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FULL PAPER

Sources of the lithosphere magnetic field based on magnetic data obtained at different heights

Yury P. Tsvetkov[1], Konstantin V. Novikov[2], Andrey A. Ivanov[3*] and Oleg M. Brekhov[4]

Abstract

Our investigations are based on the property that the fields of sources, whose depths are numerically equal to survey heights, are most brightly presented in the data of magnetic survey. Therefore, the magnetic field created by the upper boundary of the magnetically active layer is well presented in the data of magnetic surveys (survey heights are up to the first kilometres), whereas the geomagnetic field of the centre mass is well presented in the data of gradient magnetic surveys at heights of 20–40 km. These data were used separately for the interpretation of the depths of the upper and lower boundaries of the lithospheric magnetically active layer by spectral methods. This fact is especially valuable for estimating the positions of deep sources. For the central part of the East European platform, we obtained by spectral methods, the following values: the depth of the upper boundary of the layer is 8.5 km and that of the lower boundary of the layer is 64.3 km. The discrete localisation of the source depths along the profile is performed by the methods of converting the initial information into transformed fields, continuation upward, and reduction to the pole with the determination of singular points. The Poisson integral, representing the solution of the outer Dirichlet problem for the plane, served as a theoretical base for such an interpretation. These approaches made it possible to determine more exactly the localisation of deep sources along the profile and showed that the published magnetic maps based on aeromagnetic data do not contain in full measure the fields of deep-seated magnetic sources.

Keywords: Crustal magnetic anomaly, Balloon magnetic surveys, Depths of anomalous magnetic field sources, Curie point depth

Introduction

One of the main problems associated with the investigation of potential fields of the solid Earth is the determination of parameters of magnetic anomaly sources. The anomalous magnetic field is presented by analytical models and graphical (digital) ground-based maps (e.g. VSEGEI 2004; GSJ and CCOP 1996). These maps are based on data of aeromagnetic survey at a low height of flight (first hundreds of metres). The data of such a survey contain highly intense local anomalies from near-surface sources. However, the cited maps do not represent in full measure the fields of deep sources, which are several orders smaller than local anomalies produced by near-surface sources (Tsvetkov et al. 2015). That is why the fields of deep sources become lost in the process of constructing the maps presented in VSEGEI (2004), GSJ and CCOP (1996). In support, it is written in the book (Pecherskii 1994) that deep sources substantially contribute to MAGSAT anomalies but cannot completely explain their intensity. This implies a hypothesis about neglected fields of deeper sources. In order to study in detail the magnetic field of deep sources, it is necessary to perform magnetic surveys at heights of 20–40 km. Fields of these sources are most brightly presented in the data of magnetic surveys performed at the heights numerically equal to the depth of the sources under consideration. Thus, the geomagnetic field of the top of the lithospheric magnetically active layer is well presented in the data of aeromagnetic survey, whereas the geomagnetic field of the

*Correspondence: biwolf@mail.ru
[3] Russian State Geological Prospecting University (MGRI-RGGRU), Miklukho-Maklaya Str. 23, Moscow, Russia 117997
Full list of author information is available at the end of the article

mass centre of the sources is well presented in the data of magnetic survey at heights of 20–40 km. At these heights (20–40 km), the anomalous magnetic field is formed with natural averaging of local anomalies. At these heights, the averaged magnetic fields from surface and deep sources are of the same order.

One of the approaches to high-altitude magnetic measurements is proposed by Hildenbrand et al. (1996). However, we used stratospheric balloons as carriers because, first, they are capable of performing round-the-world flights in zonal airflows at heights of 20–40 km (Gorham 2013). Second, during the drift of stratospheric balloons, it is possible to obtain from them vertical differentials (or gradients) of the magnetic field produced by lithospheric sources.

The differentials of the main geomagnetic field obtained from analytical models for points spaced 6 km along the vertical line do not contain any appreciable regular error of these models, as well as models of the secular variation of the geomagnetic field. It follows from the fact that for the sources located at depths exceeding 3000 km, on rather a small distance between gradiometer sensors (6 km), these errors are practically identical and are mutually excluded in the process of calculating the differentials. Thus, magnetic differentials (gradients) of the anomalous geomagnetic field are more precisely identifiable than the anomalous geomagnetic field itself. It is especially important for estimations of centre depths of mass of magnetic sources in conditions of weakened magnetic field of the deep sources identified above the surface of the Earth.

The advantage of balloon gradient magnetic measurements on the vertically oriented measurement base 6 km long, lies in the fact that such measurements allow the reliable separation of magnetic fields into the normal and anomalous parts (the latter is the subject of our investigations) owing to the deep minimum in the fields of gradients (Tsvetkov et al. 1997). Thus, using the ground-based and balloon magnetic data, we can separately estimate the depths of sources of magnetic anomalies in the lithosphere.

