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Long-Wavelength Magnetic Anomalies as a Source of Information About Deep Crustal Structure

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Abstract. The nature of long-wavelength magnetic anomalies ($\lambda = 60$–300 km) computed for the Ukrainian Shield from the original field by a continuation upward to a height of 10 km is studied. The correlation betweeen the regional anomalies, the crustal thickness and the topography of the Curie isotherm of magnetite is examined. The strongest correlation is established between the regional anomalies and the crustal thickness. Similar results have been obtained by us for the Baltic Shield and by D.H. Hall for the Canadian Shield. It is concluded that the entire lower crust is magnetized, the average magnetization being almost the same for all the ancient shields. These results have been used for the construction of a magnetic model of the earth's crust.

With some exceptions, the magnetization of the lower crust is found to be inhomogeneous and 5–10 times higher than that of the upper crust. Theoretical modelling and experimental results show a high magnetization in the entire sequence of blocks for the case of a thickened crust and, vice versa, weakly magnetized rocks correspond to a smaller thickness of the crust. The present approach may be of potential use for distinguishing and studying crust-upper mantle interaction areas as well as for predicting the topography of the Moho discontinuity.

Key words: Magnetic anomalies – Deep crustal structure – Magnetization of earth's crust.

1. Introduction

The problem of the nature of long-wavelength geomagnetic anomalies has been discussed for many years. Numerous publications offer different explanations for the anomalies with wavelengths of 60 to 1,600 km. These anomalies usually have been explained by a superposition of shallow sources, by the existence of local magnetized bodies, by anomalous thermodynamic conditions in the

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lower crust and upper mantle, or by the topography of the Curie isothermal surface of magnetite. A complete list of corresponding references may be found in Green (1976) and Krutikhovskaya (1976).

It is only in recent years that convincing data have been obtained for the Canadian and Ukrainian Shields indicating the relation of the long-wavelength anomalies to deep structure of the crust and upper mantle (Hall, 1974; Krutikhovskaya and Pashkevich, 1974; Krutikhovskaya, 1976). Conclusions have been drawn about a high and inhomogeneous magnetization of the lower crust and about possible applications of magnetic field studies to the solution of deep geology problems.

In the present paper the results of the long-wavelength magnetic component studies for the Ukrainian Shield are discussed. The studies have been carried out at the Institute of Geophysics of the Ukrainian Academy of Sciences.

The Ukrainian Shield was chosen for the investigation as the most favourable geologic region. The shallow Precambrian basement and the availability of data on the distribution of geologic units and on their magnetization make it possible to estimate the high-frequency anomaly effect and provide reliability to separating the magnetic component related to the deep crust.

It is very important that deep seismic sounding (Sollogub and Chekunov, 1975) and heat flow (Kutas, 1976; 1977) investigations have made it possible to study the relationship between the long-wavelength anomalies and both the crustal thickness and the topography of the Curie isotherm of magnetite.

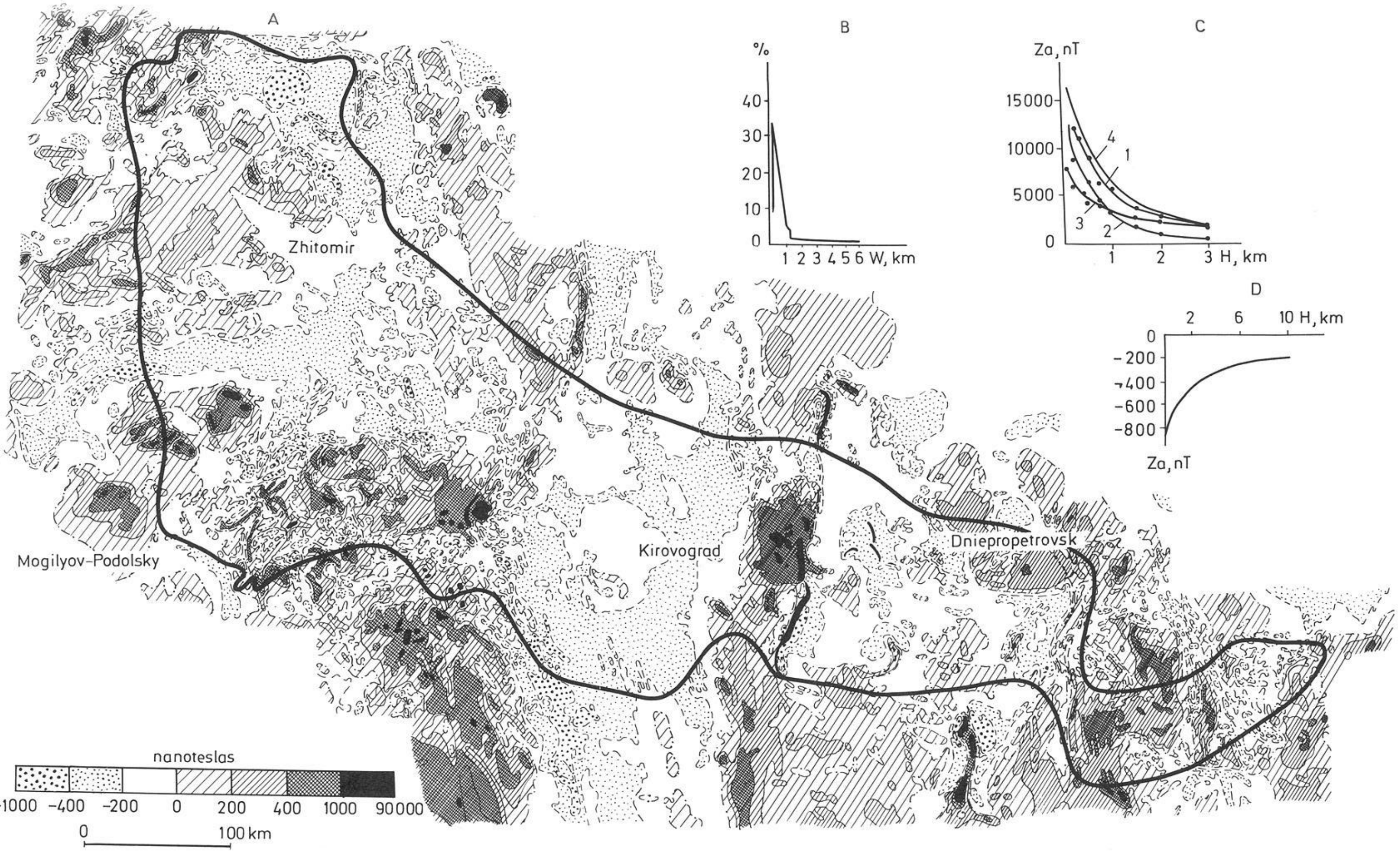
2. Given Data and Data Processing

The anomalous magnetic field of the Ukrainian shield region (Fig. 1a) reflects the block structure of the shield and varies from block to block in number, size, intensity, and dominant strike of the more local anomalies. As shown in Fig. 1b the main contribution to the magnetic field is made by anomalies with widths of no more than 1 km. On the other hand, the magnetic field includes a long-wavelength component with wavelengths of more than 60 km, the existence of which is confirmed by the zero-correlation radius value of the autocorrelation function. These anomalies are called regional ones by us.

