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VLF-METHOD OF GEOPHYSICAL PROSPECTING: A NON-CONVENTIONAL SYSTEM OF PROCESSING AND INTERPRETATION (IMPLEMENTATION IN THE CAUCASIAN ORE DEPOSITS)

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Summary. Investigation of the electromagnetic (EM) fields from distant VLF (very low friquency) military transmitters is one of the fastest and low-expensive geophysical methods. At present, it finds frequent application in prospecting for various deposits, search of subsurface underground water, archaeogeophysical studies and various types of geological mapping. For geophysical investigation can be utilized a few dozens of the VLF transmitters disposed in various countries. The different frequencies and angles of registered EM radiation enable to obtain additional preferences by interpretation. A depth of investigation depends on the radiowave frequency and averaged resistivity of the host medium and usually ranges from several tens to several hundred meters (last values – under very favorable conditions). Both the electric and magnetic components of EM field are used in investigation by the VLF method. Generally only the magnetic field (*H*) is employed. A wide using of the VLF-technique was limited by absence of reliable methods for elimination of the EM field time variations, rugged relief influence and procedures for quantitative interpretation of the VLF-anomalies. These problems are successfully solved and the unified methodological system is developed. For elimination of the temporal variations a special procedure based on the direct continuous filtering is proposed. The correlation technique enables to significantly reduce the rugged relief influence. For quantitative interpretation is proved a possibility to use the modern interpreting methods elaborated in magnetic prospecting for complex geological-geophysical conditions. Finally, for revealing hidden objects against the high-intensive geological noise background, an application of non-conventional statistical, informational and wavelet algorithms is suggested. The main components of the developed system were successfully tested in the Caucasian polymetallic and copper deposits.

1. Introduction

Investigation of the electromagnetic (EM) fields from distant Very Low Frequency (VLF) military transmitters is one of the most mobile and economical geophysical methods. At present, it finds frequent application in prospecting for the searching and localization of ore deposits, for revealing archaeological targets, in environmental geophysics (identification of rock-slide, faults and underground cavities), in military geophysics, and for some other purposes. The VLF-radiations are propagated in a spherical waveguide formed by the Earth and ionosphere where the studied frequencies (10-30 kHz) are not attenuated even at great distances from transmitter due to the channel effect (Wait, 1962). Freely and readily available primary VLF field signals anywhere around the Earth make the VLF method prompt and efficient instrument for geophysical field investigations. Location of some typical VLF-transmitters and their parameters are presented in Table 1.

The VLF wavefront is thus assumed to be plane while the primary field intensity is taken to be constant within the area of the geophysical investigations. Moreover, the VLF field variations caused by the variations of imperfectly conductive channel walls are relatively small.

Both the electrical and the magnetic components of a VLF EM field are used in geophysical investigations by the VLF method, but mainly the magnetic field (*H*) is employed. The geophysical studies in the USSR, Russia, Czech Republic and many other countries have been performed with the VLF equipment constructed on the heterodyne detection principle.

Table 1

Location, abbreviation and some characteristics of several military VLF-transmitters

Location (abbreviation)	Frequency, kHz	Power, kW
Bordeaux, France (FUO)	15.1	500
Rugby, Great Britain (GBR)	16.0	750
Kaliningrad, Russia (UGK)	16.2	?
Negeland, Norway (JXZ)	16.4	350
Nizhnii Novgorod, Russia (ROR)	17.0	315
Grimelton, Sweden (SAQ)	17.2	200
Yosamai, Japan (NDT)	17.4	500
Murmansk, Russia (UPP)	18.1	500
Le Blank, France (HWU)	18.3	200
Oxford, Great Britain (GPS)	19.6	550
North West Cape, Australia (NWC)	19.8	1000
Annapolis, USA (USS)	21.4	400
Onagawa, Japan (JJI)	22.1	?
Northwest Cape, Australia (NWC)	22.3	1000
Burlage, Germany (DHO)	23.4	800
Laulualei, Hawaii, USA (NPM)	23.4	600
Cutler, Maine, USA (NAA)	24.0	1000
Seattle, Washington, USA (NLK)	24.8	125
La Moure, North Dakota, USA (NML)	25.2	250
Pearl Harbor, Hawaii, USA (NPM)	26.1	480
Aguada, Puerto Rico, (NAU)	28.5	100

The instrument is made as an amplitude meter with a radio loop and makes it possible to measure the following VLF field characteristics: *x*-, *y*- and *z*-axis components, H_x *Hy* and H_z, respectively: the total horizontal component $H_\phi = \sqrt{H_x^2 + H_y^2}$, semi-major and semi-minor axes of the polarization ellipse, H_a and H_b; deflection of the semi-minor axis of the polarization ellipse from the vertical; and the azimuth angle corresponding to the bearing. The angles are measured by the degrees, while the other parameters are expressed on the amplitude meter scale in microvolts since their true values are directly proportional to the voltage generated by the magnetic field across the loop terminals.

Because of the light measuring equipment, the VLF method can be employed even in almost inaccessible regions such as mountainous and foothill regions. However, rugged terrain relief can introduce distortions into the observations producing so-called topographic anomalies of great intensity, making it difficult to interpret the observed fields. Additional disturbances provide presence of numerous geological inhomogeneities with different electric properties (it is typical for the mountainous regions, e.g. Caucasian region).

Depth of investigation usually ranges from several tens of meters to a few hundred meters (this parameter depends on the employed radiowave frequency and averaged resistivity of the surrounding medium). For estimation of this parameter, the following simplified formula can be used (e.g., Zhdanov and Keller, 1994):

$$\delta \approx 503\left(\frac{\rho}{f}\right)^{1/2},$$

where δ is the skin depth value (in meters), ρ is the resistivity of the medium (in Ohm·m), and f is the frequency of the VLF radio-wave (in Hz) (see Table 1).

The skin depth is the depth at which EM fields are attenuated to $1/e$ of its surface amplitude (e = 2.718) during the propagation through isotropic layer. For instance, in the permafrost regions (where ρ ~10,000 Ohm·m) the depth of investigation can reach several hundred meters.

