar structure in ordered multivariate data as applied to progressive demagnetization of paleomagnetic remanence. Geophys. J. R. Astr. Soc. **75**, pp. 593–621

KOVÁČ M., KRÁL' J., MÁRTON E., PLAŠIENKA D., UHER P. 1994: Alpine uplift history of the Central Western Carpathians: geochronological, paleomagnetic, sedimentary and structural data. Geologica Carpathica **45**, 2, pp. 83–96

LOWRIE W. 1990: Identification of ferromagnetic minerals in a rock by coercivity and unblocking temperature properties. Geophys. Res. Lett. **17**, pp. 159–162

MÁRTON E. 1986: Paleomagnetism of igneous rocks from the Velence Hills and Mecsek Mountains. Geophysical Transactions **32**, pp. 83–145

MÁRTON E., 1990: Kinematics of the principal tectonic units of Hungary from paleomagnetic observations. Acta Geod. Geoph. Mont. Hung. **25**, pp. 387–397

MÁRTON-SZALAY E., MÁRTON P. 1978: On the difference between the palaeomagnetic poles of the Transdanubian Central Mountains and the Villány Mountains (in Hungarian). Magyar Geofizika **19**, pp. 129–136

MÁRTON E., MÁRTON P. 1989: A compilation of paleomagentic results from Hungary. Geophysical Transactions **35**, 1–2, pp. 117–133

MÁRTON E., MÁRTON P. 1983: A refined apparent polar wander curve for the Transdanubian Central Mountains and its bearing on the Mediterranean tectonic history. Tectonophysics **98**, pp. 43–57

MÁRTON E., MÁRTON P. 1995: Large scale rotations in North Hungary during the Neogene as indicated by palaeomagnetic data. *In:* MORRIS A. & TARLING

D.H. (*eds.*): Palaeomagnetism and Tectonics of the Mediterranean Region. Geol. Soc. Spec. Publ. No. **105**, pp. 153–173

MÁRTON E., VASS D., TÚNYI I. 1996: Rotation of the North Hungarian Paleogene and Lower Miocene rocks indicated by paleomagnetic data (S. Slovakia, N-NE. Hungary). Geologica Carpathica **47**, pp. 31–41

MÁRTON E., PAVELIĆ D., TOMLJENOVIĆ B., PAMIĆ J., MÁRTON P. 1999: First palaeomagnetic results on Tertiary rocks from the Slavonian Mountains in the Southern Pannonian Basin, Croatia. Geologica Carpathica (in press)

MÁRTON P., MÁRTON–SZALAY E. 1969: Palaeomagnetic investigation of magnetic rocks from the Mecsek Mountains, Southern Hungary. Annales Universitatis Scientiarum Budapestinensis de Rolando Eötvös Nominatae, Sectio Geologica XII, pp. 67–80

PANAIOTU C., PANAIOTU C. E., PÉCSKAY Z., ROŞU, E.: Fast clockwise rotation in the eastern part of Carpatho-Pannonian region during the Miocene. Physics and Chemistry of the Earth (in prep.)

PĂTRAŞCU St., BLEAHU M., PANAIOTU C. 1990: Tectonic implications of paleomagnetic research into Upper Cretaceous magmatic rocks in the Apuseni Mountains, Romania. Tectonophysics **180**, pp. 309–322

PĂTRAŞCU St., BLEAHU M., PANAIOTU C., PANAIOTU C. E. 1992: The paleomagnetism of the Upper Cretaceous magnetic rocks in the Banat area of South Carpathians: tectonic implications. Tectonophysics **213**, pp. 341–352

A Mecsek neogén paleomágnességének tektonikai vonatkozásai

MÁRTON Emő és MÁRTON Péter

Noha a mecseki harmadkor feltártsági viszonyai meglehetősen kedvezőtlenek, többszöri erőfeszítések árán 29 mintavételi helyről sikerült paleomágneses mintákat gyűjteni, amelyekből a megfelelő laboratóriumi vizsgálatok elvégzése után 15 szolgáltatott értelmezhető paleomágneses irányokat az ottnangitól a felső pannonig terjedő időszakra.

Az eredmények a következőképpen csoportosithatók: A neogén üldékes medence északi peremén sorakozó ignimbritek 60°-os nyugati rotációt mutatnak. Ugyanezen medence fiatalabb üledékein nincs mérhető rotáció. A Mecsek fő tömegét képező paleozoós–mezozoós képződményein lévő harmadkori mintavételi helyek hasonló mértékű keleti rotációval jellmezhetők mint a kréta bazaltok és egyéb magmás kőzetek. Végül a Mecsek környezetében lévő három felső pannon korú képződmény rotáció mentesnek bizonyult.

Ezek az eredmények, összevetve egyrészt az Erdélyi–középhegységből (Apuseni hegység) és a Déli Kárpátokból, másrészt a Szlavóniai Szigethegységből származó adatokkal (a Mecsekkel együtt mind a Tisza egység részei), arra utalnak, hogy — ellentétben kurrens tektonikai modellekkel — a Tisza egység a harmadkorban még nem tekinthető konszolidálódott merev tömbként.

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Péter Márton graduated as a geophysicist from the Eötvös Loránd University, Budapest, in 1957; he obtained his doctor's degree from the same university in 1964. In 1970, he was awarded his Candidate's degree by the Hungarian Academy of Sciences and his D.Sc. in 1985. Initially working on seismic interpretation he was susequently invited to join the staff of the Geophysics Department of Eötvös Loránd University in 1961. Since that time, Professor Márton's main field of interest has been geomagnetism — in particular, palaeomagnetism and archeomagnetism. He has published over a hundred papers and has produced many geophysics' teaching aids. Peter Márton has been professor of geophysics since 1989.

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Field line resonance studies in North America and Central Europe

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It is believed that geomagnetic pulsations in the Pc3–Pc4 range can have both magnetospheric and solar wind origins. Some researchers have found relationships between the frequencies of some Pc3–Pc4 pulsations and parameters of the solar wind. Others have found Pc3–Pc4 pulsations that did not agree with those relationships. We believe that there are at least two types of Pc3–Pc4 pulsations, one which is derived from solar wind upstream waves, and another which represents resonant oscillations of local field lines. Unfortunately, their frequency spectra are similar. This means, that if one mistakes a field line resonance for an upstream wave derived pulsation, attempts to use the pulsation frequency to derive solar wind parameters will fail, because the field line resonance frequency depends only on field line parameters. We show that the high spatial gradients of amplitude and phase which characteristises field line resonances may be used to identify them. Other pulsations exhibiting extremly low or zero spatial gradients in amplitude and phase may be those derived from upstream waves. Phase and amplitude gradients were measured over 150 km baselines, along magnetic meridians, in North America and 100 km in Central Europe. Cross power spectral density analysis of data from station pairs clearly and reliably identified field line resonances during local daylight hours in Central Europe and North America. Pulsations having zero spatial gradients were also identified and may be derived from solar wind upstream waves.

Keywords: Earth, magnetic field, plasmasphere, magnetosphere, solar wind

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1. Discussion

TROITSKAYA et al. [1971] as well as GUL'ELMI and BOLSHAKOVA [1973] showed that some pulsations in the Pc2–Pc4 band, recorded at Borok in the former USSR, seemed to demonstrate a dependence of oscillation period on the amplitude of the Interplanetary Magnetic Field (IMF). Satellite measurements of the IMF were used to verify the relationship. This relationship became known as the Borok B–Index. Pulsations whose characteristics (such as oscillation period) seem to be diagners were unable to verify the Borok B–Index, suggesting the presence, sometimes, of other pulsations not obeying the Borok B–Index relationship [RUSSELL, FLEMING 1976]. We think that upstream waves, propagating in the solar wind can enter the dayside magnetosphere, giving rise to pulsations in the Pc3–Pc4 band, having a relatively broad frequency spectrum and exhibiting coherence over a large extent of longitude (ten's of degrees) and latitude (at least a few degrees). Evidence for these assertions is presented later in this paper. We further think that these broad spectrum, solar wind controlled upstream waves are ubiquitous in the dayside magnetosphere and are capable of exciting local field lines at their individual resonance frequencies. It is shown that the field line resonance spectra are very narrow and that field line resonances are characterized by high spatial gradients of amplitude, phase, and frequency along magnetic meridians. Upstream waves, on the other hand, are characterized by very low spatial gradients in meridional and longitudinal directions. *Table I*, below, summarizes what we believe are salient characteristics of these two classes, of dayside pulsations.

A. Upstream Waves/Solar Wind Controlled Pulsations

1. Originate in solar wind; some penetrate into Earth's magnetosphere.
2. Frequency spectrum probably determined by solar wind parameters.
3. Broad frequency spectrum.
4. Low or zero spatial gradients of amplitude, phase, and frequency.
5. May excite local field line resonances.
6. Occur mainly on dayside.