The regional anomalies are separated from the local ones by upward continuation of the magnetic field to a certain height. This kind of filtering, compared with others, has some advantages. The main advantage is the possibility to study the attenuation of the amplitudes of the regional anomalies with increasing height of continuation and to compare them with that of the local anomalies.

For the separation of the regional and local anomalies an optimum height should exist where the local anomalies are negligibly small whilst the regional anomalies which are of course also attenuated are still as big as possible.

Fig. 1. A Map of the observed anomalous magnetic field (vertical component Z_a) for the Ukrainian Shield region (border of shield indicated by *thick line*); **B** Frequency distribution of widths of the anomalies shown in part A; **C** Dependence of strongest anomalies on height: 1–3 aeromagnetic survey data, for different parts of the Krivoy-Rog synclinorium; 4 calculated data, for Kremenchug synclinorium; **D** Like C, but for a conjugate negative anomaly from the Verkhovtsevo region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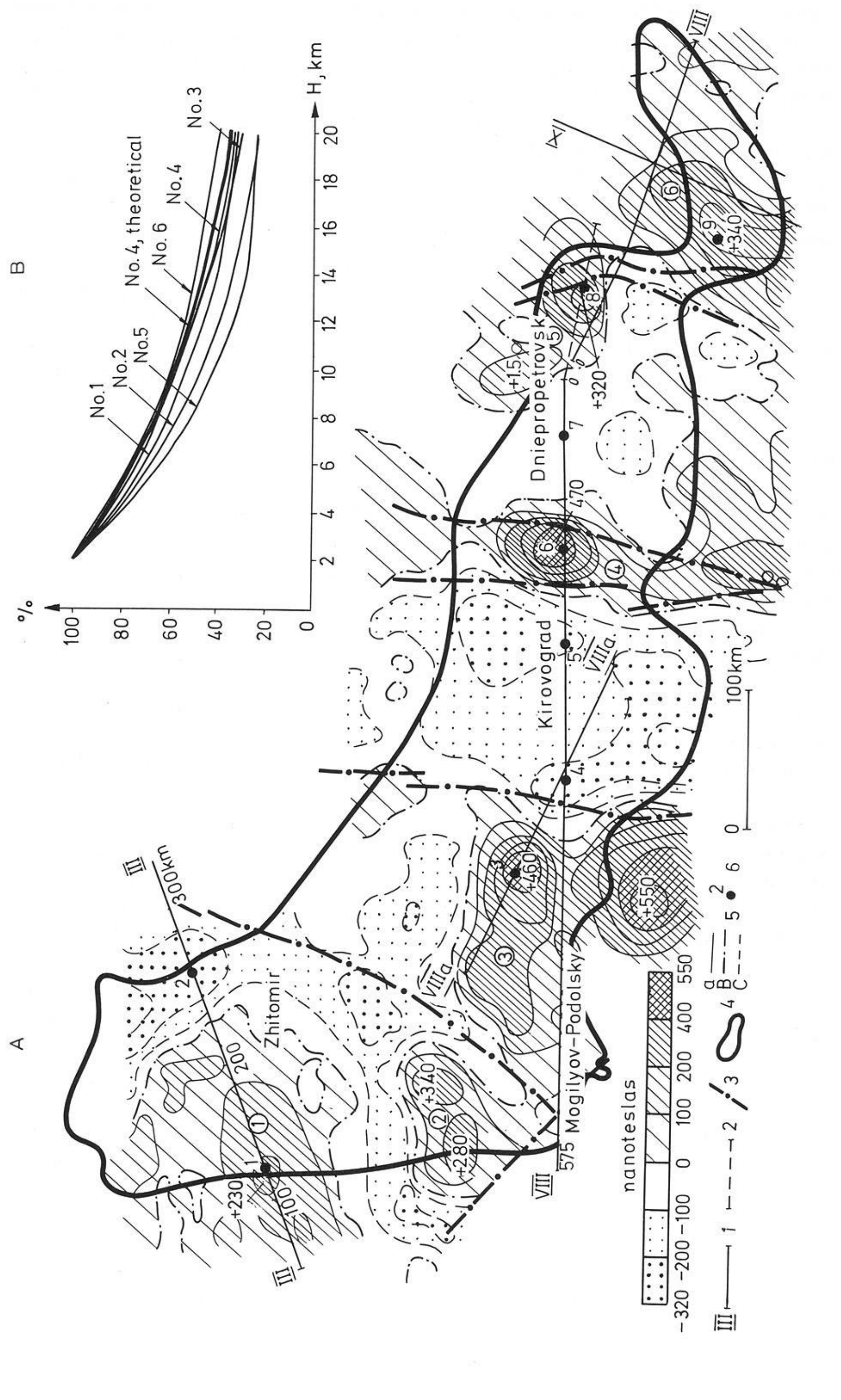
In Fig. 1c the attenuation of the strongest local anomalies within the area of investigation which are situated above the iron-bearing rocks of the Krivoy-Rog-Kremenchug synclinorium is shown. This attenuation is derived from the data of the aeromagnetic survey at different heights and from modelling results. As one can see at a height of 3 km even the biggest anomalies 5 km wide are reduced to 7%–17%. On extrapolating the rate of attenuation and taking into account the modelling data we have found that such anomalies disappear almost completely at a height of 10–15 km. It is reasonable to expect that, at this height, smaller and weaker anomalies should be completely suppressed.