Many investigators have been applied the VLF method for searching and localization of ore deposits (e.g., Гинзбург и др., 1981; Гордеев и др., 1981; Гинзбург, 1982; Bayrak, 2002; Basokur and Candansayar, 2003; Liu et al., 2006; Sandrin and Elming, 2006; Mohanty et al., 2011; Eppelbaum and Khesin, 2012; Sharma et al., 2014; Shendi et al., 2017), different types of geological-geophysical mapping (e.g. Fischer et al., 1983; McNeill and Labson, 1991; Guerin and Benderitter, 1995; Xu, 2001; Pedersen and Oskooi, 2004; Bosch and Müller, 2005; Drahor and Berge, 2006; Santos et al., 2006; Zlotnicki et al., 2006; Al-Tarazi et al., 2008; Gürer et al., 2009; Hamdan et al., 2010; Sharma et al., 2014; Timur, 2014; Abtahi et al., 2016; Rajab, 2021) and discovering of archaeological artifacts (e.g., Ogilvi et al., 1991; Darnet et al., 2004; Drahor, 2006; Khalil et al., 2010; Tawfik et al., 2011; Pazzi et al., 2016; Simon et al., 2019).

2. Elimination of temporal VLF variations

The problem of eliminating time variations in the VLF method is crucially important since the intensity of these variations is often compatible with the intensity of the averaged VLF signal during the time of field survey. The following approaches have been used to overcome this problem.

During the initial period of VLF method, an approximated technique was used, which was based on field intensity measurements at a control point (*CP*) before and after fieldwork (Тархов, 1961). The corresponding corrections were introduced by interpolation assuming that the field intensity change was linear one. However, practical application of this method led to considerable errors.

A modification of this method is described in (Инструкция по электроразведке, 1984). The difference when the time variations have probable linear character is assumed to be 1 hour. The VLF survey is rejected if the level of variation for 1 hour exceeds 20%. This method, however, suffers from following disadvantages. Experience in field explorations in various regions indicates that the intensity changes of the VLF fields under study (even over the course of one hour) often cannot be approximated by a straight line with a sufficient accuracy. In addition, the amount of variations during this period may exceed 20%. It is also worth noting that this method neglects the effect of variation noise intensities on useful anomalies. It is obvious, however, that time variations in VLF field intensity affect the radiowave energy passing from the air into the ground. The intensity of the secondary field tends to increase or decrease, respectively (especially in the presence of anomalous objects of increased or decreased conductivity), and the variations are non-uniform. When disregarded, this fact can distort the interpretation of the results.

One western company developed an automatic attachment to a VLF receiver. Variations are eliminated by obtaining a synchronous ratio of the vertical component H_z of the VLF magnetic field to the total horizontal component H_φ. However, it was found by experimental field exploration that the H_z/H_φ ratio may vary even for observations at the same point. Quantitative interpretation of the H_z/H_φ curve presents certain difficulties. Another approach, described by this company in a recent guide for using the VLF equipment, consists of the selection of the frequency and time interval that is the most stable temporally for the area under study. Villee et al. (1992) suggested a similar method. However, this approach would benefit from improvement.

The VLF wavefront is assumed to be a plane whereas the primary field intensity is taken to be constant within the area of the detailed geophysical investigation (25÷100 km^2). The large distance from the utilized VLF transmitters (2,000 to 10,000 km) accounts for the uniformity of the primary field (Wait, 1962; Barr et al., 2000) both at control point (*CP*) and in the investigated area.

The following additive model of a geophysical field is applicable in practice for investigation by the VLF method (Eppelbaum and Mishne, 2011):

$$F_j = \sum_j S_j\left[n_j(x), x\right] + \sum n_j(x), \qquad (1)$$

where F_j is the field observed along profile, $\sum_j S_j\left[n_j(x), x\right]$ is the sum of effects from the anomaly-forming objects and geological inhomogeneities of the section (taking into account the dependence on the VLF field variations), $\sum n_j(x)$ represents the noise of field variations in time (time dependence is omitted in Eq. (1) for simplicity).

It is known that for the VLF field the conduction currents dominate the displacement currents (Заборовский, 1963; Гордеев и др., 1981), which is the major condition for quasi-stationarity (Альпин и др., 1985). The proportionality of the secondary EM fields (both magnetic and electric) to the primary fields has been confirmed in a number of publications (e.g., Дмитриев и др., 1977; Дмитриев, 1982). Hence given the physical effect of the subvertical radiowave propagation in the ground (Гордеев и др., 1981; Olsson, 1983) and taking into account Eq. (1), the following simplified model of the VLF observations (Figure 1) can be used in practice (Эппельбаум, Мишне, 1988):

$$\left\{\begin{matrix} H_o(t) = H(t) + B_o H(t) \\ H_j(t) = H(t) + C_j(t) \end{matrix}\right\}, \qquad (2)$$

where $H_o(t)$ is the VLF observation at the control point (*CP*); $H_j(t)$ is the VLF observation on the profile, $H(t)$ is the VLF primary field intensity, *B* and *C* are certain coefficients reflecting EM properties of the medium; indices “*j*” and “o” mark the observation point on the profile and *CP*, respectively.