B. Field Line Resonances

1. Originate as standing wave, Alfven resonances on local field lines.
2. Frequency spectrum determined only by local field line parameters.
3. Narrow frequency spectrum.
4. High spatial gradients of amplitude, phase, and frequency.
5. Resonant oscillations may be excited by upstream wave energy.
6. Occur only on dayside.

Table I. Salient characteristics of dayside pulsations
I. táblázat. A nappali pulzációk legfontosabb tulajdonságai

A plot of the power spectral density of one component of the geomagnetic field (say, the North Horizontal component) at a single point would yield a broad spectral 'bump'. This 'bump' would represent the superposition of power from local and neighboring field line resonances, upstream waves, and other phenomena. Determining the centroid of this broad spectral bump would likely tell us nothing about either the frequency of the local field line resonance or the frequency spectrum of the upstream waves. Since, in practice, these spectral bumps may span a decade or more of frequency, one can readily understand why using power analysis alone will usually not give us accurate enough information about upstream wave frequency to determine IMF to within an order of magnitude.

Recent work has shown that spatial gradients of amplitude and phase may be used to uniquely identify field line resonances [BARANSKY et al. 1990 and GREEN et al. 1993]. The work described in the present paper verifies those results and further suggests that phase gradients may be used to identify upstream waves, as well.

2. The Global Field Line Resonance Network

Scientists from the U.S. Geological Survey (USGS) Geomagnetism Group, Golden, Colorado, USA, and from the Eötvös Loránd Geophysical Institute of Hungary, at Budapest and Tihany, proposed a global network of gradient stations to identify field line resonances. Stations will eventually be located at the six sites shown on the map of *Figure 1*. These sites span a range of L shells from 1.4 to 5.5 and a range of over 170 degrees of longitude as shown below in *Table II*.

Fairbanks-Healy, AK, USA	L=5.5	Longitude = 147 W
St. Petersburg-Red Lake, Russia	L=3.5	Longitude = 30 E
Nurmijärvi-Hankasalmi, Finland	L=3.4	Longitude = 25 E
Boulder-South Park, CO, US	L=2.4	Longitude =105 W
Lviv-Kovel, Ukraine	L=2.1	Longitude = 23 E
Tihany-Hurbanovo, Hungary/Slovakia	L=1.9	Longitude = 18 E

Table II. Gravity stations
II. táblázat. Gravitációs állomások

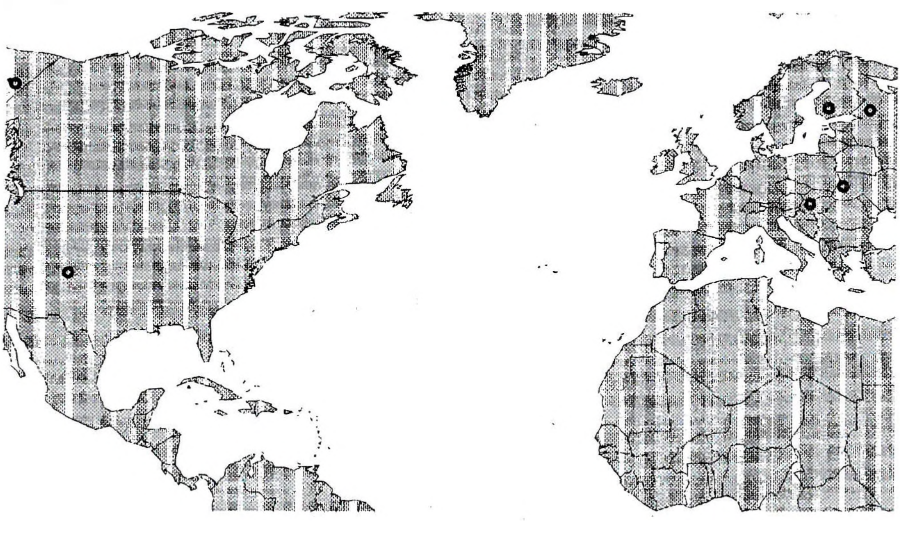


Fig. 1. Location of existing and planned gradient pair sites. At each site there are 2 stations separated by about 100 km along the local magnetic meridian
1. ábra. A tervezett és már meglévő regisztráló állomáspárok elhelyezkedése. Két mérőhely minden esetben a mágneses meridián mentén egymástól 100 km körüli távolságra van

Two additional Hungarian sites are planned in order to refine our observations in Hungary and also to investigate East–West phase gradients.

At each site there are located a pair of stations separated by about 150 km along the local magnetic meridian. For example, the Tihany site consists of a station at the Tihany Geomagnetic Observatory and another station at Hurbanovo, Slovakia, which is about 100 km to the North of Tihany along the magnetic meridian. At each station there is a three component magnetometer, a Global Positioning System (GPS) receiver, and a digital data acquisition system. Sampling rate is 1.0 Hz; data are band pass filtered from 3 millihertz to 200 millihertz; GPS time accuracy is at least 1.0 millisecond, and overall system noise less than 0.02 nanotesla. Data are recorded on magneto optical discs. Cross power spectral density is computed continuously for each station pair for a 24 hour Universal Time (UT) interval. Cross power spectral density is the Fourier transform of the cross correlation function between the two time series. Unlike auto power spectral density, cross power spectral density is a complex function having both real and imaginary parts. It may be represented by amplitude and phase functions. By continuously computing cross power spectral density between the two points over time, one can identify a frequency at which a distinct phase difference exists; this is the resonance of the field line half way between the two points. The phase shift may be of the order of 40 degrees for pairs separated by 150 km [BARANSKY et al. 1995] and may persist during the daylight hours (10 hours or more) as the field line resonance slowly changes frequency during the course of a day [GREEN et al. 1993]. With support from the U.S.–Hungarian Science and Technology Joint Fund, ELGI, and the U.S. Geological Survey, we have established a pair of stations in North America (Boulder and South Park, Colorado) and in Central Europe (Hurbanovo, Slovakia, and Tihany, Hungary). This paper describes preliminary results from analysis of data from these two pairs of stations.

Figures 2 and *3* show simultaneous pulsations for a 15 minute period at Hurbanovo, Slovakia, and Tihany, Hungary.

Figure 4 shows cross power amplitude and cross power phase for a 24 hour period. The field line resonance is readily identified on the phase plot as the red/brown line (about 20 to 40 degrees of phase shift) at a frequency of 55 millihertz between about 0800 and 1500 UT. The resonance is not at

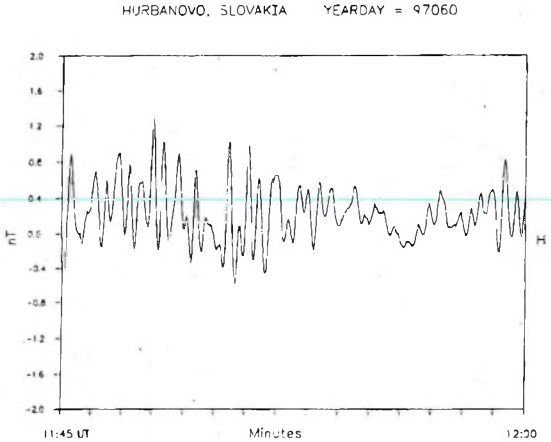


Fig. 2. Field line resonance pulsations at Hurbanovo, Slovakia between 11:45 UT and 12:00 UT on 1 March 1997. They have been recorded in a frequency band from 3 mHz to 200 mHz and exhibit a typical resonance frequency of 50 mHz (period of 20 seconds)

2. ábra. Erővonalrezonancia okozta pulzációk Hurbanovoban, 1997 március 1-én 11:45 UT és 12:00 között. A felvételek a 3 mHz és 200 mHz közötti tatományban készültek és 50 mHz-es jellemző rezonanciafrekvenciát mutatnak (20 másodperces periódus)