Considering these facts, a height of 10 km was chosen as an optimum level for the field separation. For the purpose of upward continuation the original data were selected over a 2×2 km grid. Such a grid makes it possible to retain the main features of the original field. Anomalies exceeding ± 1000 *nT* – that is a threefold value of the field dispersion – were subtracted from the observed field in advance. However, as studies show, a quite large distortion of the regional anomaly field may be caused by conjugate wide weak lows. They are weaker than 1000 *nT*, but their widths are many times larger than those of the positive part of the anomalies. These lows are attenuated with height much slower than are the conjugate highs (Fig. 1c and d), and the rate of attenuation is commensurable with that of the regional component (Fig. 2b). Therefore when calculating the field at a height of 10–20 km it appears practically impossible to get rid of them (Pashkevich, 1976). The error of field continuation arising from the finiteness of integration varies from block to block and does not exceed 80 *nT*.

3. Results of Data Processing and Comparison to Other Geophysical Results

The derived Ukrainian Shield regional anomalies at a height of 10 km are represented in Fig. 2. Six positive regional anomalies with maxima up to 550 *nT* and with wavelengths from 60 to 300 km are found above the shield. In the upper right-hand corner of the figure the attenuation of these anomalies is shown. Compared with local anomalies (Fig. 1c) the rate of attenuation is much smaller. These anomalies were assumed to be produced by magnetized bodies at greater depths. The results of our interpretation show that this assumption corresponds well to our knowledge about the amount of magnetization of basic crystalline rocks and about the block structure of the lower crust (see below and Figs. 7 and 8). The negative part of the field includes lows the minimum of which reaches -340 *nT*. As may be seen, almost all of the

Fig. 2. A Map of the derived regional magnetic anomalies above the Ukrainian Shield. *Legend:* 1: deep seismic sounding lines; 2: eastern section of the line for which the magnetic model has been constructed; 3: deep-seated faults; 4: border of shield (cf. Fig. 1A); 5: magnetic field isolines (*a*: positive; *B*: zero; *C*: negative); 6: points used for study of correlation between regional field values and crustal thickness. **B** Dependence of regional anomalies (cf. *encircled numbers within part A*) on height. The *curve labelled No. 4, theoretical* has been calculated for a three-dimensional model of the source of this anomaly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regional highs are located in marginal zones of the shield or above deep-seated faults separating large blocks. An analysis of these anomalies in combination with deep seismic sounding data (Fig. 3) and with results of the upper crust magnetization studies shows that, in the area of the regional highs, the earth's crust is characterized by a higher magnetization of the basement rocks, a greater thickness and the presence of strong reflectors within the mantle ('duplicate'-surfaces according to Sollogub and Chekunov (1975)). According to Chekunov (1976) the layered character of the Mohorovicic discontinuity is caused by crust-mantle merging in the transition zone.

All the areas of an intensive increase of crustal thickness are confined to zones of deep-seated faults. Therefore it is natural to suppose that the magnetic highs are caused by highly magnetized rocks of basic and ultrabasic composition intruding into the fault zones. On the other hand, the correlation of the magnetic anomalies with crustal thickness holds as well for the areas where the M surface is being uplifted. These areas are characterized by minor magnetic anomalies and a predominance of relatively weak magnetization values of the upper crust rocks.

The statistical correlation between the regional anomalies and the crustal thickness as derived from deep seismic sounding is shown in Fig. 4a–d. The correlation coefficients range from 0.70 to 0.84. A higher value from 0.86 to 0.92 is obtained for the relict M surfaces represented by strong mantle reflectors found at depths of 50 to 70 km under the seismic profile VIII.

In Fig. 4e the general correlation between regional anomalies and crustal thickness as established for the whole area of the Ukrainian Shield is shown. The correlation coefficient is computed from the extremum values of the magnetic field and corresponding values of crustal thickness. The corresponding points are shown in the Figs. 2 and 3, respectively. The correlation coefficient amounts to 0.68. This low value may be explained by the following fact: Seven anomalies out of nine correlate with the Moho topography. The value of the correlation coefficient grows up to 0.97 if the points Nos. 6 and 9 are left out of consideration. Any relationship between the regional anomalies and the crustal thickness is not found for these points. There are reasons for excluding these points from the calculation. They belong to anomalies Nos. 4 and 6 (cf. numbers encircled in Fig. 2). A deep origin of the anomaly No. 4 has been proved by Krutikhovskaya et al. (1973). However, the deepest trough in the Moho surface is restricted to the eastern part of the anomaly. There is another version of the deep seismic sounding data interpretation for this region (Pavlenkova, 1973). Therefore, a further detailed study of the position of the crustal bottom is necessary here.

In the case of anomaly No. 6, the position of the Moho discontinuity is not convincingly defined here because the deep seismic sounding profiles cross only the marginal parts of the anomaly (see Fig. 2). Therefore the source of the anomaly is still to be studied.

In Fig. 4f the correlation between the regional magnetic anomalies and the crustal thickness is systematically shown for different ancient shields. For the Soviet part of the Baltic Shield the data were obtained by us along the Sortovala-Belomorsk profile. For the western part of this Shield we have used the data