Experiment

From the 1970s and up to now, we proposed and realised the project of gradient magnetic measurements onboard stratospheric balloons with the use of scalar magnetometers, having the measurement base 6 km long along the gravitational field (Tsvetkov et al. 1996a, b). In our opinion, as distinct from the opinion expressed in Nelson et al. (1992), it is possible to directly obtain vertical gradients of the anomalous magnetic field produced by deep sources only in the stratosphere by using the gradiometer measurement base equal to several kilometres (approximately 6 km). This task was realised and described in Tsvetkov et al. (2007a) and Brekhov et al. (2013). It was proved in Tsvetkov et al. (2015) that the use of the gradiometer with the measurement base equal to 6 km heights of 30 km makes it possible to obtain with certainty vertical gradient of the anomalous geomagnetic field generated by deep sources, which are located down to the lower boundary of the lithosphere.

Scalar proton magnetometers, whose sensors are insensitive to their azimuthal position, ensured the necessary accuracy of measurement of magnetic gradients with the use of rope systems. Deviations from the vertical line of the 6 km measuring base of the gradiometer, caused by possible disturbances in the carrying airflow attaining 1500 m (hodograph), were obtained experimentally. The method of correcting these deviations (based on the data of GPS receivers and the analytical model of the main geomagnetic field) is described in Tsvetkov et al. (2007b). Taking into account the height of balloon magnetic survey (30 km), only large regional structures can be reflected in the resulting anomalous magnetic field.

One of the described flights of the stratospheric balloon with the mounted gradiometer occurred on 22 March 2013 from the starting platform located in the city of Vol'sk, Saratov oblast. The balloon flew about 900 km (Vol'sk-Yuzhno-Uralsk), of which 700 km was at a height of about 30 km in the area of strike of the regional Kama-Embensk magnetic anomaly (KEMA). The route of this flight and that of the doubling flight in 2008 are presented in Fig. 1. The exclusive data obtained onboard the balloon show the scalar field (ΔF) and its vertical gradient (differentials on the base $3+3$ km). The results of magnetic surveys of 2013 and 2008 are presented as the exponent in Fig. 2. The experiment is described in detail in the author's publications (Tsvetkov et al. 2015, 2016).

The satellite magnetic profile ($H=400$ km) based on the data of the MF-7 model (http://geomag.org/models/index/html) was invoked into the analysis. Note that the magnetic anomaly at the height of 400 km (known as the satellite Kama-Embensk magnetic anomaly (KEMA), which is shown in Fig. 2) was identified from magnetic data of the MAGSAT satellite (Coles et al. 1982), and was supported by magnetic measurements performed aboard satellites launched subsequently. Consequently, this anomaly is the objective reality, and its parameters can be reasonably used in investigations. The balloon flight route crossed this anomaly in the eastern direction; the cross section of its intensity is shown in Fig. 2.