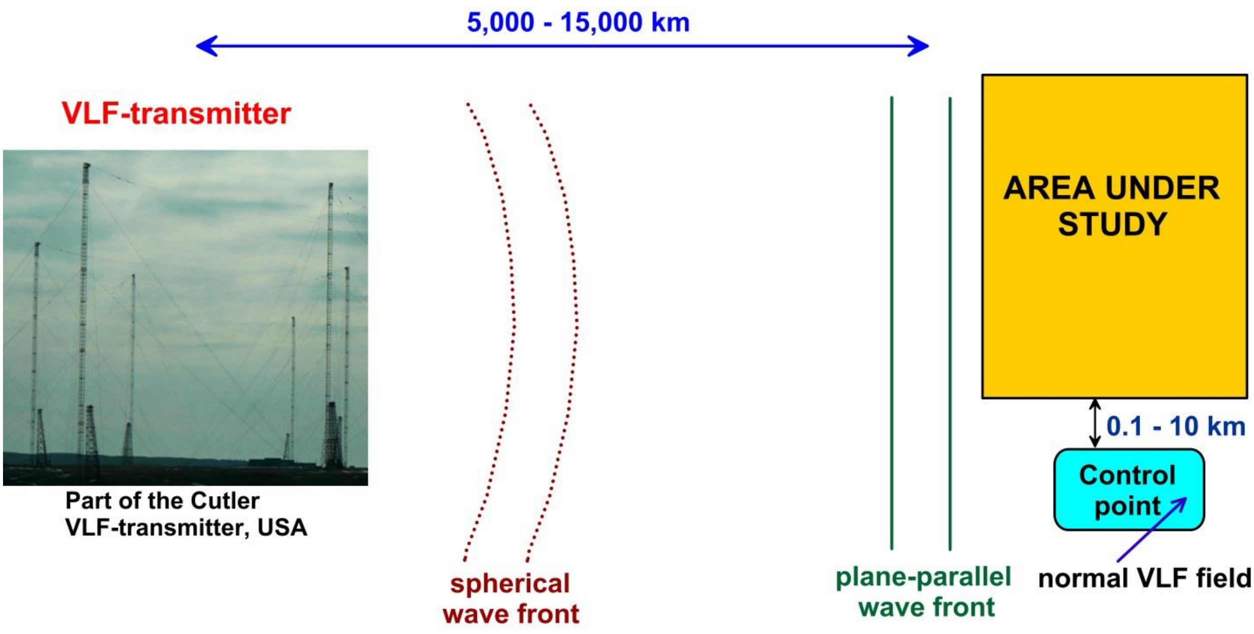

Fig. 1. Simplified scheme of temporal variations removal in the VLF method

Considering that B_o = const, this parameter which is a basic value for the studied area, can be assumed for convenience to be equal to zero. Solving Eqs. (2) in the parametric form, we obtain the values H_{clear} cleared from the temporal variations for each profile point:

$$H_{\text{clear}} = \frac{H_j(t)}{H_o(t)}\overline{H}, \tag{3}$$

where $\overline{H}$ is a certain averaged value of the field.

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Thus, the proposed scheme of eliminating variations in the VLF method is based on synchronous recording of the VLF observations along the profile and VLF temporal variations at *CP*. Automatic variation recordings can be carried out with a discretization interval of 0.5-1 seconds that allows accepting such procedure as continuous one. This method substantially eliminates observation distortions caused by field variations with time (both over the course of a day and at different days during a VLF-survey) by reducing observation results to the some common level (Eppelbaum and Mishne, 2011; Эппельбаум, Мишне, 1988).

It should be noted that later Bozzo et al. (1994) also noted the necessity of normalization of the field VLF measurements to the primary field observations.

3. Elimination of terrain relief influence

Many investigators have made attempts to reduce the terrain relief effect. An analytical approach was suggested by Tarkhov (1961); however, the analytical calculations proved to be too cumbersome even for a model of a uniform slope made up of homogeneous rocks and, above all, were at variance with the experimental results. Sedelnikov (1983) analyzed in detail the theoretical problem of VLF electric field distortions caused by a single mountain and a mountain range, but suggested no method for eliminating the topographic effects.

Karous's (1979) publication about the topographic influences on the vertical component of the VLF magnetic field (H_z) is evidently of interest, but no numerical results were reported. Eberle (1981) proposed simplified formulas to calculate the relief corrections for the observed EM fields; their application is, however, limited by a number of conditions, e.g., the requirement that the disturbing object and the observation profile should be in the most favorable position excitation by the primary VLF magnetic field. This requirement is seldom obtained or difficult to meet.

The second approach is based on a physical (analog) simulation of EM fields. Gordeyev et al. (1981) constructed models, which describe quantitatively the distribution of the VLF EM field over different terrain relief forms. Baker and Myers (1980) suggested an EM field "reduction" method based on their model investigations. This method, nevertheless, has the same limitations as found in Tarkhov (1961).

Gordeyev (1983) proposed a third approach. It is based on employment a graticule (chart) method to reduce the topographic effect on the total horizontal magnetic field component of the EM field of remote transmitters. It is difficult to apply at greater relief dips and it can, in some cases, impair the interpretation. This limitation is traceable to the "build-up effect" of a rectangular graticule in a complicated (relative to the observation profile) topography, which is, in addition, often characterized by different electric properties.

It should be noted that the effect of the Earth's surface topography on the radiowave propagation is a fairly important problem in radiophysics and has been investigated by quite a number of researchers. An overview of the literature suggests that this problem is still awaiting an adequate solution. A numerical calculation of radiowave scattering is a complicated electrodynamic problem even for the simplified case of diffraction by a homogeneous wedge displaying the finite conductivity (e.g., Захаров, Пименов, 1992; Ishimaru, 2017). The difficulties increase progressively for statistically inhomogeneous (i.e. real) surfaces. Pinel and Boulier (2013) emphasized that under natural conditions there is no need to find the detailed structure of a scattered field and that it is sufficient to ascertain some reflected-signal parameters averaged for the whole class of surfaces and targets. In general, these researchers have apparently come to the conclusion that wave scattering is determined largely by coordinate functions and represents a combination of wave diffraction on an arbitrary surface and the theory of probabi1ity plus mathematical statistics.

A review of the literature and results of VLF surveys leads to the following general rules:

(1) The plots of H_x (the *x*-axis is aligned with the observation profile) and the total horizontal magnetic field component H_φ substantially repeat the surface topography. There is a direct correlation between the increase or decrease in the recorded field intensities and positive or negative landforms, respectively.

(2) The intensity of the recorded VLF magnetic field is directly proportional to the relative elevation of observation points. The topographic anomalies caused by the local relief forms are similar to those from conductive bodies but have a smoother appearance.

(3) Where the angle between the radiowave arrival direction and that of a relief element is close to 0°**,** the relief effect is relatively large, and where this angle is close to 90°, it is relatively small, but in any case the relief effect is always present. Since all observations are made in the "distant" ("wave") zone, the bearing changes negligibly along the profile and the topographic anomaly is quasi-independent of the bearing change.

(4) VLF field intensity is mainly dependent on the resistivity of the rocks in the upper portion of a geological section.