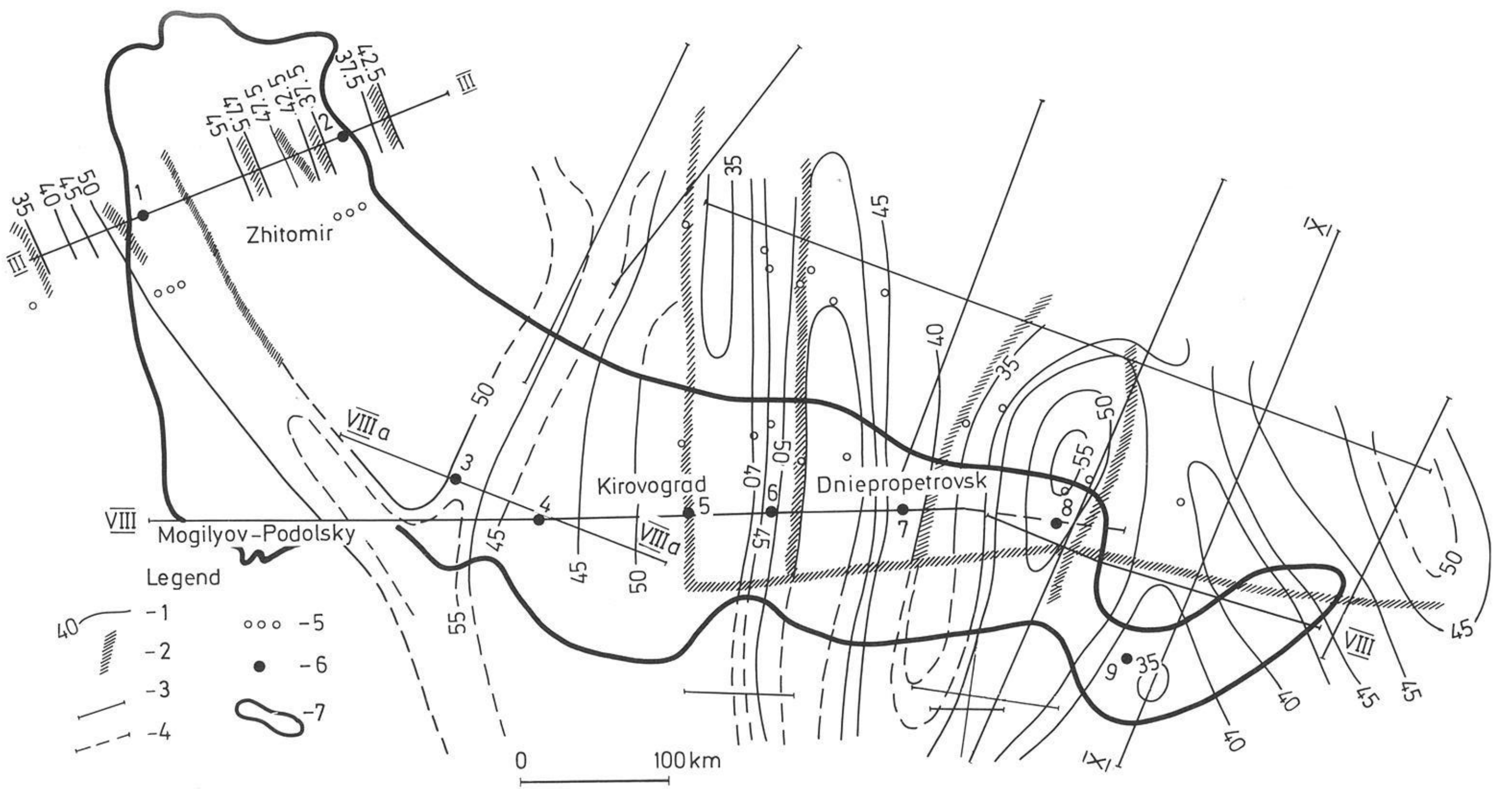


Fig. 3. Map of the Moho topography within the Ukrainian Shield region for the end of the early Proterozoic, after Sollogub (1975). *Legend:* 1: lines of equal depth (as indicated by numbers, in km); 2: faults in the *M* discontinuity; 3: deep seismic sounding lines; 4: eastern section of the line for which the magnetic model has been constructed; 5: points where the depth to the *M* discontinuity has been determined; 6: points used for study of correlation between the regional magnetic field and the depth of the *M* discontinuity; 7: border of shield (cf. Fig. 1 A)

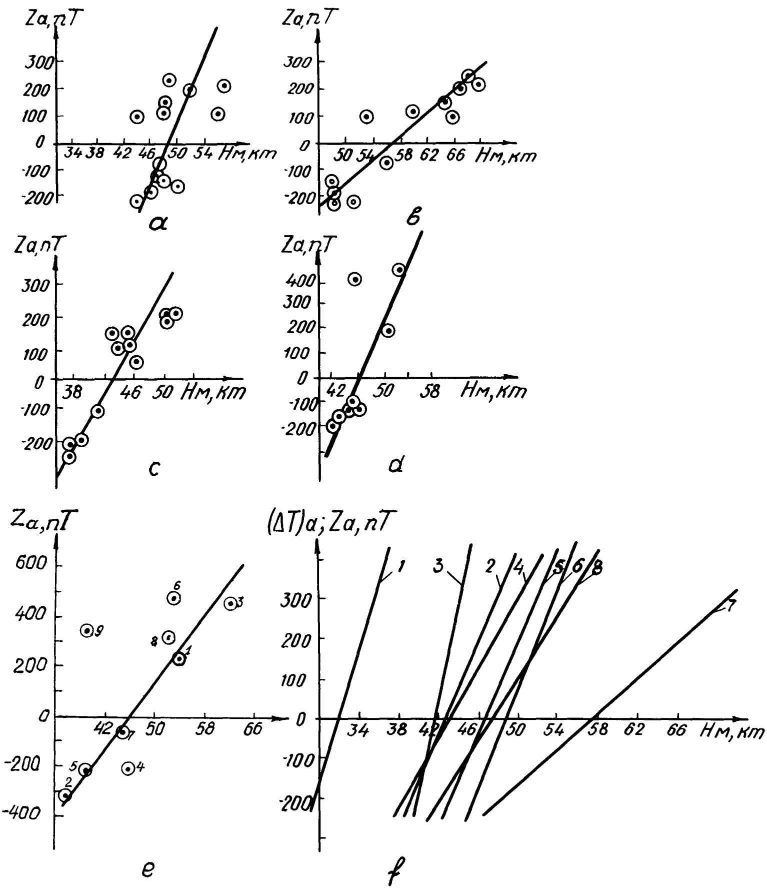


Fig. 4. Graphs showing the correlation between the regional magnetic field (Z_a or ΔT_a) and the crustal thickness (H_M); *a*: deep seismic sounding line VIII, western section; *b*: same line, but for lower positions of *M* discontinuity (horizon B of Fig. 7); *c*: seismic sounding line III; *d*: deep seismic sounding line VIIIa; *e*: whole area of Ukrainian Shield; *f*: ancient shields, with 1: Canadian Shield (Hall, 1974); 2: eastern part of Baltic Shield; 3: western part of Baltic Shield (data from (Vogel and Lund, 1970)); 4–7: parts of Ukrainian Shield, (4 corresponds to part c, 5 to part d, 6 to part a, 7 to part b of this figure); 8: whole Ukrainian Shield (generalized)

reported by Vogel and Lund (1970) for the Trans-Scandinavian deep seismic sounding profiles and the regional magnetic anomalies map published by Riddihough (1972). For the Canadian Shield the correlation has been presented by Hall (1974). A consideration of these data leads to the conclusion that the lower crust of shields is composed of magnetized rocks in such a way that the anomalous magnetic field reflects the Moho topography. However, an analysis of our results for the Ukrainian Shield shows that the regional anomaly No. 4 (Fig. 2) exhibits an exception from this rule. It is located at the border between Precambrian blocks of different age.