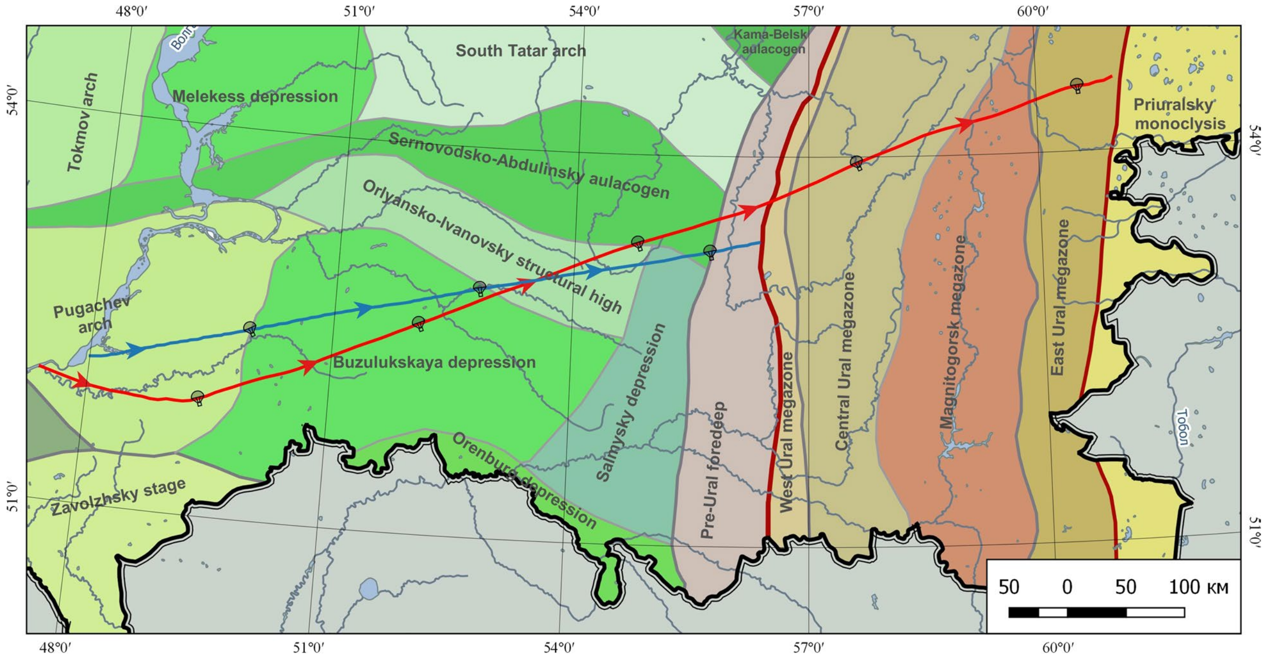

Fig. 1 Route lines of the stratospheric balloon magnetic survey in 2013 and 2008, and the tectonic scheme of the study area. The trajectory of flight is shown by a red colour for 2013 and a dark blue line for 2008

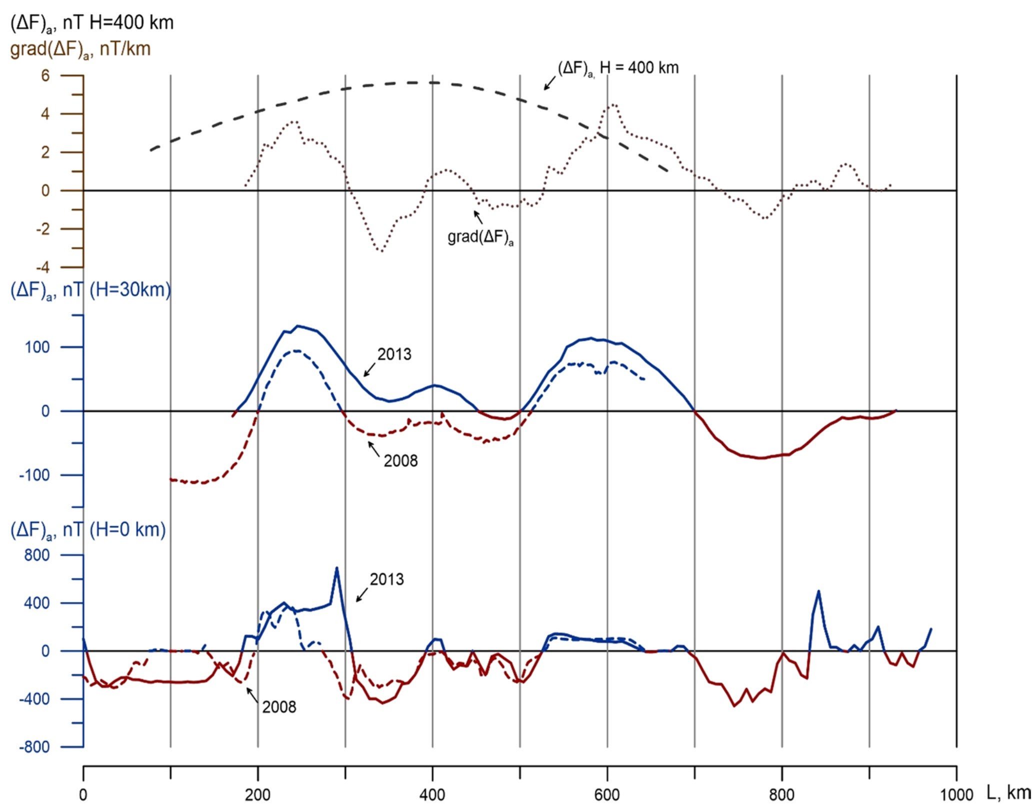

Fig. 2 Data of geophysical fields along the lines of flights of stratospheric balloons in 2008 and 2013. Results of the balloon magnetic surveys performed in 2013 and 2008, as well as the intensity of the satellite KEMA (top). The data of the ground-based magnetic surveys along the routes of the balloon flights in 2013 and 2008 (bottom) taken from maps (VSEGEI 2004) showing balloon flight routes

Methods

The methods applied for identification of magnetic anomaly sources are mainly based on the results of spectral analysis of their data. The method described in Spector and Grant (1970) is widely used for estimating the depths of geological objects (Gao et al. 2017; Tanaka et al. 1999), which will be considered in "Spectral analysis" section of this paper.

In the paper of Tanaka et al. (1999), two relations for the logarithms of spectra for high and low harmonic frequencies, respectively, were obtained from the general expression for the spectrum of the field of magnetic sources (Blakely 1995). According to these relations, the depths of the upper edge and the centre of mass of magnetic sources are obtained separately from ground-based data (GSJ and CCOP 1996). However, the estimation of depths in areas with a deep position of the Curie isotherm by using approaches described in Tanaka et al. (1999) and using the ground-based data array, can give erroneous results.