The method suggested here for removing the terrain effect is simply to derive a linear least-squares relation (Eppelbaum, 1991)

$$H_{appr} = c + bh$$

approximating the observed field *H* as a function of elevation *h* (where *b* and *c* are the coefficients of a linear regression) and then to construct the residual field:

$$H_{resid} = H_{observ} - H_{appr},$$

where H_{obser} is the any of the observed components of the VLF-filed.

Measurement points indicating the obvious lateral inhomogeneities are usually disregarded. Sometimes the correlation may be not linear and the observed can be approximated by hyperbolic, polynomial and other function. However, a linear approximation is preferable since here the artificial mistakes are minimized.

The standard deviation (S.D.) of parameter *b* can be calculated using the following formula:

$$\text{S.D.} = \frac{\pm \left\lfloor b\left(1-r^2\right)^{1/2} \right\rfloor}{r}, \qquad (4)$$

where *r* is the correlation coefficient.

All the above mentioned points make it possible to apply the correlation method, developed earlier in magnetic prospecting, to the VLF method (Eppelbaum, 1991). An example of employment of the correlation in the Eastern Kur-Kol ore zone (Northern Caucasus, Russia) is presented in Fig. 2. Here the VLF-transmitter working at the frequency of 16.0 kHz (Rugby, UK) (see Table 1) was employed. The commercial pyrite zones occur in tuffs and tuffites of Middle and Upper Devonian (Fig. 2c). After removing the uneven relief influence by the aforementioned correlation method (correlation field is shown in Fig. 2a), the VLF anomaly is more clearly selected (Fig. 2b).

Fig. 3 illustrates the correlation procedure application in the VLF method in the area of the Katsdag pyrite-polymetallic deposit (the southern slope of the Greater Caucasus, Azerbaijan). The relief slope is about 40° (which would create problems for many geophysical methods, but not for the VLF survey) and the ore bodies occur in Middle Jurassic deposits. The employed frequency was 19.6 kHz (the VLF transmitter located in Oxford (UK) was utilized; see Table 1).

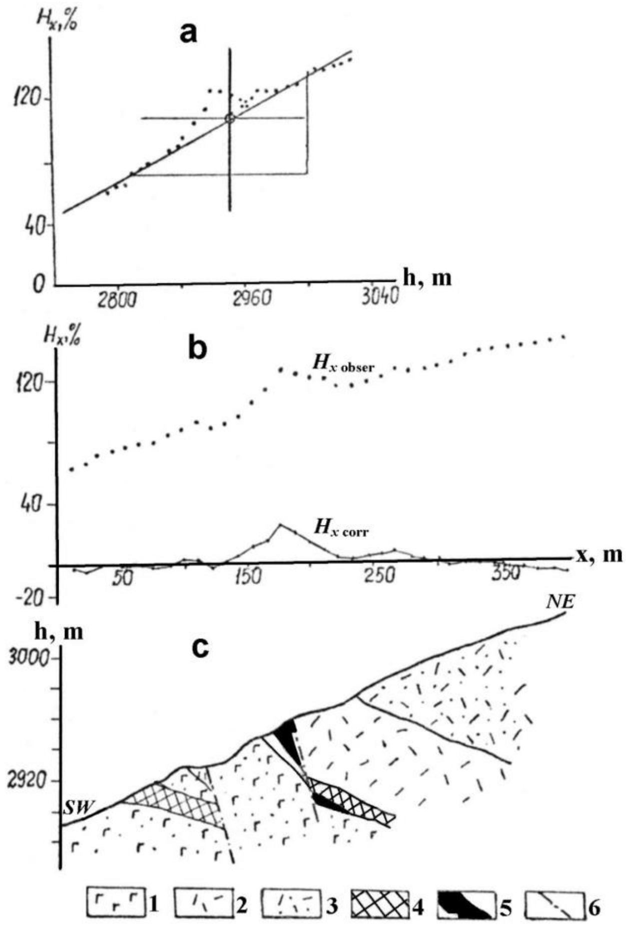

Fig. 2. Correlation technique for reducing terrain relief on the portion of Eastern Kur-Kol zone (Northern Caucasus, Russia). a) correlation field, b) observed and corrected H_x graphs, c) geological section (observed VLF anomaly and geological section are from Гордеев, 1970)
1 – tuffs, 2 – tuffites, 3 – tuff-sands, 4 – and 5 – poor and rich polymetallic ores, respectively, (6) faults

The different geological units in this area have the following resistivities (Fig. 3c): the pyrite-polymetallic ore bodies – fractions of Ohm·m; the mineralized zone (outcropping in the upper portion of the section) – l-3 Ohm·m: the sandstones – 1200-1500 Ohm·m; the clay shales – 700-1000 Ohm·m; and the liparite-dacites – 500-700 Ohm·m. These values indicate a relatively uniform background medium as far as resistivity is concerned. However, a distorting topographic effect tends to impair the visual detection of the VLF anomaly from a hidden ore body (tilted plate). The correlation coefficient r consists of 0.97 (the broad anomaly from a mineralized zone was neglected) (Fig. 3b). When the topographic effect is removed, a weak anomaly due to the ore body and a wide anomaly from the thick mineralized zone appear more clearly (Fig. 3a).

Following example shows application of the correlation technique on a portion of the Katekh pyrite-polymetallic deposit (southern slope of the Greater Caucasus, Azerbaijan) (Fig. 4). A frequency of 16.0 kHz was used in the investigation (the transmitter was in Rugby, Great Britain; see Table 1), and the profile azimuth was 60°. The ribbon-like band of the pyrite-polymetallic ore is located at a depth of about 60-80 m in the sandy argillaceous series of Upper Aalenian. The average resistivity of the nearly uniform surrounding medium is in the range of 700 to 900 Ohm·m; the resistivity of the massive ore body is a fraction of 1 Ohm·m. The skin depth is estimated about 110 m. Since a topographic anomaly was superimposed on a small signal from a relatively deep-seated anomalous object, it was difficult to detect the latter.