The stated statistical correlation between regional anomalies and crustal thickness raises, above all, the question whether this connection is functional that is, whether the M boundary separates magnetic and nonmagnetic rocks such as, for example, hyperbasite and altered hyperbasite. This suggestion has been checked by various methods, especially by an analysis of the temperature distribution data reported for the Ukrainian Shield crust by Kutas (1976; 1977) and Gordienko (personal communication). The results of the two authors are based on the same original data on heat flow, but when calculating the temperature field different values of the mantle heat flow were adopted. Accordingly, both authors arrived at different results on the topography of isotherms within the crust and, especially, the upper mantle. However, the temperature ranges derived for the M surface were almost the same. They varied from 320°–350° to 540°–575°.

The heat flow change along the deep seismic sounding line VIII, and the corresponding temperature distribution within the crust are shown in Fig. 5. The accuracy of the temperature determination is indicated by hatching. Apparently, a temperature of about 400° C corresponds to the average depth of 40 km of the Moho discontinuity. Both versions of the 575° C isotherm shown suggest that, almost everywhere, the Curie point isotherm of magnetite is estimated to be situated below the Moho. Such thermal conditions justify the assumption that both the lower crust and upper mantle may be magnetized. Therefore the relationship between the regional magnetic anomalies and the depth to the Curie isotherm of magnetite shown in Fig. 5 was studied. The correlation between them seems to be weaker than the correlation of the regional anomalies with crustal thickness.

Previously, the magnetic effect of the earth's crust has been calculated by us assuming the bottom of the magnetized layer at 40 km depth and a magnetization of 4 A m^{-1} below the Conrad discontinuity (extended reflector).

In order to estimate the effect of the bottom of magnetic masses the thus derived effect was subtracted from the regional magnetic anomalies. It has been found that the residual anomalies correlate with the depths of the Curie isotherm of magnetite according to Gordienko (see above, and Fig. 5), the correlation coefficient amounting to 0.80 (Krutikhovskaya and Pashkevich, 1976). However, for the crustal temperature distribution derived by Kutas (1976; 1977; cf. Fig. 5) the correlation coefficient is only 0.45.

We may conclude, that the problem of the upper mantle magnetization cannot be solved unambiguously with the present accuracy of temperature determinations for the crust and upper mantle. At the present stage of studies the correlation between the regional magnetic field and the crustal thickness established for the Ukrainian and other shield regions does not contradict to the assumption that the bottom of the magnetized masses coincides with the Moho surface.

4. Construction of a Model and Geological Implications

The former conclusion has been accepted by us as a basis for constructing a magnetic model of the earth's crust of the Ukrainian Shield. For this purpose the magnetization of different parts of the crustal section along the deep seismic

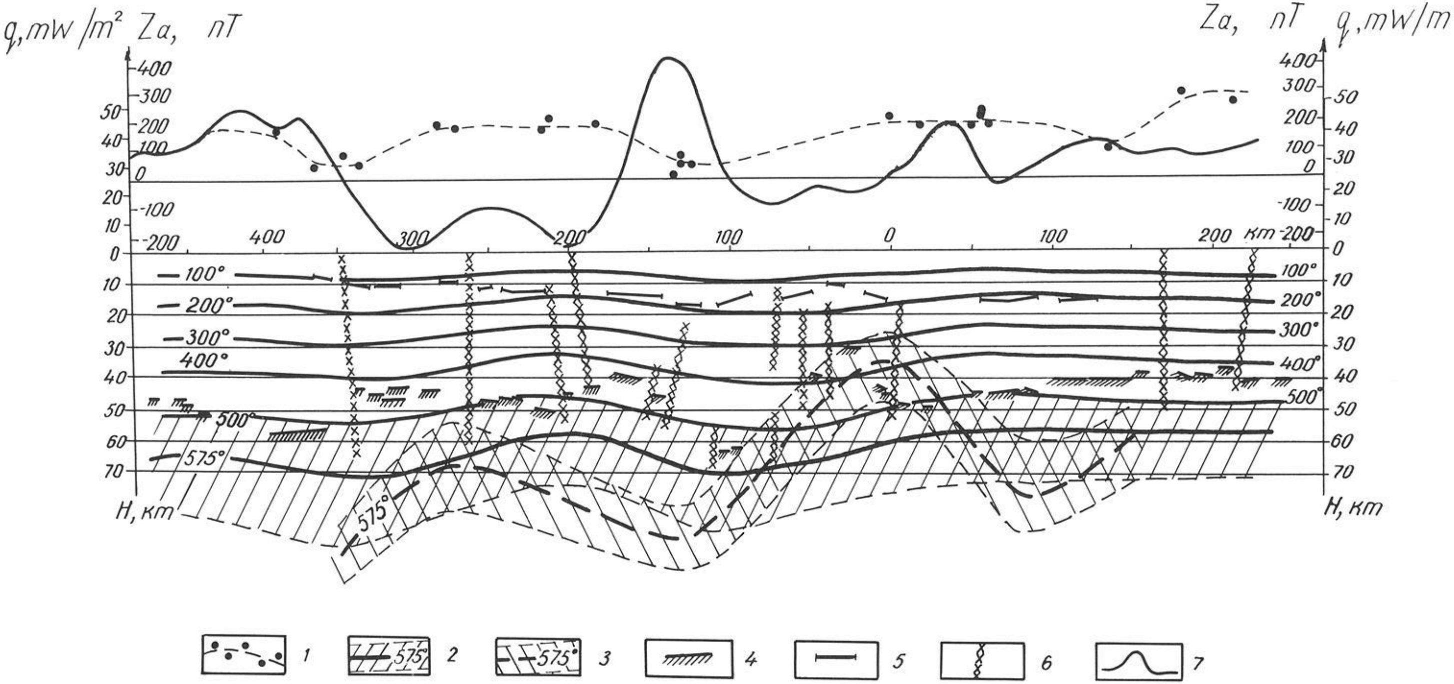


Fig. 5. Regional magnetic field (Z_a), heat flow (data from geothermal line Taganrog-Golovanevsk (Kutas, 1977), crustal seismic reflectors (Sollogub and Chekunov, 1975), and calculated temperature distribution within earth's crust, along the deep seismic sounding line VIII. *Legend:* 1: heat flow; 2: isotherms, partly with errors (*shaded*), according to Kutas (1977); 3: 575° C isotherm (with errors indicated) according to Gordienko (personal communication); 4: *M* discontinuity; 5: seismic boundaries within crust; 6: deep-seated faults; 7: regional magnetic field