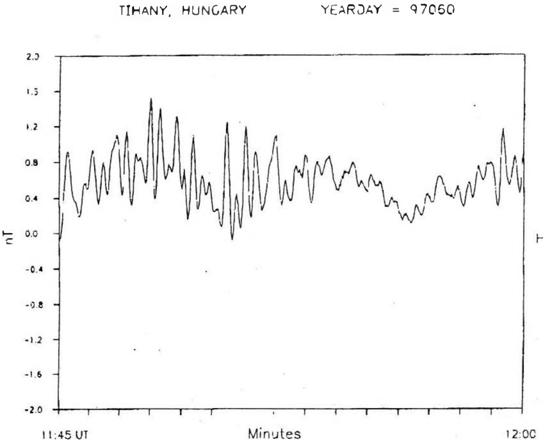
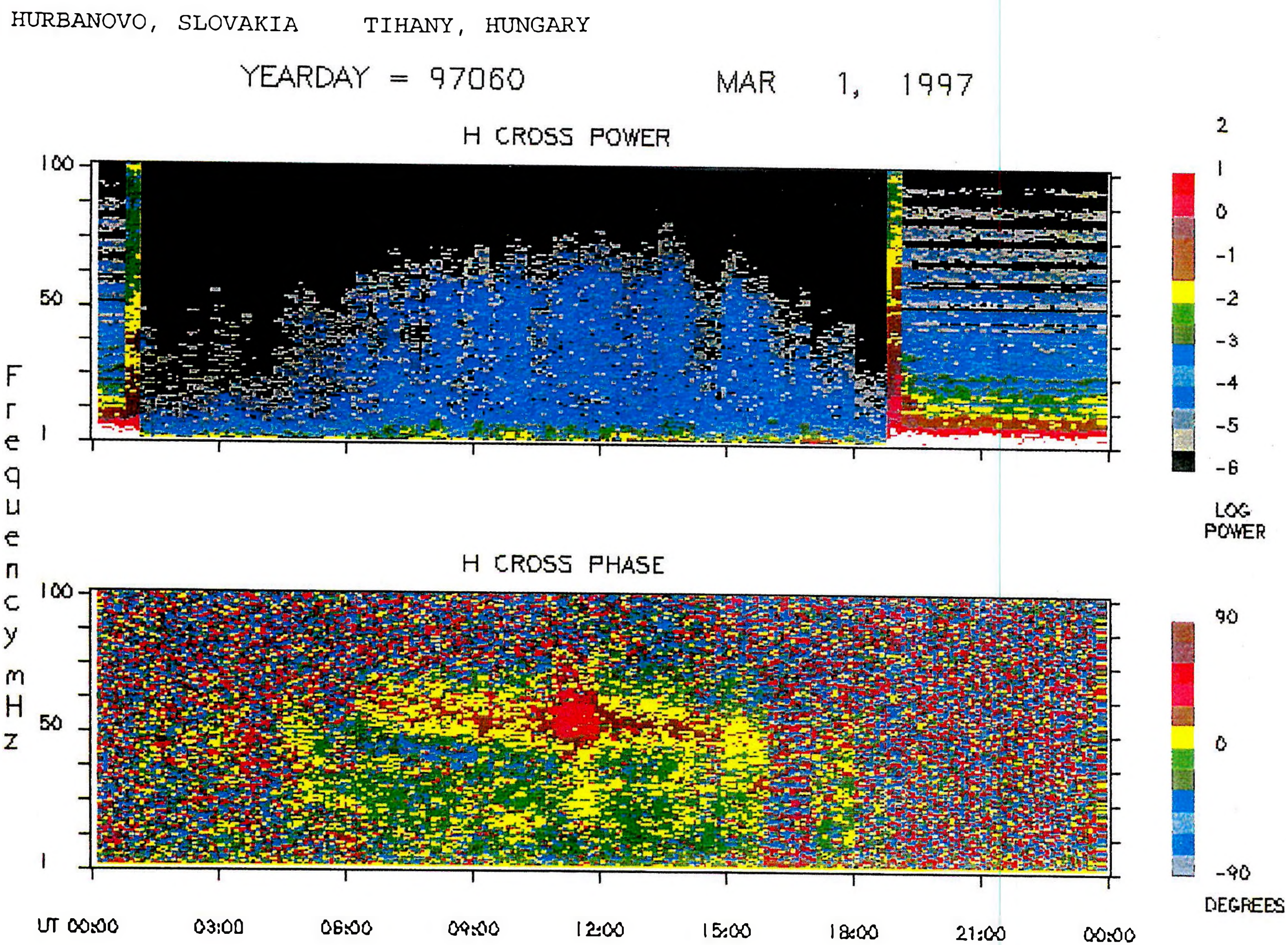


Fig. 3. Field line resonance pulsation at Tihany, Hungary between 11:45 UT and 12:00 UT on 1 March 1997. They have been recorded in a frequency band from 3 mHz to 200 mHz and exhibit a typical resonance frequency of 50 mHz (period of 20 seconds)

3. ábra. Erővonalrezonancia okozta pulzációk Tihanyban, 1997 március 1-én 11:45 UT és 12:00 UT között. A felvételek a 3 mHz és 200 mHz közötti tatományban készültek és 50 mHz-es jellemző rezonanciafrekvenciát mutatnak (20 másodperces periódus)


HURBANOVO, SLOVAKIA TIHANY, HUNGARY
YEARDAY = 97060 MAR 1, 1997
H CROSS POWER
H CROSS PHASE
Frequency mHz
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06:00
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15:00
18:00
21:00
00:00
2
1
0
-1
-2
-3
-4
-5
-6
LOG POWER
90
0
-90
DEGREES

Fig. 4. Cross Phase versus time and frequency between Hurbanovo and Tihany on 1 March 1997. The resonance frequency is clearly outlined in the phase function

4. ábra. Keresztkorrelációs amplitudó és fázis 1997. március 1-re Hurbanovo és Tihany állomásokra. A rezonancia frekvencia világosan látszik a fázisfüggvényben all apparent from the power plot: since the power plots contribute nothing to the identification of the resonance, they are omitted in the subsequent plots.

The resonance has a phase gradient of about 0.45° per km over the 100 km separaton of the stations. It may be shown from GREEN et al. [1993] that the calculated frequency gradient is 0.028 Hz/km (increasing southward) and the amplitude gradient is 0.025 nT/km. It is also shown that the cross power density spectrum is a more reliable means of identifying the resonance frequency than are amplitude and frequency grades. So we use the phase gradient exclusively.

Figures 5 and *6* show simultaneous pulsations for a 15 minute period at Boulder, Colorado, and South Park, Colorado, in the USA. The phase plot of *Figure 7* shows a resonance at about 30 millihertz from about 1400 to 2300 UT. The red color shows that the phase shift is between 45 and 60 degrees.

In all cases for both Central Europe and North America, the field line resonances are a dayside phenomena. This fact is illustrated by the five-day series of repeated strong resonances shown in *Figure 8*.

We have also observed that, on the phase plots, a region of yellow-green color extends from a frequency below the field line resonance frequency to one above the resonance frequency. Since yellow-green represents a phase difference between the stations of near zero degrees, we think that the yellow-green region signifies the presence of pulsations having a broad frequency spectrum and having spatial coherence over the distance between the stations. We think that these represent upstream waves, and that when the upstream wave power extends through the local field line resonance frequency, the local resonance is triggered.

The examples cited above suggest that the waves corresponding to the broad spectrum power having zero phase between stations are coherent over distances of at least 100 km. Indeed, these upstream waves may be spatially coherent over distances considerably in excess of 150 km. In an effort to test coherence over long distances, we computed cross power spectral density on simultaneous records at Boulder, Colorado, USA, and Tihany, Hungary. These sites are separated by about 120 degrees of longitude. At the time we had only a few simultaneous recordings from North

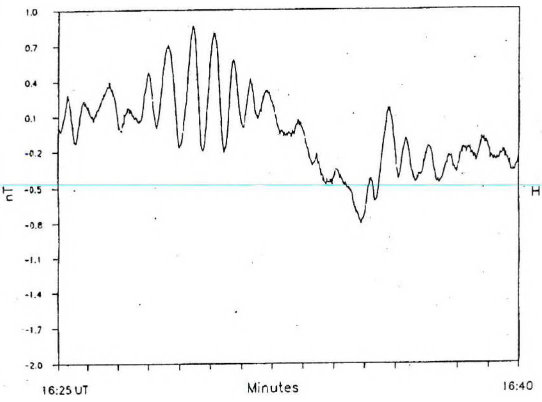

Fig. 5. Field line resonance pulsations at Boulder, Colorado, USA between 16:25 UT and 16:40 UT on 23 March 1997. Because of the longer field line (higher *L* shell) the frequency is lower, about 30 mHz (or 33 second period)

5. ábra. Erővonalrezonancia okozta pulzációk Boulderben, 1997 március 23-án 16:25 UT és 16:40 UT között. A hosszabb erővonalak miatt (nagyobb *L* érték) a frekvencia itt alacsonyabb, körülbelül 30 mHz (vagy 33 másodperces periódus)

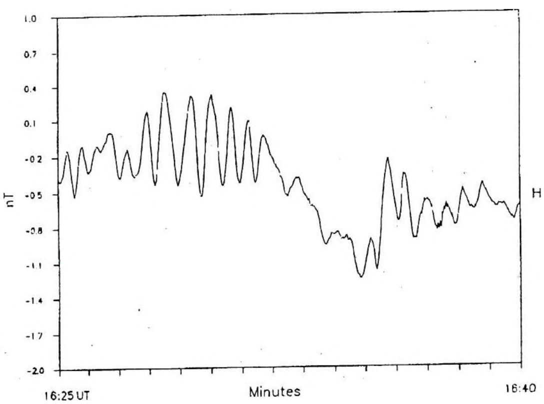

Fig. 6. Field line resonance pulsations at South Park, Colorado, USA between 16:25 UT and 16:40 UT on 23 March 1997. Because of the longer field line (higher *L* shell) the frequency is lower, about 30 mHz (or 33 second period)