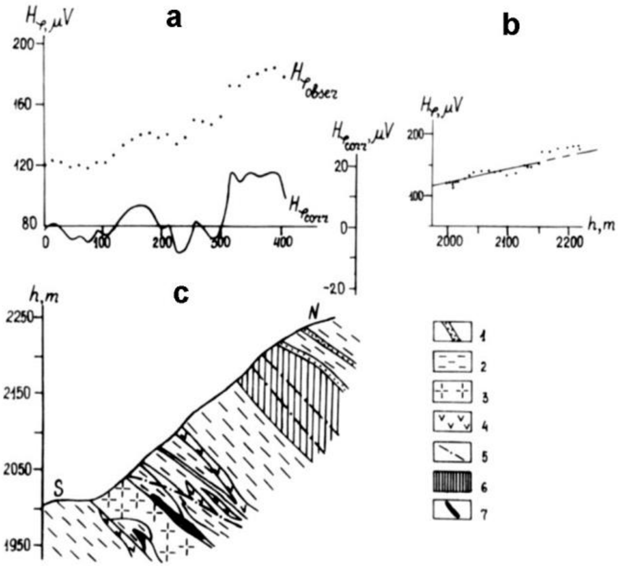

Fig. 3. Correlation technique applied for terrain relief elimination in the Katsdag pyrite-polymetallic deposit (northern Azerbaijan). a) Graphs of observed and corrected H_φ values, b) Correlation field, c) Geological section
1 – sandstone, 2 – clay shales, 3 – liparite-dacites, 4 – dioritic porphyrites, 5 – faults, 6 – ore mineralization zone, 7 – massive ore body

Two different correlations were made for the southwestern and the northeastern slope, yielding coefficients of correlation (between the relief heights and VLF intensity) of r_1 =0.988 and r_2 = 0.85. The results for the southwestern slope are (after calculation of S.D. for parameter b by the use of equation (4): for the southwestern slope $H_{\varphi\,\mathrm{appr}} = 84 + (0.6 \pm 0.09)h$, and for the northeastern slope – $H_{\varphi\,\mathrm{appr}} = 105 + (0.79 \pm 0.49)h.$ After removing the relief effect, a positive anomaly can clearly be seen on the northeastern slope in the $H_{\varphi\,\mathrm{corr}}$ plot (Fig. 4). This anomaly may be due to the edge effect from the deep ore body, whereas the minimum on the southwestern slope may correspond to the opposite edge of the subhorizontal tabular ore body, since the anomaly is not large in this case (Eppelbaum, 1991).

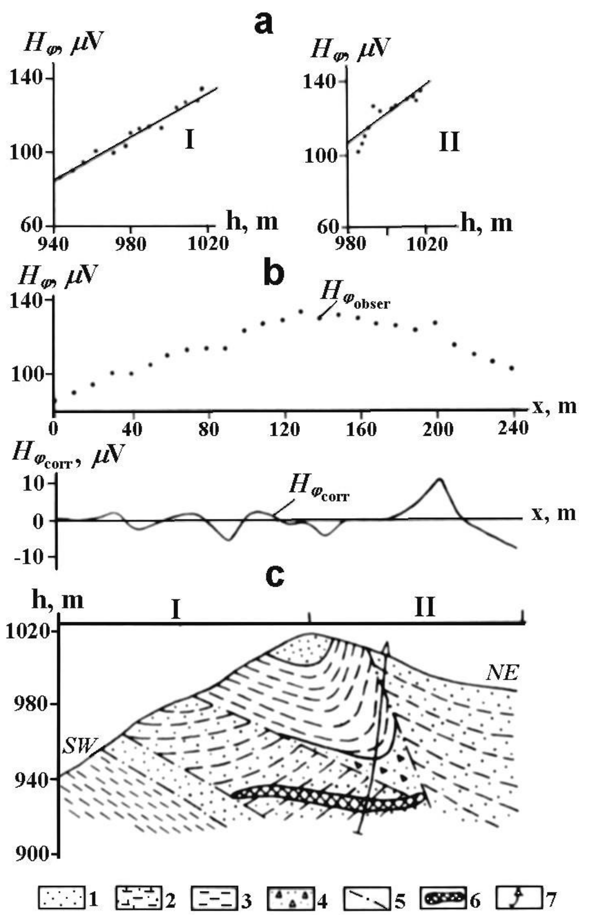

Fig. 4: Correlation technique for reducing the terrain relief effect on a portion of the Katekh pyrite-polymetallic deposit (northern Azerbaijan). a) Correlation, b) Plots of observed and corrected H_φ values, c) Geological section
1) fine and medium-grained sandstones, 2) alternating sandstone and clay shale strata, 3) clay shales, 4) brecciated zone, 5) fractures, 6) ore body, 7) prospecting borehole

The last example illustrates elimination of the terrain relief effect in the VLF-studies (f = 19.6 kHz) in the portion of the Gyzylbulagh gold-copper deposit (Agdara area, Nagorny Garabakh, Azerbaijan) (Fig. 5). Even simple visual analysis indicates that the observed VLF field (Fig. 5a) strongly correlates with the topography along the geophysical profile. The obtained correlation (without anomalous VLF points) is visualized in Fig. 5b, and the corrected VLF curve is shown in the lower part of Fig. 5a. The corrected VLF anomaly well corresponds to the known inclined ore body (Fig. 5c), while the left corrected anomaly obviously indicates an undiscovered ore body of the vertical dipping. These conclusions confirm the results of VLF physical modeling obtained from the models of two aforementioned types (Fig. 5d).

4. Advanced quantitative analysis of VLF anomalies

4.1. A brief review of available methods of quantitative analysis

An overview of the literature indicates that there are practically no reliable or rapid techniques of quantitative interpretation in the VLF method.