sounding lines III and VIII was estimated. The magnetization of the granite-gneissic layer was determined from magnetic susceptibility measurements of the rocks outcropping on the crystalline basement surface and from results of the magnetic anomalies interpretation. The ratio of the remanent magnetization to the induced one as derived from the experimental data is 1. The average magnetization values in different blocks of the Ukrainian Shield range from 0.1 to 0.5 A m^{-1}. The average value for the granite-gneissic layer is extended to depth down to a long reflecting horizon which, probably, marks the lower boundary of the most intense folding of this layer and, correspondingly, the limit depth of the lower edges of the sources of local magnetic anomalies.

In estimating the lower crust magnetization the general results on composition and ferromagnetic content of deep-seated rocks have primarily been used. Most of the investigators in the Soviet Union believe that the lower crust is composed of various sedimentary-volcanic complexes with predominance of basic and intermediate rocks both metamorphosed to the granulite facies, and essentially nongranitized. These rocks probably consist of charnokite, amphibolite, and eclogite-like formations. The general tendency of basicity to grow with depth is confirmed by the corresponding seismic velocity increase.

According to Kalyaev (1976) the ophiolitic association of the Ukrainian Shield representing the ancient oceanic crust is composed of amphibolite, gabbro-amphibolite, gabbro-peridotite, pyroxene gneiss and associated orthoschists alternating with highly metamorphosed pelitic rocks. The high total content of iron in sedimentary, effusive, and intrusive primary rocks of the ophiolitic association has resulted in its separation in the form of magnetite as a result of the subsequent metamorphism. Nalivkina (1976) recognizes several stages in the process of magnetite formation. In the Archean, it had a regional character with transformation of basic rocks from the ophiolitic association into the charnokite association. Several stages are stated by the author for the early Proterozoic as well.

As follows from the data reported by Christencen and Fountain (1975), the lower crust is composed mainly of granulite facies rocks and has lateral inhomogenities in chemical and mineralogical composition.

The observation of the high magnetization of the lower crust corresponds to the results of experiments on the thermodynamic conditions of the occurrence of magnetite. Our conclusion on the magnetization of the lower crust is also supported by the existence of a correlation between density and magnetization of widely developed rocks of various metamorphic facies and by the existence of magnetic inhomogeneities within the lower crust as derived from the interpretation of regional anomalies. By accepting a direct relationship between the seismic velocity and the density of rocks and by basing on the relation between magnetic susceptibility and density, a magnetization increase with depth may be deduced. Numerous experimental and published data have been used in studying that relation. Sedimentary-volcanogenetic rocks of granulite facies and intrusive rocks of normal line have been investigated (Fig. 6). For intrusive rocks, the correlation between susceptibility and density was studied by the SiO_2 content.