One of the methods, which was used for estimating the depths of objects, was based on the expression for the logarithm of the amplitude spectrum (Ivanov 1956). The spectrum of data of aeromagnetic surveys begins from harmonics with wavelengths of several hundred metres and is restricted by fields of medium-depth sources in the lithosphere. The spectrum of data of the balloon magnetic profile begins from 60 km harmonics (the doubled height of the survey) and has no restrictions by fields of deep sources in the lithosphere. Therefore, the high-altitude data virtually carry no reliable information about the position of upper edges of magnetic sources. However, they carry information about the centres of magnetic masses of these sources in the entire thickness of the lithosphere. In our opinion, unlike that presented in Tanaka et al. (1999), the method proposed by us, which is based on the separate use of ground-based and balloon magnetic data, in conditions of a deep position of the Curie isotherm, provides more accurate results. In this case, the upper boundary of the position of magnetic sources is determined from aeromagnetic data, whereas depths of the centre of mass are estimated from data of the balloon survey at a height of 30 km. The well-known estimate (Tanaka et al. 1999) for the boundaries of magnetically active layer of the lithosphere, according to the data of the anomalous magnetic field map, requires certain assumptions, which are not imposed in the method described in this paper. Note that the depths of magnetic sources calculated by spectral methods give the integral result along the profile. The depths along the profile can be localised by the methods of transformation of the initial information into the transformed fields, continuation upward, and reduction to the pole with the determination of singular points, which considerably widens the possibilities of solving the inverse problem (This will be considered in "Localisation of singular points" section of the paper.) In this paper, we localised the singular points by a combination of different methods (Berezkin 1988; Blokh 1998; Strakhov 1984; Troshkov and Groznova 1985). The Poisson integral, representing the solution of the outer Dirichlet problem for the plane, served as the theoretical basis for our interpretation, which was in turn based on the analytical continuation of the fields.

Spectral analysis

Spectra of the ground-based (VSEGEI 2004) and balloon magnetic profiles along the route of balloon surveys of 2013 are analysed in Tsvetkov et al. (2016) by the methods of wavelet analysis and Fourier discrete transform. Components with wavelengths of 300–550 km can be seen in the long-wavelength parts of the spectra for both of the profiles. Taking into account the fact that the active profile length (~700 km) insignificantly exceeds the periods of harmonics identified in the long-wavelength parts of the spectra, as well as the fact that the ground-based profile does not represent in full measure the fields of deep sources (see above), this method of spectral analysis of the ground-based magnetic profile makes it impossible to state with certainty that such harmonics are contained in the data under investigation. The patterns of inhomogeneities in the anomalous magnetic fields are obtained by the method of wavelet analysis of the balloon and ground-based magnetic profiles (Tsvetkov et al. 2016). Data of the balloon magnetic profile along the route are shown to contain inhomogeneities from 60 to 450 km in size, whereas the pattern of wavelet analysis based on the balloon magnetic data along the balloon flight route reveals a large inhomogeneity 450 km in size, which exactly coincides with the position of the maximum of the satellite KEMA cross section (52°E) (Tsvetkov et al. 2016). Such an approach with the use of an independent method demonstrates that the spectrum of data of the balloon profiles is saturated with low-frequency components, whereas such components are absent in aeromagnetic data, because the wavelet pattern constructed on the basis of aeromagnetic data is devoid of inhomogeneities, whose size exceeds 130 km (Tsvetkov et al. 2016).

The method of estimating the depths of objects from the amplitude spectrum is based on the relation for the logarithm of the amplitude spectrum, which was proved by Ivanov (1956):

$$H = -\lim_{\omega \to \infty} \sup \frac{\ln |(S(\omega, 0)|}{|\omega|}$$

This relation shows that the plot of the logarithm of the amplitude spectrum for the fields of such models at

$\omega \to \infty$ tends to the inclined asymptote with the equation (Blokh 1998; Serkerov 1991):

$$y = c - H|\omega|,$$

where H characterises the depth of the uppermost singular point of the function, and c is the free member of the linear function. The works of Spector and Grant (1970) have the same meaning. However, these authors use the energy spectrum.

Spectral analysis of the results of the balloon magnetic survey was performed in the framework of the InterSprect 1.0. program package (developed by Novikov, K.V. and Ivanov, A.A.). The package makes it possible to calculate the Fourier spectrum for profile surveys (in a moving window) and estimate the depths of upper edges of anomaly forming objects by the inclination angle of the asymptote of the amplitude spectrum logarithm for selected harmonics. It is shown in Tsvetkov et al. (2015) that the anomalous magnetic field at the height 30 km is mainly formed from fields of sources within the 100 km band on the Earth's surface. Repeated flights, due to a scatter of their trajectories, make it possible to obtain a wider band of surveys, i.e. to have a certain analog of the 3D survey for the data processing in a moving window. According to the programme, the interpretation of data is performed in the interactive regime. The equation of the asymptotic straight line is determined by the method of least squares.