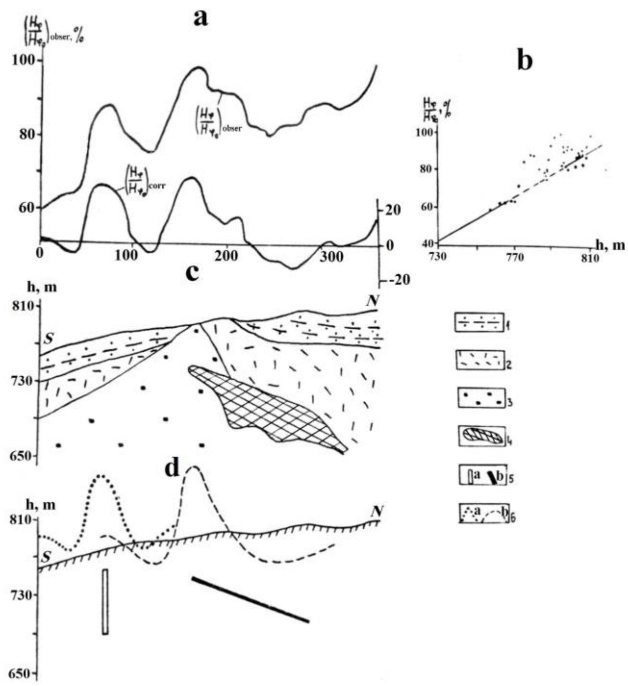

Fig. 5. Correlation technique for reducing terrain relief on the portion of the Gyzylbulagh deposit (Lesser Caucasus, Agdara area, Azerbaijan). a): Observed and corrected H_x graphs, b): Correlation field, c): geological section, d): model VLF curves
1) lavas of liparite-dacite porphitites, 2) tuffs lavas of liparite-dacite porphitites, 3) breccia zone, 4) ore body, 5) model bodies for a) vertical thin bed, b) inclined thin bed, 6) H_φ theoretical curves for 5a and 5b

The methods suggested by Tarkhov (1961) are semi-quantitative. The procedure developed by Fraser (1969) is useful primarily only for qualitative revealing anomalous targets. Karous and Hjelt (1983) proposed to apply conventional methods of linear filtering to remove various kinds of noise containing in the VLF data. Singh et al. (2020) indicate that Fraser (1969) and Karous and Hjelt (1983) techniques are insufficient ones, since many categories of noise in the VLF-method have expressed nonlinear character.

The techniques presented by Gordeyev and Sedelnikov (1974), based on calculating the anomaly extreme ratio, require knowing the zero line (or a normal field). The wrong choice of the zero line entails the substantial errors in determining the anomalous object’s quantitative parameters. Moreover, these techniques are not intended for interpretation in conditions of the rugged terrain relief.

Dmitriyev et al. (1977) solved the direct problem for a number of geophysical EM methods (including the VLF method). They provide a numerical analysis of the anomalies due to bed-like bodies as a function of their electric properties, dimensions and position with respect to the Earth's surface and the observation profile. However, computational difficulties restrict the range of models to simple ones.

Zhdanov and Keller (1994) noted that the finite differences method is the most effective method of the EM field mathematical simulation. However, the expediency of its application depends on the size of the design area and the desired accuracy of the computations. For a large area of calculations or when the simulation problem needs higher accuracy, the computations exceed all possible limits even for high-performance modern computers.

Khesin et al. (1996) pointed out that some approaches developed for the magnetotelluric sounding (Kaufman and Keller, 1981; Zhdanov and Keller, 1994) could be employed in the VLF method. Basokur and Candansayar (2003) suggested to apply the same methodologies (though, these authors concluded that this interpretation could only be qualitative). However, the application of these procedures is usually limited by the extreme variations of electric properties in the (upper) part of geological section.

Gordeyev and Sedelnikov (1974) and Gordeyev et al. (1981) have presented the physical (analog) simulation of VLF curves from the models of a vertical inclined thin bed. The accuracy of the physical simulation and that of the numerical computations (for simple models) is at present approximately the same, and is roughly 8-10%.

Numerous other works, in many respects similar to those mentioned above, have dealt with the anomaly interpretation in the VLF method. For instance, Karous and Hjelt (1979) and Olsson (1980) report the calculation of plots for the vertical and horizontal components of the VLF magnetic field using the model of an inclined thin bed with the different dip angles; the depth of the upper edge of the bed varies as well. Olsson (1980), Tesmull and Crossley (1981) and Poddar (1982) computed components of the VLF fields for the different types of geoelectric sections. Miecznik (1986) calculated the magnetic components of the VLF field caused by another model of an anomalous object – conductive cylinder placed in a homogeneous medium (the cases of both **E**-polarization and **H**-polarization are discussed).

The characteristic VLF diagrams developed by Sinha (1998) can provide useful information on the vertical and inclined conductive beds in simple geological-geophysical conditions. The VLF first derivative method proposed by Djeddi et al. (1998) is based on perspective methodology (the authors suggest eliminating the topographic effect of peculiarities in the interpretation process).

Olsson (1983) solved the direct problem for an ideal conductive half-plane with different dip angles, when the half-plane is covered by variable-depth loose deposits. In addition, he proposes the techniques for a simplified interpretation of VLF data based on the utilization of the extremum points in the anomaly plot. The synthetic models presented by Pedersen and Oskooi (2004) provide better understanding of the resolving power of the VLF data. The same authors propose employing a tensor variant of VLF measurements. Santos et al. (2006) described a quantitative interpretation of VLF-EM data using 2-D models (the authors developed a 2-D regularized modeling of VLF-EM data based on a forward solution using the finite-element method) that yields practical results about the average resistivity in the survey area. Kaikkonen and Sharma (2001) performed a 2-D simulation of the noise-free and noisy media with single-body and complex models. The authors highlight the need to use reliable *a priori* information before running such a simulation.

Singh and Sharma (2016) modeled subsurface structure in terms of apparent current density distribution and compared obtained results with the inversion models for resistivity distribution computed using numerical techniques. Their study demonstrates that the results obtained using both approaches (current density and resistivity distribution) are comparable, but due to applied analytical expression, current density imaging is faster.

Singh et al. (2020) suggested the nonlinear empirical mode decomposition technique to minimize the noise from the VLF data. These authors proposed an inversion approach based on triangular grid to reduce the problem size by utilizing minimal number of model parameter and accurate model of the rugged topography.

4.2. Application of procedures developed for potential field analysis

The main equations used in the theory of alternating EM field are the Maxwell's equations:

$$\mathrm{rot}\,\mathbf{H} = \mathbf{j} + \frac{\partial \mathbf{D}}{\partial t}, \tag{5a}$$

$$\mathrm{rot}\,\mathbf{E} = \mathbf{j} + \frac{\partial \mathbf{D}}{\partial t}, \tag{5b}$$

$$\mathrm{div}\,\mathbf{B} = 0, \tag{5c}$$

$$\mathrm{div}\,\mathbf{D} = q. \tag{5d}$$

Here **H** and **B** are the magnetic field vectors (**H** stands for intensity and **B** for induction); **E** and **D** are the electric field vectors (**E** stands for intensity and **D** for induction); *q* is the charge density; **j** is the conduction current density.