6. ábra. Erővonalrezonancia okozta pulzációk South Parkban, 1997 március 23-án 16:25 UT és 16:40 UT között. A hosszabb erővonalak miatt (nagyobb *L* érték) a frekvencia itt alacsonyabb, körülbelül 30 mHz (vagy 33 másodperces periódus)

BOUDLER, CO, USA SOUTH PARK, CO, USA

YEARDAY = 97082 MAR 23, 1997

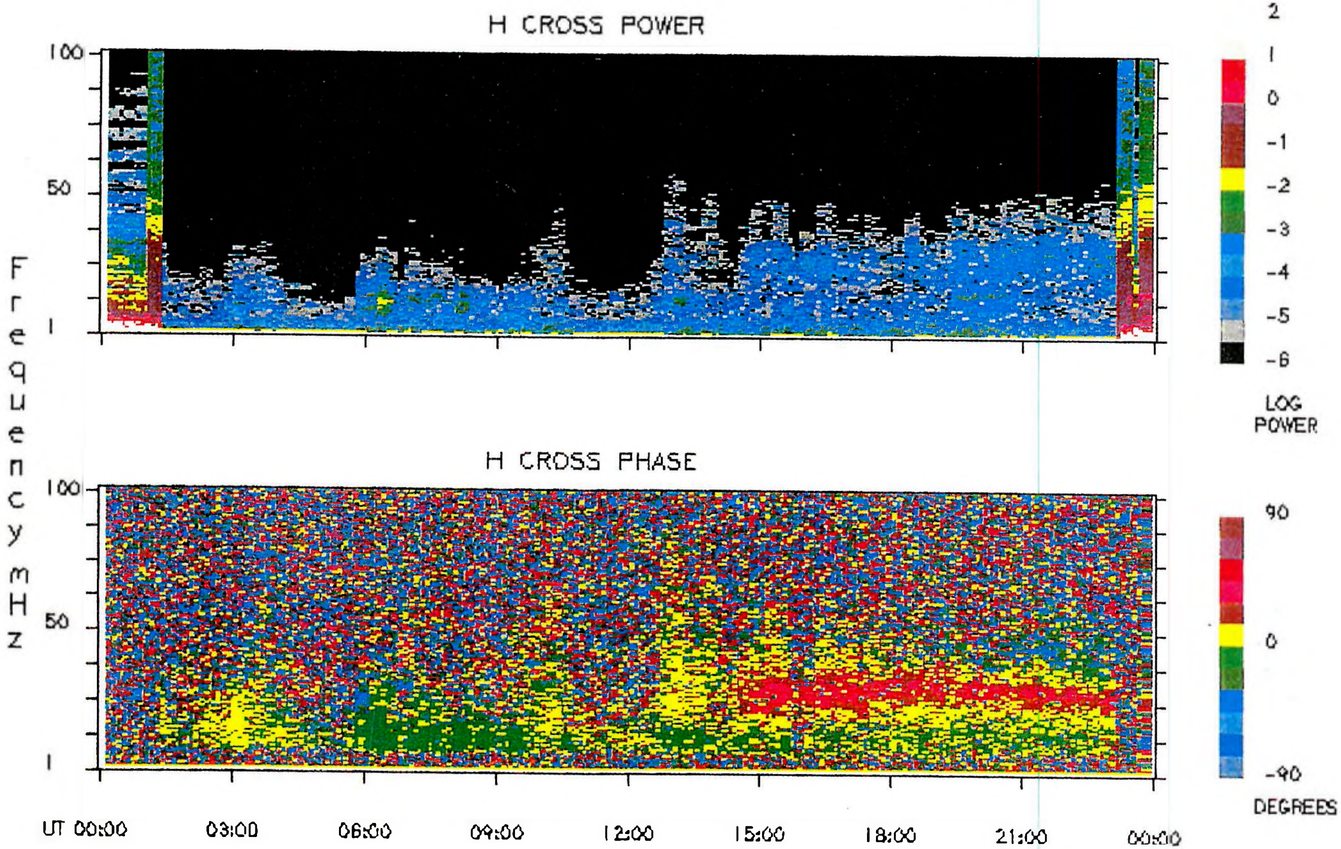

Fig. 7. Cross phase versus time and frequency between Boulder and South Park on 23 March 1997. The circled region suggests upstream waves with central frequency of 25 mHz having zero phase difference

7. ábra. Boulderi és South Park-i adatok teljesítmény- és keresztkorrelációs függvénye 1997. március 23-ára. A bekeretezett tartomány 25 mHz központú upstream pulzációkat sejtet nullához közeli fázisdiferenciával

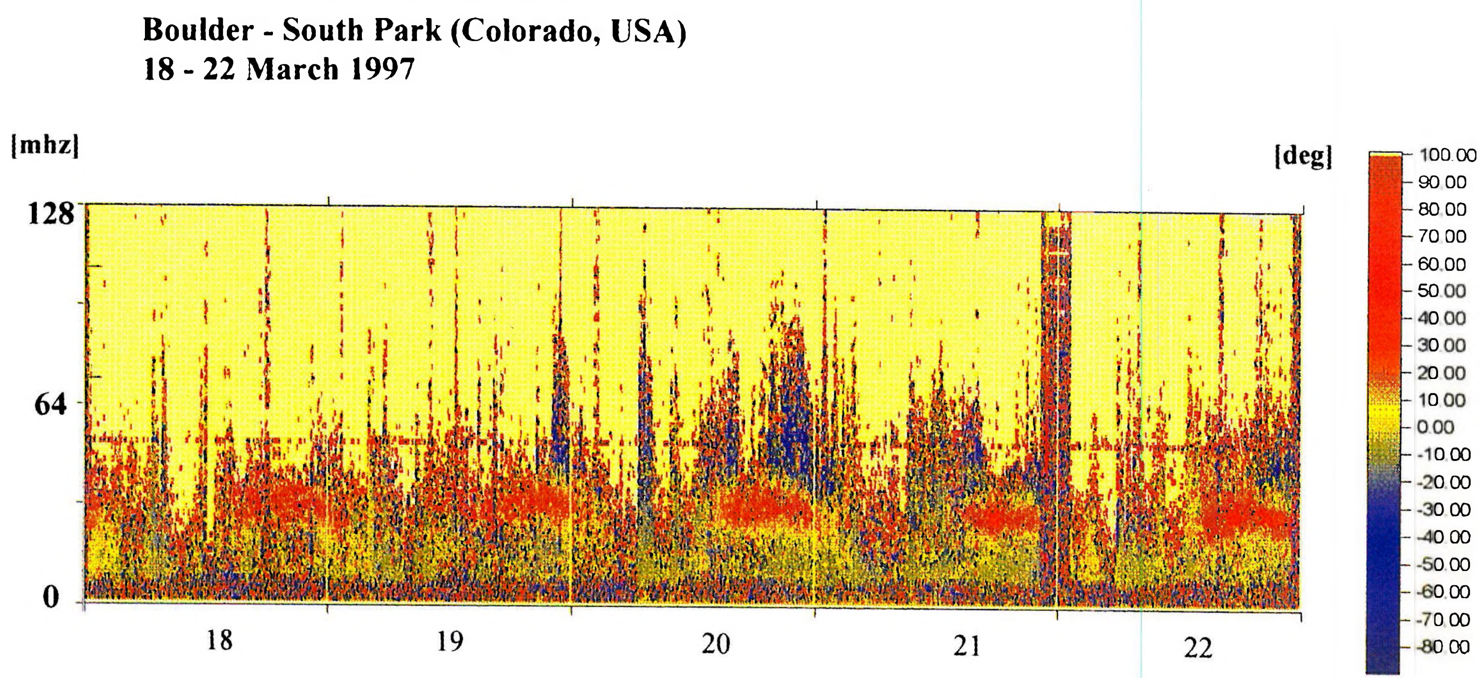

Fig. 8. Repeat daytime resonances for 5 days at Boulder on 18-22 March 1997, indicate that field line resonances are daytime events

8. ábra. 5 egymást követő napon jelentkező, ismétlődő rezonanciák Boulderben, 1997. március 18-22. között. Az ábra csak nappal előforduló jelenségre utal