The final result is given for the experiment of 2013, which had the longest distance of the balloon flight. First, the Fourier spectrum logarithm was obtained from map data (VSEGEI 2004) along the balloon flight route of 2013 (Fig. 3), and the depth was estimated from the inclination of asymptote of the logarithm of the spectrum. For this aeromagnetic survey, the logarithm of the amplitude spectrum has, in essence, only one asymptote in the entire range of frequencies. The depth of upper edges of sources is about 8.5 km (Fig. 3).

Figure 4 shows the logarithm of the spectrum for the balloon magnetic profile. The low-frequency region of this spectrum is characterised by the coefficients reflecting the inclination angle of the asymptote for the 2013 profile. This coefficient was equal to 66.4, which, taking into account the balloon flight height (~30 km), corresponds to the depths equal to ~36.4. The depths of lower edges of the lithospheric magnetically active layer were calculated by the formula: $Z_{be} = 2Z_{ac} - Z_{te}$, where Z_{be} is the depth of lower edges; Z_{ac} is the depth of the centre of mass; and Z_{te} is the depth of upper edges. According to this relation, the depths Z_{be} were equal to 64.3 km for the 2013 route.

Localisation of singular points

The interpretation of magnetic source depths by the methods of spectral analysis (described above) shows the average values of depths along the profile. Therefore, at the second stage of the interpretation, the data along the balloon flight route were localised by estimating singular points through a complex application of different methods (Berezkin 1988; Blokh 1998; Strakhov 1984; Troshkov and Groznova 1985). The singular points are closely related to the types and positions of field sources. The results are considered in the aggregate, which makes it possible to obtain the most accurate interpretation model correlated with respect to all of the methods.

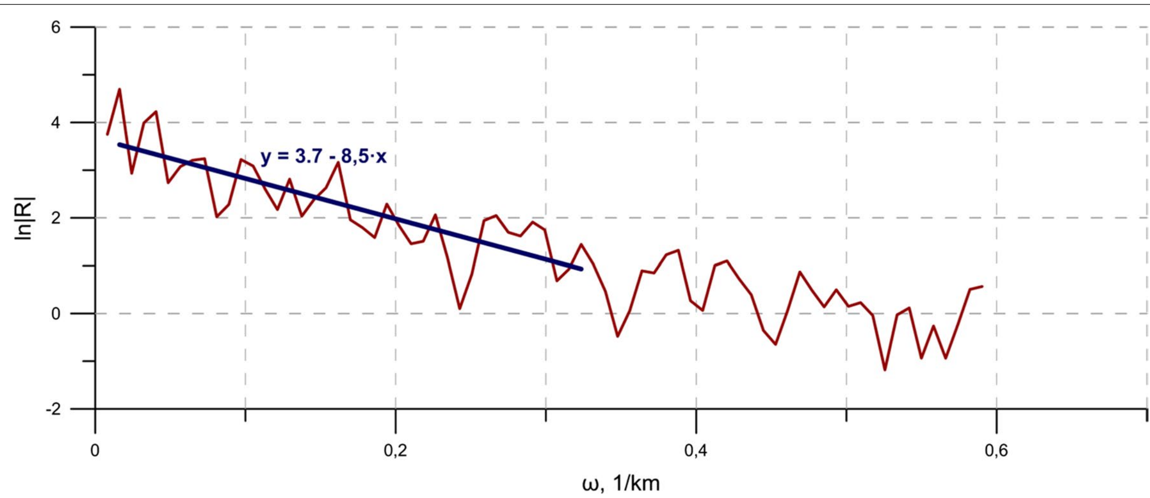

Fig. 3 Logarithms of the amplitude spectrum and the asymptote of the anomalous magnetic field from the data presented and map (VSEGEI 2004) for the balloon flight route of 2013