Eq. (5a) can be written as (Заборовский, 1963):

$$\mathrm{rot}\,\mathbf{H} = \mathbf{C} = \mathbf{j}_{\mathrm{cond}} + \mathbf{j}_{\mathrm{disp}}, \tag{6}$$

where **C** is the total current density; $\mathbf{j}_{\mathrm{cond}}$ and $\mathbf{j}_{\mathrm{disp}}$ are the conduction and displacement current densities, respectively.

It has been found that at the frequencies of 10 to 30 kHz, $\mathbf{j}_{\mathrm{disp}} \approx 0$ (Wait, 1962). Therefore,

$$\mathrm{rot}\;\mathbf{H} = \mathbf{j}_{\mathrm{cond}} \tag{7}$$

or

$$\mathbf{H} = \nu\mathbf{E}, \tag{8}$$

where ν is the electric conductivity.

An *EM* field can be considered as quasi-stationary if it satisfies the three conditions of quasi-stationarity. Landau et al. (1984) described the common physical meaning of these conditions. Alpin et al. (1985) formulated these conditions as applied to geophysics. These requirements are as follows:

(A) Slow field variation,

(B) Closed currents,

(C) To avoid an appreciable lag in the magnetic field variations, the domain including magnetic field generating currents and observation points must not be too large.

Let us consider these conditions in more detail.

(A) The study of time variations of the VLF fields has shown that sharp changes in intensity are not characteristics of these fields. Nonetheless, these variations should be eliminated by use a special procedure during fieldworks (see section “Elimination of temporal VLF variations”).

(B) This condition follows from Eq. (7), since div rot **H** = 0 and, therefore, div **j** = 0. Almost closed currents do not violate this condition.

(C) This condition can be formulated in the following way: the length of an EM wave in the ground should essentially exceed the length of the investigated targets. This condition, as a rule, is fulfilled in the prospecting of mineral deposits, and often fulfilled in the geological mapping and object analysis in environmental and military geophysics.

It is known that the fundamental solution of the Laplace equation in the 2-D case is the following function:

$$g_0(M,P) = \frac{1}{2\pi}\ln\left(\frac{1}{R_{MP}}\right), \tag{9}$$

where R_{MP} is the distance between points *M* and *P* (*M* is the observation point and *P* is the point of the body).

The fundamental solution of the Helmholtz wave equation is a Hankel function of the first kind with the zero order $H_0^{(1)}$:

$$g_0(M,P) = \frac{i}{4}H_0^{(1)}(kR_{MP}), \tag{10}$$

where *k* is the wave number and *i* is the imaginary unit.

The function (10) is the analog of the function (9) for a Laplace equation.

Using the above correspondence, Hänl et al. (1961) and Dmitriyev (1982) proved the relationship between Green’s solutions of the Laplace and Helmholtz equations. This allowed them to conclude that the results obtained in the potential theory could be extended to the Helmholtz equation.

Dmitriyev et al. (1977) indicated that the association of the singular points resulting from the VLF field anomaly plots with geometrical parameters of the anomalous bed is analogous to the well-known behavior of singular points in the potential field anomalies. Zhdanov (1988) carried out a theoretical investigation of the application of a set of Cauchy-type integral analogs to the problems of electromagnetism. It was suggested that the methods developed in potential theory for the analytical continuation, separation and quantitative interpretation could be applied to the quasi-stationary EM anomalies.

The quasi-stationarity of the EM field follows from the condition (A).

An overview of publications (Гордеев и др., 1981; Poddar, 1982; Poikonen and Suppala, 1989; Sharma and Kaikkonen, 1998; Beamish, 2000) indicates that a conductive thin bed (TB) is the most common model for the VLF technique. The analytical expressions of the fields for this model (the 2D case) are presented in Table 2.

Table 2

Comparison of analytical expressions for TB in the magnetic prospecting and the VLF method

Field	Analytical expression	
Magnetic	$Z_v = 2I2b\frac{z}{x^2+z^2}$	$X_v = 2I2b\frac{x}{x^2+z^2}$
VLF	$H_x = kH_0\frac{z}{x^2+z^2}$	$H_z = kH_0\frac{x}{x^2+z^2}$

In this table, Z_v and X_v are the vertical and horizontal magnetic field components for the vertical magnetization, respectively; H_x and H_z are the horizontal and vertical VLF magnetic field components, respectively; H_0 is the VLF primary field intensity; k is the coefficient reflecting the geometry and conductivity of the anomalous body.

Evidently, Z_v is proportional to H_x, whereas X_v is proportional to H_z. Similar results were obtained for the horizontal circular cylinder (HCC) model (Eppelbaum and Khesin, 1992).

Thus, the plots of magnetic fields of VLF transmitters can be interpreted by the special methods elaborated in potential field theory (in particular, in magnetic prospecting, for conditions of the rugged terrain relief, oblique magnetization (polarization) and an unknown level of the normal field). The **E**-polarization vector, in the first approximation, is the analog of the magnetization vector (Eppelbaum and Khesin, 2012).

In this context, the advanced interpretation techniques (improved modifications of areal, characteristic point and tangents methods) presented in (Khesin et al., 1996; Eppelbaum et al., 2001; Eppelbaum, 2011, 2015; Eppelbaum and Mishne, 2011) are of practical interest in the VLF method. Application of the improved methods of tangents and characteristic point methods developed in magnetic prospecting for the model of thin bed is shown in Fig. 6.