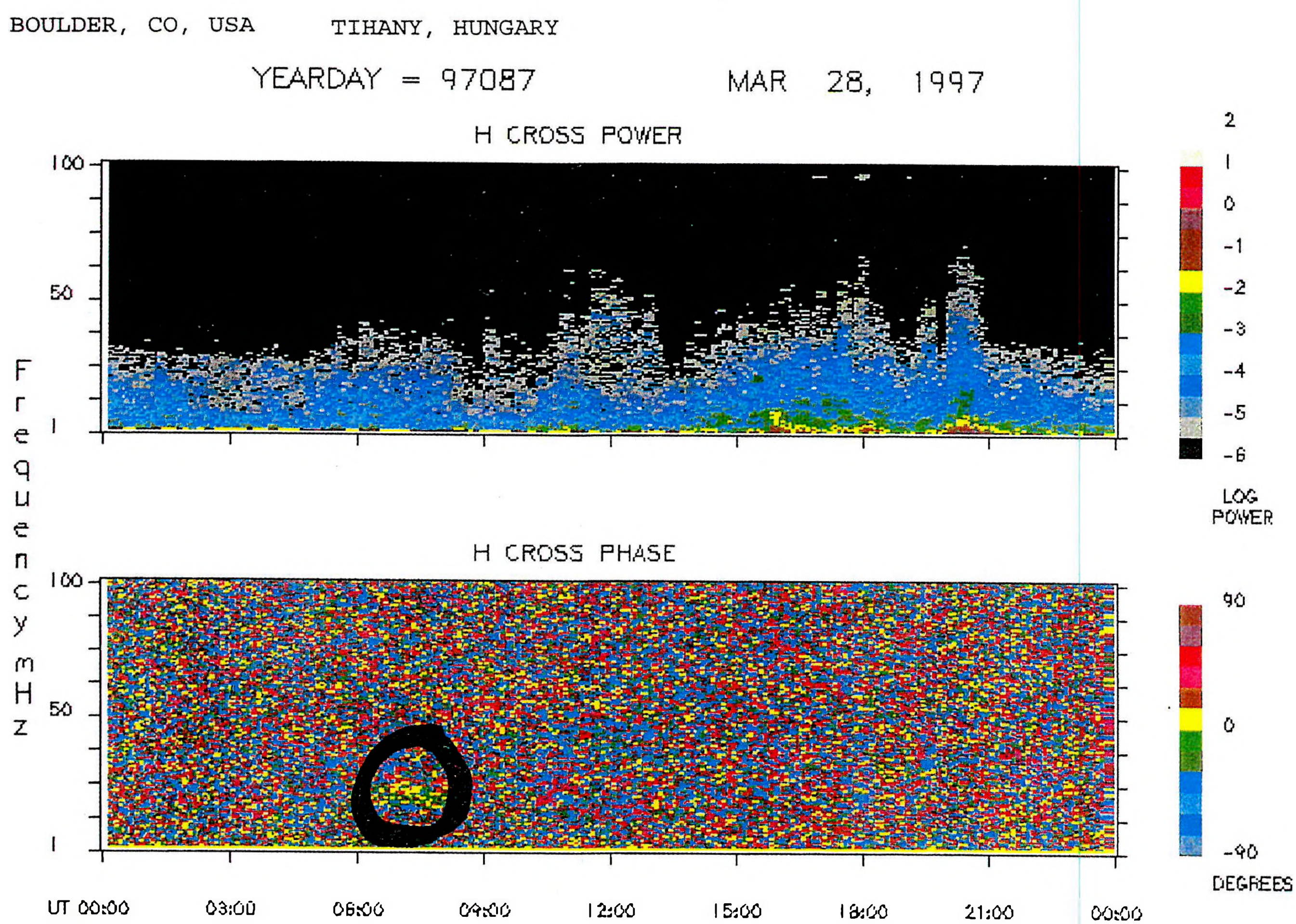
BOULDER, CO, USA
TIHANY, HUNGARY
YEARDAY = 97087
MAR 28, 1997
H CROSS POWER
H CROSS PHASE
Frequency mHz
100
50
1
2
1
0
-1
-2
-3
-4
-5
-6
LOG POWER
90
0
-90
DEGREES
UT 00:00
03:00
06:00
09:00
12:00
15:00
18:00
21:00
00:00

Fig. 9. Region of zero phase between Boulder and Tihany, 28 March 1997

9. ábra. Nulla fáziskülönbségű tartomány boulderi és tihanyi adatok összehasonlításából 1997. március 28-ra

America and Central Europe. One set of records, however, showed an example of apparent coherence of waves over this great distance. In *Figure 9*, we see a yellow-green region of zero phase from 0700 to 0800 UT on 28 May 1997 in a frequency band from about 13 to 30 mHz. We belive that the lack of phase difference between Colorado and Hungary means that these waves are upstream waves whose characteristics are unrelated to local *L* values and are determined only by conditions of the solar wind. In *Figure 10*, we have superimposed records of pulsations for Boulder and Tihany during this interval of small zero phase. The coherence is quite good, suggesting the presence at those widely separated sites of upstream waves with essentially zero phase difference. At this point, the paucity of data means that these results are to be considered tentative.

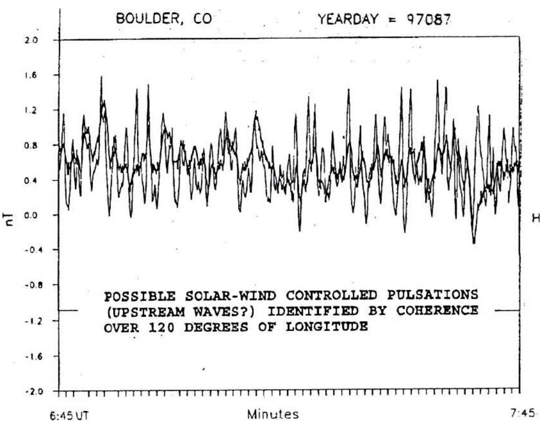

Fig. 10. Superimposition of pulsations from Boulder and Tihany at the time of the zero phase event suggests coherence over this great distance, suggesting that these are upstream waves

10. ábra. A nulla fáziskülönbségű időszak egymásrahelyezett boulderi és tihanyi regisztrátuma nagy távolságokra fennálló koherenciára és így upstream típusú hullámokra enged következtetni

3. Conclusions

— Cross power spectral density (CPSD) analysis may be used to separate waves having high spatial gradients of amplitude, phase, and frequency from those having low spatial gradients of amplitude, phase, and frequency.

— CPSD gradient analysis (particularly, phase) may be used to very accurately determine field-line resonance (FLR) frequencies and their time dependence. FLR's are characterized by very high spatial phase gradients.

— CPSD phase analysis has identified waves whose broad frequency spectra span the field line resonance frequency line. Those 'spanning' waves have been present during all field line resonance events that we analyzed. Those 'spanning' waves maybe upstream waves and may trigger FLR's. These upstream wave candidates are characterized by very low spatial wave gradients.

Acknowledgements

The authors wish to acknowledge financial support from the U.S. -- Hungarian Science and Technology Joint Fund (JFNo.439), the Eötvös Loránd Geophysical Institute of Hungary, and the U.S. Geological Survey. Without their support the Global Field Line Resonance Network would not have been begun. Particular recognition is due to E. A. Sauter and L. W. Pankratz who spent many hours developing, testing, and installing the instruments at the 4 stations in Central Europe and North America. Without their devotion and their efforts in the field, this piece of scientific work would not have been possible.

REFERENCES

BARANSKY L. N., BELOKRYS S. P., BOROVKOV YU.E., GREEN C. A. 1990: Two simple methods for the determination of the resonance frequencies of magnetic field lines. Planet. Space Sci. **38**, pp. 1573–1576

BARANSKY L. N., GREEN A. W. , FEDOROV E. N. , KURNEVA N. A., PILIPENKO V. A., WORTHINGTON E. W. 1995: Gradient and polarization methods of ground-based monitoring of magnetospheric plasma. J. Geomag. Geoelectr. **47**, pp. 1293–1309

GREEN A. W., WORTHINGTON E. W. , BARANSKY L. N., FEDOROV E. N., KURNEVA N. A., PILIPENKO V. A., SHVETZOV D. N., BEKTEMIROV A. A., PILIPOV G. V. 1993: Alfven field line resonances at low-latitudes (L=1.5). J. Geophys. Res. **98**, pp. 15693–15699

GUL'ELMI A. V., BOLSHAKOVA O. V. 1973: Diagnostics of the interplanetary magnetic field from ground-based data on Pc2–4 micropulsations. Geomagn. Aeron., **13**, pp. 513–521, .