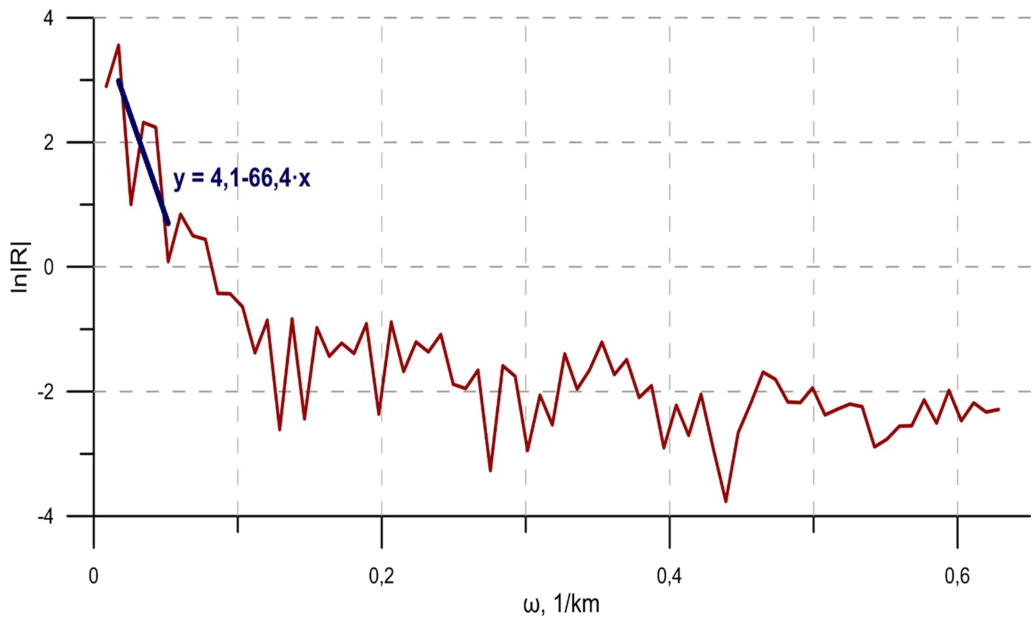

Fig. 4 Logarithms of the amplitude spectrum and the asymptote of the anomalous magnetic field obtained from the results of balloon magnetic surveys along the balloon flight route of 2013

The Lowille theorem states that if a function is analytical on the entire plane and restricted, it is constant. If such a function is not constant, it must have singular points. Therefore, if a potential field differs from the identical constant, i.e. contains anomalies, the function describing such a field must have singular points. In a singular point, the function loses its analyticity. Singular points of the functions, which describe magnetic anomalies, are related to the objects producing them and can carry information on the position and form of the object. For localisation of singular points, it is possible to continue the field for its derivatives to a number of levels in the vertical plane and extrapolate them downward to their intersection.

Consecutive differentiation of the function leads to a regular change of its singular points, whereas their positions remain constant. In the process of differentiation, singular points change in the following order: exponential-logarithmic point of branching, logarithmic point of branching, first-order pole, second-order pole, third-order pole, etc. Logarithmic points of magnetic field branching characterise the positions of the upper edges of the object. First-order poles of the magnetic field characterise edges of the equivalent plate at the level of the magnetic mass centre. The second-order pole of the magnetic field is related to the centre of mass. Upper singular points are stably localised in the anomalous field. In order to localise deeper points (the centre of mass and edges of the equivalent plate), it is necessary to continue the field into the upper half-space, which decreases the influence of upper singular points.

According to the Strakhov method (Strakhov 1984), the geomagnetic field and the first vertical derivative are approximately continued into the horizontal layer. The fields and their transformations are continued into the upper and lower half-spaces in the spectral form by transition from the functions themselves to the Fourier spectra. This method makes it possible to determine the upper singular point through the extrapolation of isolines of the continued field or its derivative downward, up to their intersection.

In agreement with the Berezkin method (Berezkin 1988), the singularities are localised by the continuation of the magnetic field. For the magnetic field, the modulus (scalar) is calculated at several levels. Then, for each point, the obtained function is divided by its mean value at the level under consideration. In order to determine the positions of singular points, a “pseudo cross section” should be constructed, which represents the map of isolines of the normalised function in the vertical plane. This method makes it possible to localise the upper singularities without determining their types.

Conforming to the Troshkov method (Troshkov and Groznova 1985), the positions and types of singular points are determined from the relations of three consecutive derivatives of different orders calculated at some reference points of the upper half-space (above the surface of observation), i.e. at places where the potential of the geomagnetic field and its elements are harmonic functions satisfying the Laplace equation. In this case, the singular points become poles of different orders. The pole order carries the information about the singular point of the initial field. The first order of the pole (+) corresponds to the vertex of a polygon. The second order (×) corresponds to the edge of a thin plate, layer. The third order (o) corresponds to the centre of magnetic mass of the object. The symbols in parentheses mean the orders of singular points as they are presented in the figures. The results obtained correlate well with the method of the field continuation into the horizontal layer, providing additional information about the depths of magnetic anomaly sources.

The results of complex application of the methods described above are presented as a model consisting of the map of isolines (the Strakhov method) and the positions of poles of different orders (the Troshkov method) and are given in Figs. 5 and 6.

The depths shown in Figs. 5 and 6 are less stable than those obtained from the interpretation by the methods of spectral analysis due to their integral result in the last case. This is also due to the fact that the data used in calculations are characterised by noticeable scatters, and "the error in the identification of anomalies is determined, first of all, by the representativity of the initial data" (Simonenko 1976). Thus, the diagram shown in Fig. 5, which is constructed from the map data (VSEGEI 2004), stably indicates the depths of upper edges of magnetic anomaly sources and does not follow the depths of centres of magnetic mass, because the latter nearly coincide with the depths of upper edges in the process of interpretation. This additionally points to the fact that the fields of deep sources cannot be presented in the data map (VSEGEI 2004).