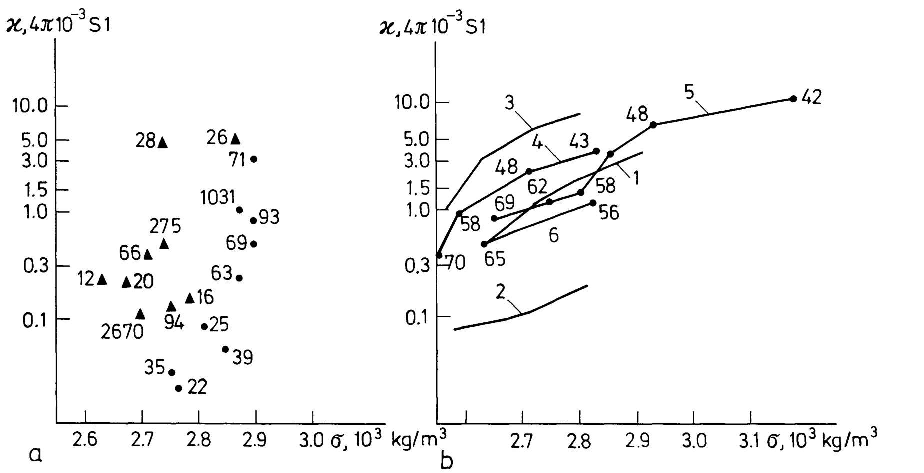


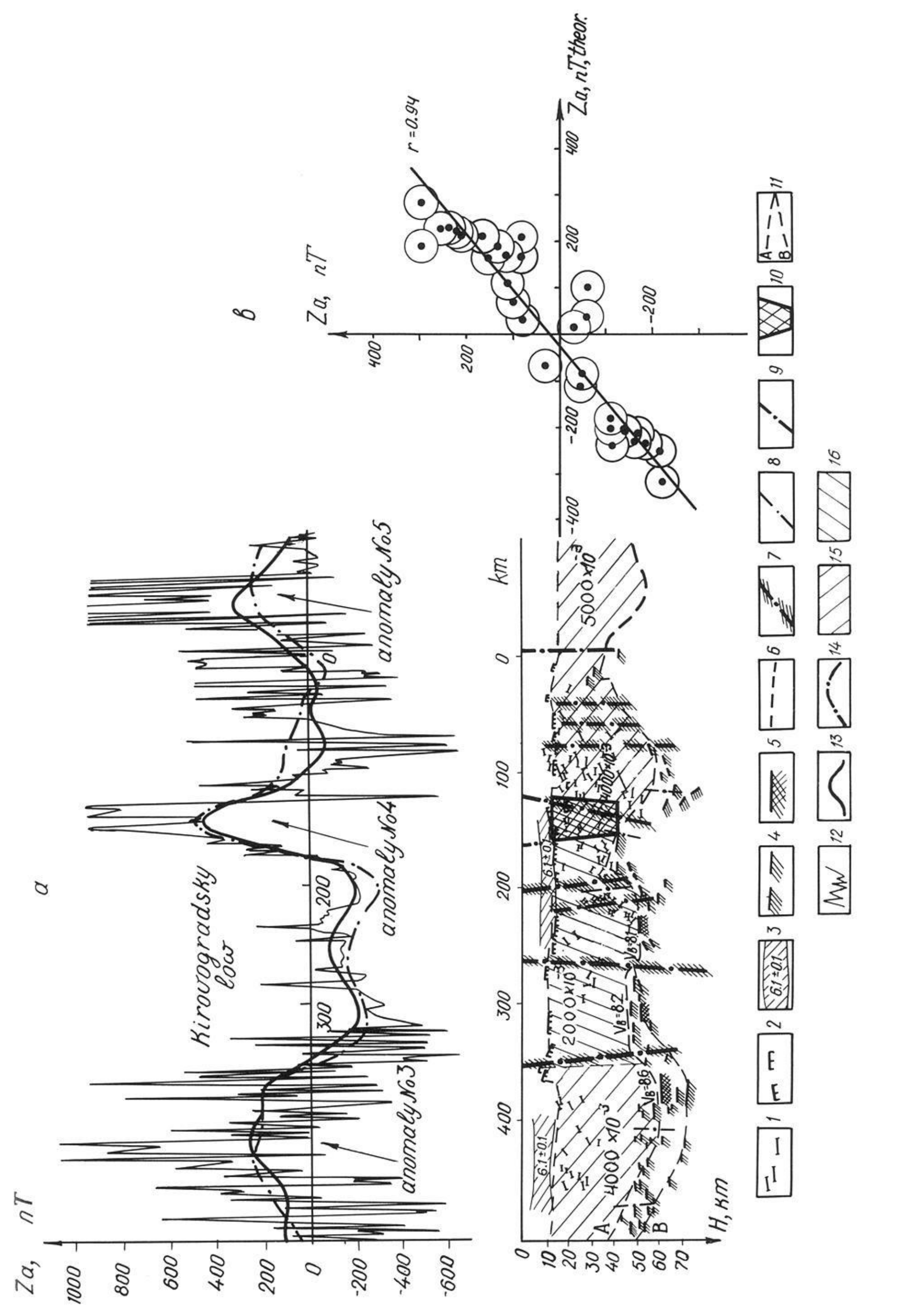
Fig. 6a and b. Graphs demonstrating the correlation between the magnetic susceptibility and the density. **a** Rocks of granulite facies from Ukrainian Shield: ● pyroxene plagioclase gneiss, garnet pyroxene plagioclase gneiss, hypersthene gneiss (1949 specimens); ▲ charnokite (3207 specimens. Average κ- and σ-values for uniform data sets have been used; numbers indicate numbers of specimens which have been averaged. **b** Intrusive rocks: 1: gabbro-diorite-granodiorite formation; 2: granite formation; 3: granite-granosyenite formation (1–3 according to Dortman, 1976) magmatic rocks of normal line according to Semyonova, 1973); 4: abyssal rocks; 5: hypabyssal rocks; 6: effusive rocks. Numbers indicate SiO_2 content (%)

The use of the aforementioned data and the following modelling of the magnetic effect enable us to determine the possible limits of the magnetization values for the lower crust. The average value ranges from 0.3 to 4 A m^{-1}, reaching 6–7 A m^{-1} in certain blocks. The magnetic data thus independently lead to a conclusion about the chemical and mineralogical inhomogeneity of the lower crust.

According to the experimental data the maximum depth at which the formation of the ferromagnetic minerals took place is believed to be 50–60 km (under a pressure of 15–18 kbar). Hence, the magnetization values obtained for the rocks in the lower crust may be considered valid for the entire of its thickness.

Direct modelling included the determination of the magnetic effect of the whole crust along the deep seismic sounding lines III and VIII (Figs. 7 and 8).

Fig. 7. a Magnetic model of the crust along the deep seismic sounding line VIII. *Legend:* 1: crustal reflectors; 2: extended refracting horizon; 3: low velocity layer; 4: *M* discontinuity reflectors; 5: *M* discontinuity refractors (V_B indicates sub-Moho seismic velocity, in km s^{-1}), 7: deep-seated large faults according to deep seismic sounding results; 8: same as 7 but minor faults; 9: faults derived from other geological and geophysical data; 10: deep reaching zone with magnetization 6 A m^{-1}; 11: averaged *M* discontinuity position used for studying correlation with regional magnetic field; *A*: position like in Fig. 3; 12: observed magnetic field (Z_a); 13: magnetic field calculated from the observed field for a height of 10 km; 14: magnetic field calculated for the same height from the magnetic model of the crust; 15: rocks with magnetization 4–5 A m^{-1}; 16: rocks with magnetization 2 A m^{-1}. **b** Graph showing correlation between the magnetic field (Z_a) at 10 km height as calculated from observed field and magnetic field ($Z_{a,\ theor.}$) at same height corresponding to the magnetic model of the crust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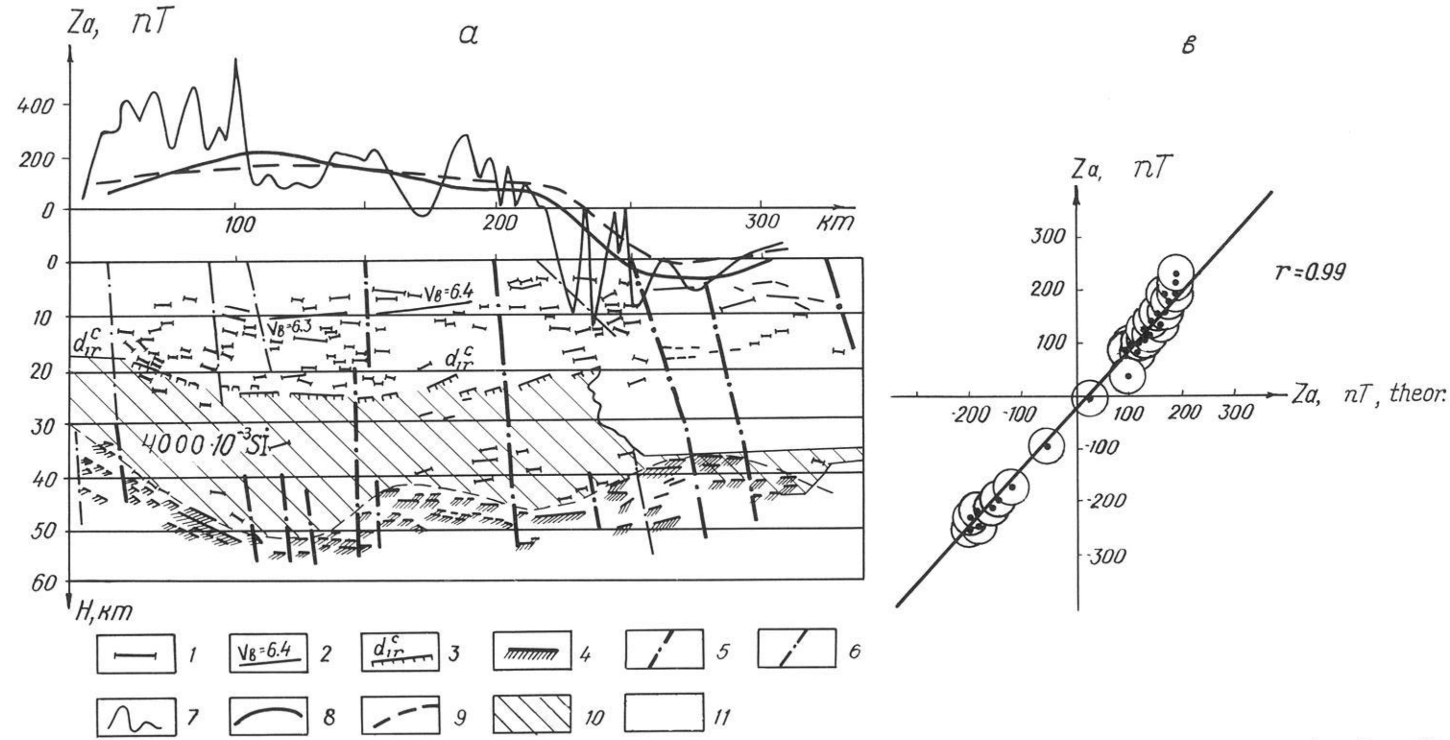