RUSSELL C. T., FLEMING B. K. 1976: Magnetic pulsations as a probe of interplanetary magnetic field. A test of Borok B-index. J. Geophys. Res. **81**, pp. 5882–5887

TROITSKAYA V. A., PLYASOVA–BAKOUNINA T. A., GUL'ELMI A. V. 1971: Relationship between Pc2–4 pulsations and the interplanetary magnetic field. Dokladi Akademii Nauk SSSR, English Transl. **197**, pp. 1312–1322

Erővonal rezonanciák tanulmányozása Észak-Amerikában és Közép-Európában

Arthur W. GREEN, Edward W. WORTHINGTON,
Tanya A. PLYASOVA-BAKOUNINA,
KÖRMENDI Alpár, HEGYMEGI László, Walter GOEDECKE, VÖRÖS Zoltán

Az általános nézet az hogy a Pc3–Pc4 tartományba eső pulzációk magnetoszférikus vagy napszél eredetűek is lehetnek. Néhányan összefüggést találtak a Pc3– Pc4 pulzációk frekvenciája és a napszélparaméterek között, mások viszont találtak olyan Pc3–Pc4 pulzációkat, melyek nem felelnek meg ennek az összefüggésnek. Mi azt állítjuk, hogy a Pc3–Pc4 pulzációknak legalább két különböző típusa van, az egyik a napszél upstream hullámaitól ered, a másik pedig a helyi erővonalak rezonanciájával kapcsolatos. Sajnos a két típus frekvenciaspektruma hasonló. Ebből az következhet, hogy ha valaki összetéveszti őket és megpróbálja a pulzációk frekvenciáját a napszél paramétereinek meghatározására használni, akkor könnnyen téves eredményre juthat, mert az erővonal rezonancia frekvenciája csak az erővonal paramétereitől függ. Bemutatjuk, hogy az erővonalrezonanciákra jellemző nagy, térbeli amplitúdó és fázisgradiens használható az ilyen pulzációk azonosítására. A többi pulzáció ugyanakkor nagyon kis térbeli amplitúdó és fázisgradienst mutat. Az erővonalak mentén 150 illetve 100 km-es távolságokban elhelyezkedő állomáspárok segítségével Észak-Amerikában és Közép-Európában fázis- és amplitúdógradienseket mértünk és

az állomáspárok adatainak keresztkorrelációja egyértelműen mutatott erővonalrezonanciákat a helyi nappali időszakokban. Ezek mellett sikerült azonosítani nagyon alacsony térbeli gradienssel jellemezhető pulzációkat, melyek a napszél upstream hullámai okozhatnak.

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Arthur W. GREEN photograph and biography not available at the time of publication.

Edward W. WORTHINGTON (1960). Education: graduate of University of Arizona, Tucson with a B.S. in Geosciences with a concentration in Geophysics, May 1983. Graduate of Colorado School of Mines, Golden, CO, with a Doctor of Philosophy in Geophysics, May 1992, Thesis title: Field Line Resonances and Plasma Diagnostics of the Earth's Magnetosphere. Experience: Research Associate, Geophysical Institute, University of Alaska Fairbanks, October 1997 to present. Perform research studying resonant pulsations at low and high latitudes. Duties range from equipment deployment, data reduction and analysis, and modeling of field line resonances. Also, I serve as the observer-in-charge of College Magnetic Observatory. This includes performing absolute observations, computation of magnetometer baselines and monitoring observatory equipment.

Tanya A. PLYASOVA-BAKOUNINA, photograph and biography not available at the time of publication.

Alpár KÖRMENDI, for a photogprah and biography, see this issue, p. 27.

László Hegymegi was born in Budapest in 1944. After graduating in geophysics at Eötvös Loránd University, Budapest, he joined ELGI in 1968. His main specialisation is instrument development for observatory measurement and data acquisition. He holds patents for a number of his instruments. His first digital magnetic recording equipment was installed in Tihany Observatory in 1971.

Walter GOEDECKE photograph and biography not available at the time of publication.

Zoltán Vörös was born in Komarno, Slovakia, in 1959. He received his degree in nuclear physics from Comenius University, Bratislava, Slovakia, in 1983, and his Ph. D. degree in geophysics from the Slovak Academy of Sciences in 1992. In 1983 he joined the Geophysical Institute SAS, Bratislava where he became head of the Hurbanovo geomagnetic observatory in 1990. His research interest is focused on nonlinear magnetosphere physics.

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The US-Hungarian Delta I - Delta D(DIDD) Quasi-absolute Spherical Coil System. Its history, evolution and future.

Leroy W. PANKRATZ*, Edward A. SAUTER*, Alpár KÖRMENDI**, László HEGYMEGI**

Standard geomagnetic recording systems in use today are relative instruments, absolute baseline of which changes with time. The absolute baseline of the instrument requires regular calibration with an absolute instrument. In order to achieve near absolute stability it would be much better if we can use an absolute instrument for recording the field variation. Several attempts in the past 35 years have been made to realize this idea, however due to cumbersome control and recording systems this concept was abandoned.

The proton precession magnetometer, which is a scalar instrument, is used to measure the components of the Earth's magnetic field by applying momentary, sequential deflection fields in mutually orthogonal coils. In the case of the classical proton precession magnetometer, the sampling rate is relatively low resulting in a time difference between the measurement of individual components which can produce measurement errrors especially during rapid variations in the field. Another problem is experienced trying to produce homogeneous fields in a large volume for the sensor of proton precession magnetometer. An inhomogeneous field yields a rapid signal decay providing a measurement which is not very precise. In order to accomodate the rather large sensors available years ago, a relatively large homogeneous volume required large Helmholtz coils. The resulting coil system is large, expensive, less stable and requires a large pier and housing.

The presented solution addresses all of the negative issues listed above including the size of coil, the expense, rapid sampling rate and long term stability.

Keywords: magnetometers, Earth, magnetic field

* US Geological Survey, Golden, Colorado

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Manuscript received: 9 February, 1999

The history of the DIDD evolved over the past four decades within the U. S. Geological Survey with the development and implementation of Helmholtz coil systems which were originally used as the ASMO and ASMOR systems [WIENERT 1970]. These systems used optically pumped rubidium and cesium magnetometer sensors and state-of-the-art (at the time), electronic systems recording on punched paper tape and magnetic tape. The ASMOR system operated as the main observatory system at Castle Rock, California from the late 1960's until the observatory was closed in September, 1976. Over the past decade we have adapted the coil systems used in these systems with proton magnetometer sensors. First with the EDA base station magnetometer sampling with the OMIS observatory system and then the Geometrics G–856 proton magnetometer sampled with the present Synergetics DCP system. The development of this technique and its use are described by Leroy ALLDREDGE in a paper published in 1960 and expanded upon in ALLDREDGE and SALDUKAS [1964]. These circular Helmholtz coils which were used in the early systems were ideally suited for initial tries as DIDD systems. The DIDD (*Fig. 1.*) consists of a double coil system the axes of which are perpendicular to the Earth's field vector and to each other. That is the axis of the D coil is horizontal and in the local mean magnetic E–W direction and the I coil axis lies in the local mean magnetic meridian plane. Although these have worked well, their size, which was of nearly 70 cm diameter has been suited to more classical observatory installations (that is large buildings and piers). Several sets of square coil systems of this same approximate size were also constructed in the early 1990's and are presently in use at several INTERMAGNET observatories.

We have previously reported of collaboration [PANKRATZ 1996] on a spherical coil design (*Fig. 2*) begun several years ago between the USGS and the ELGI. ELGI through the efforts of Alpár Körmendi designed and constructed several generations of a spherical coil system starting with individual coils constructed of phenolic, next individual coils constructed of Corian and finally the product in use today which is a molded spherical coil system utilizing epoxy resin. These new coils are approximately 30 cm in diameter and are driven by a specially designed current generator designed within USGS by Edward A. Sauter.