Geological interpretation of the results

The data of balloon gradient magnetic surveys at the height ~ 30 km make it possible to identify in full measure all magnetic fields of deep sources in the lithosphere up to its base, which allows us to calculate real depths of lower edges of the lithospheric magnetically active layer and, consequently, the depth of the Curie isotherm. It has made it possible for the first time to construct more complete and accurate maps of the Curie isotherm from balloon gradient magnetic data than the maps obtained previously.

The diagrams (Fig. 7) are obtained as the generalised result of investigations. This figure presents the results of interpretation by the Strakhov (isolines of the continued magnetic field) and Troshkov (poles of

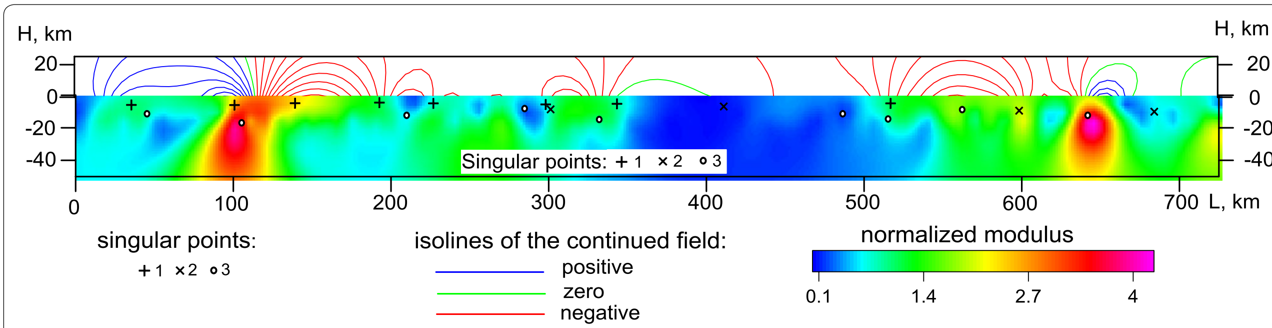

Fig. 5 Results of determination of the singular points along the balloon routes of 2013 from the anomalous magnetic field taken from map (VSEGEI 2004)

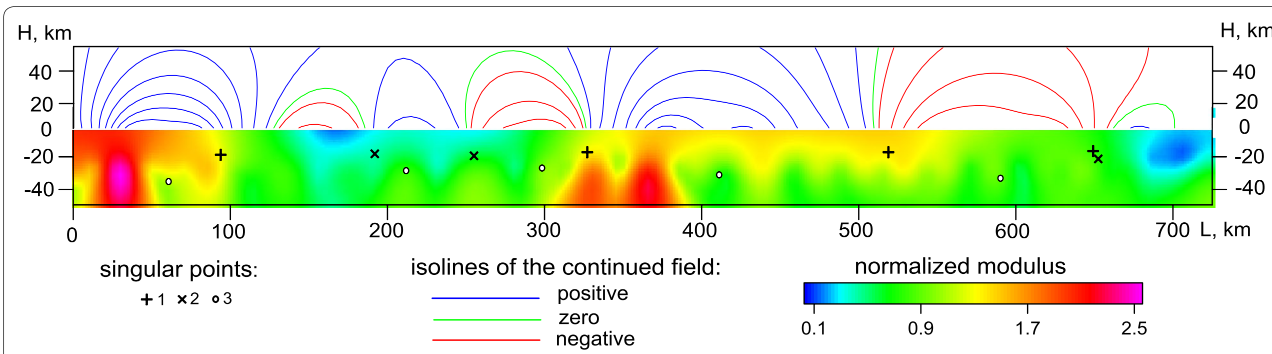

Fig. 6 Results of determination of the singular points along the balloon routes of 2013 from balloon magnetic data