Fig. 8. Same as Fig. 7, but for deep seismic sounding line III. *Legend:* 1: crustal reflectors; 2: reflectors and boundary velocity values (km s^{-1}); 3: extended refracting horizon; 4: Moho; 5: deep-seated large faults from deep seismic sounding results; 6: same as 5 but minor faults; 7–9: same as legend numbers 12–14, respectively, within Fig. 7; 10: rocks with magnetization 4 A m^{-1}; 11: rocks with average magnetization 0.3–0.5 A m^{-1}

Average magnetization values for the upper crustal section of large blocks were estimated, as mentioned, from the experimental data and from results of the magnetic field interpretation. However, as calculations show, the effect of the upper crust at a height of 10 km falls within the error of the regional anomalies separation. Hence, the field produced by the entire crust corresponds actually only to the effect of the lower crust.

The ambiguity in estimating the magnetization has necessitated a discussion of two versions of the magnetic model, with the effective magnetization of large blocks remaining at a constant value.

A magnetization of the lower crust with values relatively smaller than in the adjacent blocks is found under the central part of the deep seismic sounding profile VIII in the area of the Kirovogradsky regional low (Fig. 7). In this block the upper crust is composed of weakly magnetized rocks of various origin including intrusive rocks. A pluton of intrusive rocks of acid and basic composition was formed during the final platform stage of the shield evolution.

The closest correlation between theoretical and original profiles of the regional magnetic anomalies has been obtained with the magnetization distribution within the lower crust as shown in Fig. 7a. The correlation coefficient is 0.94 in this case (Fig. 7b). The correlation is interrupted in the eastern section of the deep seismic sounding line at the location of anomaly No. 5. When modelling we did not intend to reach a complete coincidence of theoretical and original data since too many aspects of structure, petrology and magnetization of rocks as well as thermodynamic conditions within the earth's crust have not been thoroughly studied up to now.

In constructing the magnetic model along the deep seismic sounding line III (Fig. 8a) it is necessary to assume that the magnetization of the lower crust under the eastern section of the line is commensurable with the upper crust magnetization and amounts to $0.5\ \mathrm{A\ m^{-1}}$. According to deep seismic sounding data, in the area of the Moho discontinuity rise reflectors are absent in the lower crust and the extended reflecting horizon previously regarded as a boundary between the upper and lower crust is not found. Here, on the Precambrian basement, a large pluton of acid and basic weakly magnetized rocks has been mapped. This pluton, alike to one in the Kirovogradsky block, was formed also during the platform stage of the shield evolution. This suggests that weakly magnetized rocks build up the earth's crust down to a great depth, and that the lower crust is of intrusive nature like the upper crust. The correlation coefficient of the original profile with the theoretical curve for the given distribution of the crustal magnetization is 0.99 (Fig. 8b).

5. Conclusions

The results of the regional anomalies studies for the magnetic field of the Ukrainian Shield lead to the following main conclusions:

Regional magnetic anomalies with a wavelength between 60 and 300 km reflect, primarily, crustal thickness, allowing thus to predict the Moho topography.

The magnetization of the lower crust is not homogeneous and, generally, is considerably larger than the magnetization of the upper crust. An abnormally high magnetization of the entire crustal sequence is observed in zones with a thicker crust. On the basement surface, these zones are represented by the products of metamorphism and granitization of the most ancient predominantly magmatic and sedimentary-volcanic rocks of ophiolitic association.

Blocks with a thin crust are characterized by the lowest magnetization. The upper parts of these blocks are mostly represented by the products of metamorphism and granitization of the pelitic rocks and by plutons of gabbro-anorthosite and rapakivi granite. The lower crust in these blocks is likely to be composed of andesite and anorthosite.

The close correlation between the magnetization of the upper and lower crust reflects the processes of the crust-upper mantle interaction. Taking into account the density-magnetization correlation on the one hand, and the interrelation between gravity and magnetic anomalies on the other hand, the conclusion may be drawn that the earth's crust of the Ukrainian Shield is isostatically balanced. The 'heavy' crust corresponds to the Moho surface depressions and the 'light' crust to the Moho uplifts. An analysis of the results obtained for the Ukrainian and Baltic Shields and the published data on the Canadian shield leads to the conclusion that, in general the types and major features established for the earth's crust of the ancient shields are similar.

The problem of the nature of the regional anomalies is of utmost interest and requires further investigations. This is especially important in connection with the application of the plate tectonics concept to studying the continental crust evolution.

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