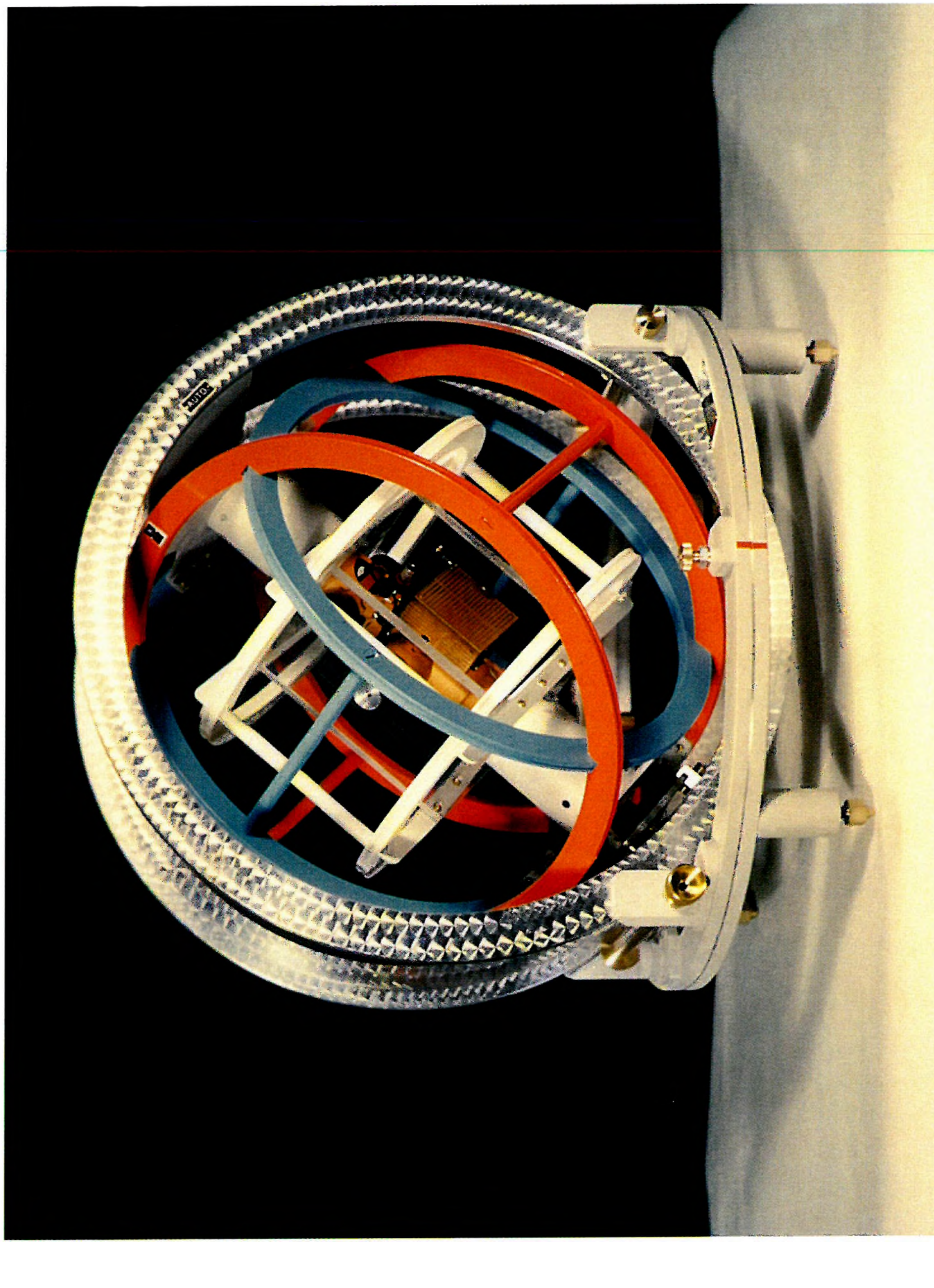

Fig. 1. Classical Helmholtz coil system

1. ábra. Klasszikus Helmholtz tekercsrendszer

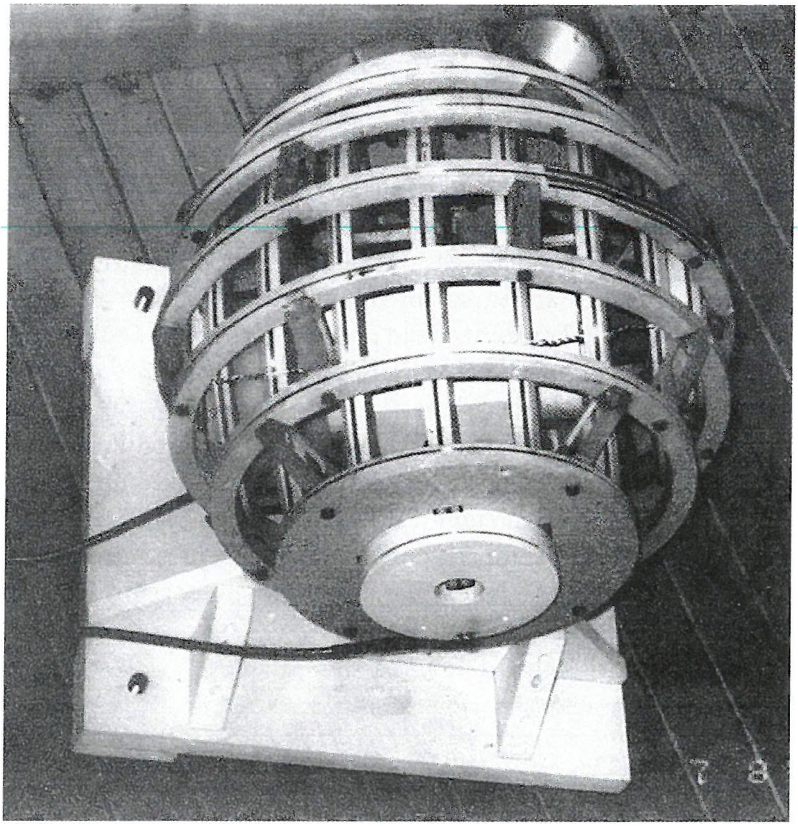

Fig. 2. An earlier version of the new compact coil system
2. ábra. Az új kompakt tekercsrendszer egy korábbi verziója

The first use of these spherical coils used a Geometrics classical proton magnetometer sensor and more recently the GEM Systems, Overhauser proton magnetometer sensor. The system measures the instantaneous pointing of the earth's field vector with reference to the axes of the coil system in the vertical (inclination) and horizontal (declination) planes. The actual absolute pointing of the coil axes is determined with an independent measurement such as with the declination-inclination magnetometer (DIM) (*Fig. 3*). The DIDD is therefore referred to as a quasi-absolute instrument. In the operation of the DIDD, equal and opposite currents are introduced into each of the coils to produce proton readings which are approximately 2500 nT greater than the total field. An automatic sequence of events commences with a deflected reading in the vertical plane for I_+ and then the reverse current far I_- (Equations 1 and 2). Next an undeflected reading is observed followed by deflected readings in the horizontal plane for D_+ and D_-. All five of these readings have been observed at ten-second spacings during the same one-minute period. It has been proven [GREEN 1986] that it is not necessary to know the values of the deflection currents, only that they are equal and opposite during the ten-second + and – cycles. Likewise the I currents need not be equal to the D currents (Equations 3 and 4). Operationally, crossfield values of one third of the ambient field or less are used with values typically ranging from 13,000 nT to 17,000 nT. Long-term stability depends on pier tilt and coil integrity which are affected by environmental conditions. Several assumptions must be considered for the DIDD system. First, that the I and D coils are perpendicular to Earth's Field vector, second, that the currents are equal and opposite in the I and D coils and lastly that the proton precession magnetometer is located at the center of coils.

The equations which are now considered are

$$A_I = \frac{1}{\sqrt{2}} \sqrt{I_+^2 + I_-^2 - 2F^2} \tag{1}$$

and

$$\Delta I = \frac{I_+^2 - I_-^2}{4 A_I F} \tag{2}$$

where

A_I is the deflection in the I coils (nT)

I_+ and I_- are the proton magnetometer readings for equal and opposite currents.