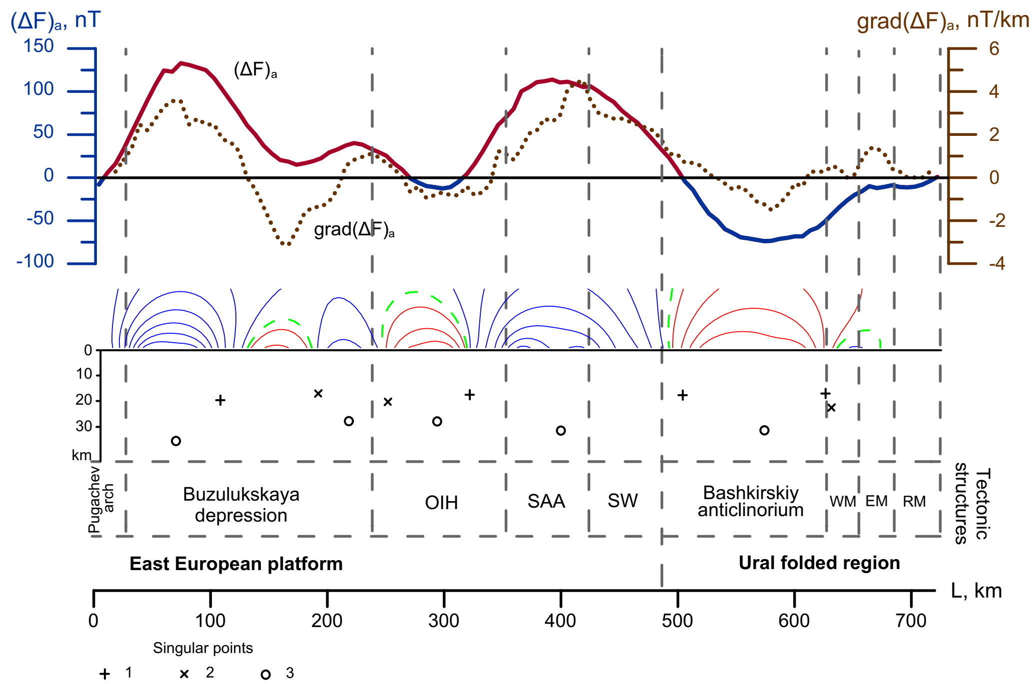

Fig. 7 Example of interpretation of the results of balloon gradient magnetic surveys along the balloon flight route in 2013. *OIH* Orlyanka-Ivanovo structural uplift, *SAA* Sernovodsk-Abduleno aulacogen, *SF* Sterlitamak foredeep, *WM* West-Magnitogorsk monoclinorium, *EM* East-Magnitogorsk synclinorium, *RF* Reftinsky monoclinorium, *MC* Mugodzharsk-Chelyabinsk ledge

different orders) methods, as well as the regional geological structure along the balloon flight route of 2013. Analysing the data of the balloon magnetic survey, it is possible to note the correlation with the regional geological structure in the area of work. The positions of singular points according to the Troshkov method clearly point to the boundaries between large geological structures, which testifies to the block structure of the region under consideration. The results presented above make it possible to estimate magnetic properties of the detected blocks (Pecherskii and Genshaft 2001). Negative anomalies of the magnetic field fixed on the 250–300 km and 500–660 km segments of the profile are related to large positive structures, such as the Orlyanka-Ivanovo uplift and the Bashkir anticlinorium, respectively. Positive anomalies are confined to the negative structures of the Buzuluk depression, i.e. to the Sernovodsk-Abduleno aulacogen and the Sterlitamak depression (see Fig. 7).

Conclusions

1. Using the experimental magnetic data obtained onboard the stratospheric balloon during its drift; it is shown that the magnetic maps based on aeromagnetic data do not contain in full measure the fields of deep-seated magnetic sources.
2. The separate use of ground-based and balloon magnetic data is shown to be important and practical for estimating the vertical thickness of the lithospheric magnetically active layer and the depth of its lower boundary, which is the Curie isotherm.
3. Aeromagnetic data, analysed by the spectral method, record with certainty the position of the upper edge of the magnetically active layer of the lithosphere but does not reveal the real positions of magnetic source centres, whereas balloon data do not fix the position of the upper edge but indicate with certainty the depths of magnetic source centres. Hence, a combination of interpretations of aerial and balloon magnetic data provides the best possible results.
4. Balloon surveys can reveal the deep-seated block structure of the lithosphere and provide a possibility for estimating physical parameters of deep sources of the magnetic field.

Abbreviations

GSJ: Geological Survey of Japan; CCOP: Coordinating Committee for Coastal and Offshore Geoscience Programmes in East and Southeast Asia; VSEGEI:

A.P. Karpinsky Russian Geological Research Institute; KEMA: Kama-Embensk magnetic anomaly.

Authors' contributions
Yury P. Tsvetkov was involved in organisation of balloon measurements of magnetic field, general editing, translation into English, sections 1, 2, 3, 6, 7. Konstantin V. Novikov contributed to calculation of spectral characteristics, design of figures 1–4, sections 4 and 6. Andrey A. Ivanov was involved in calculation of the position of singular points, design of figures 5–7, Sects. 4 and 5. Oleg M. Brekhov contributed to organisation and conduct of aerostatic measurements of magnetic field, section 3. All authors read and approved the final manuscript.

Author details
[1] Pushkov Institute of Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation RAS (IZMIRAN), Kaluzhsk Highway 4, Troitsk, Moscow, Russia 108840. [2] State-Owned Company «Hydrospetzgeologiya», Marshal Rybalko Str. 4, Moscow, Russia 123060. [3] Russian State Geological Prospecting University (MGRI-RGGRU), Miklukho-Maklaya Str. 23, Moscow, Russia 117997. [4] Moscow Aviation Institute (MAI), Volokolamskoe Shosse 4, Moscow, Russia 125993.

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Ethics approval and consent to participate
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