F is the undeflected proton magnetometer reading

I is the mean inclination angle

and equations

$$A_D = \frac{1}{\sqrt{2}} \sqrt{D_+^2 + D_-^2 - 2F^2} \tag{3}$$

Fig. 3. D/I magnetometer
3. ábra. D/I magnetometer

Fig. 3. D/I magnetometer
3. ábra. D/I magnetométer

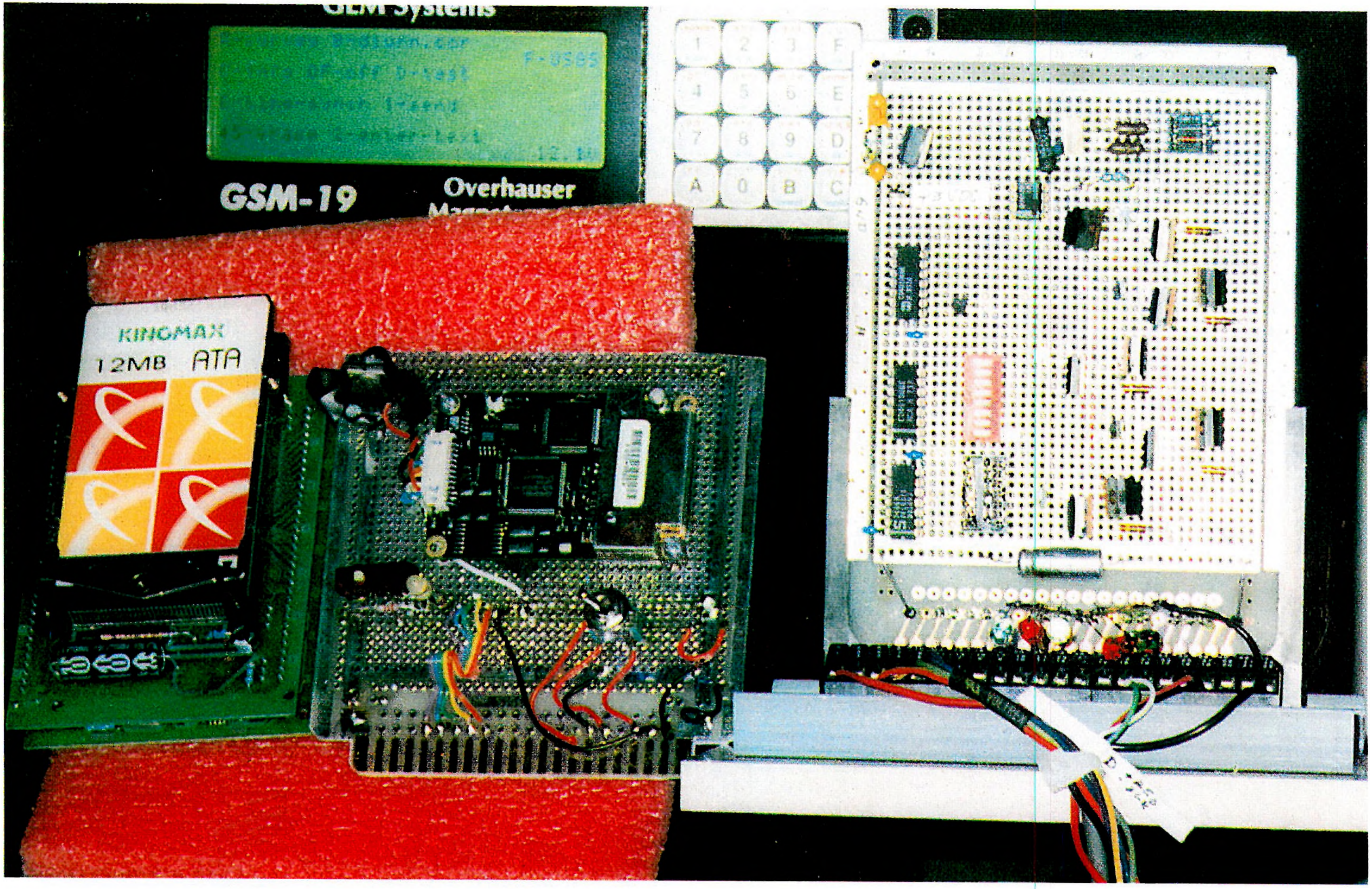
GSM-19
Overhauser
KINGMAX
12MB
ATA

Fig. 4. Electronic unit of the experimental DIDD system

4. ábra. A kisérleti DIDD műszer elektronikája

$$\Delta D = \frac{D_+^2 - D_-^2}{4\,A_D\,F\cos I} \tag{4}$$

where

A_D is the deflection in the D coils (nT)

D_+ and D_- are the proton magnetometer readings for equal and opposite currents.

F is the undeflected proton magnetometer reading

We are proceeding on the next phase in cooperation with Ivan Hrvoic of GEM Systems (Canada) in the development and demonstration of an Overhauser spherical coil DIDD which will cycle the DIDD sequence once per second thus deriving one-second variation values of the vector magnetic field. INTERMAGNET standards can thus be met applying Gaussian filtering as is already being done in our DCP digital systems which yield one minute values. Since we are presently involved with the data collection and adjustment of this instrument we do not have any data to present here. We have, however, every confidence that we will be able to achieve a quasi-absolute variation instrument which is inexpensive and adaptable for use anywhere in the world. The unit we have assembled for a short test in Tihany, Hungary in November, 1997 consists of an off-the-shelf 16-bit microcomputer data logger (*Fig. 4*). The microcomputer is located on an approximately 7 cm board with a PCMCIA adapter plugged into it. The actual CPU is located on a board directly beneath the PC Card on the left. The logging of the data is accomplished by initially storing it to RAM then to a high-capacity PC card. The microcomputer controls the entire operation with timing updated frequently from a Garmin GPS module which is on the vector board located in the center of the figure. The microcomputer triggers the GSM–19 with a pulse once each second and during this time it provides a control voltage to a DIDD generator shown on the right side of the figure. The DIDD generator provides current to the two coils in a specified sequence. During each of these 200 ms periods the GSM–19 polarizes the sensor, tunes to the approximate field value, records the field value and signal quality and forwards this information out its serial port to the microcomputer. *Figure 5* depicts the timing sequence of a one-second sample rate. The GSM–19 will cycle through the entire five value sequence in one-second. The microcomputer labels the data and forwards it to the PC card for storage.

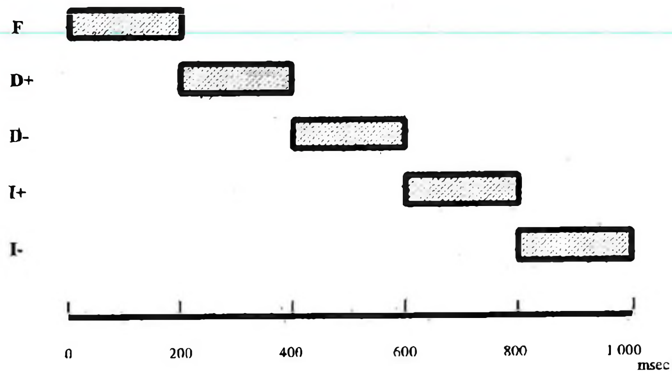

Fig. 5. DIDD timing sequence
5. ábra. A DIDD mérés idődiagramja

At the present time we are only recording the raw field values on the PC card which are later processed on a notebook computer into the field components of *H*, *D*, *Z*, *F* and *I*. The next logical stage will include processing the five field values into the field components, filtering the one second values into minute data and then storing the data on the PC card. In addition we intend to provide an LCD display of the magnetogram plot of the minute values and also to output this plot to a printer for a hard copy.

Acknowledgements

The authors wish to acknowledge financial support from the U.S.–Hungarian Science and Technolgy Joint Fund (JFNo.613). Without their sponsorship, this work would not have been possible.

REFERENCES

ALLDREDGE L. R. 1960: A proposed automatic standard observatory. J. Geophys. Res. **65**, pp. 3777–3786

ALLDREDGE L. R., SALDUKAS I. 1964: An automatic standard magnetic observatory. J. Geophys. Res. **69**, pp. 1963–1979

GREEN A. W. Jr. 1986: Remote, quasi-absolute geomagnetic station. Staff memo, 30 Jan. 1986.

PANKRATZ L. W. 1996: Test results on a Hungarian/U.S. Delta I – Delta D(DIDD) Quasi-absolute Spherical Coil System. VIIth IAGA Workshop on Geomagnetic Observatory Instruments, Data Acquisition and Processing, Niemegk, Germany, September 8–15, 1996.

WIENERT K. A. 1970: Notes on geomagnetic observatory and survey practice. UNESCO

A magyar–amerikai DIDD kvázi-abszolút rendszer története, fejlődése és jövője

Leroy W. PANKRATZ, Edward A. SAUTER, KÖRMENDI Alpár, HEGYMEGI László

A ma használt, szokásos földmágneses regisztráló rendszerek relatív műszerek, melyeknek bázisszintje az időben változik és amelyet abszolút műszerekkel végzett mérésekkel rendszeresen meg kell határozni. Ideális megoldást jelenthet abszolút műszerek használata az időbeli változás regisztrálására. Erre több kísérlet is történt az elmúlt harmincöt évben, de néhány hátrányos tulajdonságuk miatt ezek a műszerek nem váltak népszerűvé.

A földmágneses tér komponenesek protonprecessziós magnetométerrel történő méréséhez kitérítő tereket kell alkalmazni és egymás után több mérést végezni. Klasszikus protonprecessziós magnetométer esetében viszonylag ritkán lehet mérni és ez, különösen a tér gyors változásának esetében mérési hibát okoz. Egy másik probléma, hogy a protonprecessziós magnetométer szondája számára homogén mágneses teret kell előállítanunk. Ha a tér nem elég homogén, a protonprecessziós jel lecsengése túl gyors és így a mérés pontatlan lesz. A viszonylag nagy méretű protonmagnetométer szonda nagyméretű Helmholtz tekercseket kíván, ami viszont költséges, nem elég stabil és nehezen kezelhető.

A bemutatott megoldás reményeink szerint a fenti problémák nagy részére megoldást jelent.

ABOUT THE AUTHORS

Leroy W. Pankratz, photograph and biography not available at the time of publication.

Edward A. Sauter, photograph and biography not available at the time of publication.

Alpár Körmendi, for a photogprah and biography, see this issue, p. 132.

László Hegymegi, for a photogprah and biography, see this issue, p. 192.