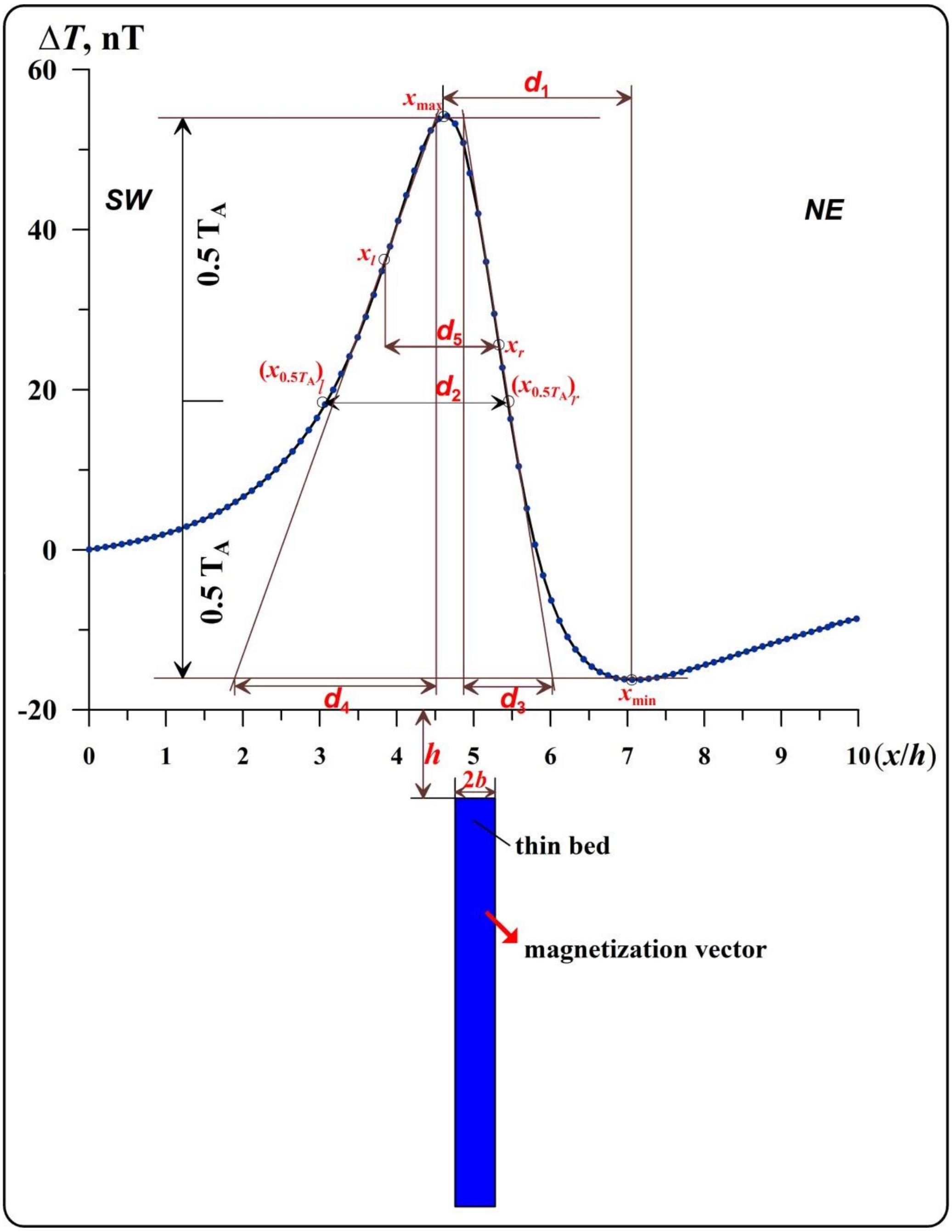

Fig. 6. Example of quantitative analysis of magnetic anomaly produced by thin bed

It should be noted that the total horizontal component of the VLF magnetic field $H_\varphi = \sqrt{H_x^2 + H_y^2}$ can be interpreted as the H_x component, since the contribution of the H_y component is usually relatively small.

The essential distinctions reflecting quasi-potential nature of the VLF EM field are as follows. In magnetic prospecting the induced magnetization vector of an inclined bed is approximately parallel to the geomagnetic field vector, irrespective of the bed dip direction, where the magnetic susceptibility does not exceed 0.1 *SI* unit. In EM prospecting by the VLF method under **E**-polarization for highly conductive objects, the equivalent vector of polarization that causes the anomalies of H_x and H_z, approaches the body axis, with a slight deviation toward the vertical for the gently sloping bodies (Гордеев и др., 1981; Poikonen and Suppala, 1989). This makes it possible to utilize the generalized angle θ derived from these anomalous components and to represent the difference in the inclination angles for the bed and the polarization vector to estimate the bed dipping α by the following empirical formulas (Eppelbaum and Khesin, 2012):

(a) for the H_x anomaly

$$\alpha = 3\theta + 90^0, \qquad (11a)$$

(b) for the H_z anomaly

$$\alpha = 3\theta - 180^0, \qquad (11b)$$

where α is the bed inclination.

For the case of observations on a sloping relief, the angle α is calculated as follows:

(a) for the H_x anomaly

$$\alpha = 3(\theta - \omega_o) + 90^0 \qquad (12a)$$

(b) for the H_z anomaly

$$\alpha = 3(\theta - \omega_o) - 180^0, \qquad (12b)$$

where ω_0 is the angle of the terrain relief inclination ($\omega_0 > 0$ when the inclination is toward the positive direction of the *x*-axis).

It should be noted that the position of the upper edge can be slightly shifted from the real upper edge downward along the bed dip. This is because the linear currents are concentrated in the upper portion of the conductive target; therefore this portion may be situated below this object's upper edge.

If anomalies are observed on an inclined profile, then the obtained parameters characterize a certain fictitious body. The transition from the fictitious body parameters to those of the real body is performed using the following expressions (the subscript "*r*" stands for a parameter of the real body) (Eppelbaum and Khesin, 2012):

$$h_r = h + x\tan\omega_0, \qquad (13)$$

$$x_r = -h\tan\omega_0 + x_0, \qquad (14)$$

where *h* is the depth of the upper edge occurrence, x_0 is the location of the source's projection to plan relative to the extremum having the larger magnitude.

An effective example of the VLF data analysis is presented in Fig. 7. It is necessary to underline that the anomalous magnetic *X*-component computed for the same model is very similar to the observed H_z VLF curve (their theoretical similarity is shown in Table 2). Fig. 7 clearly shows that the results agree well with the geological data.

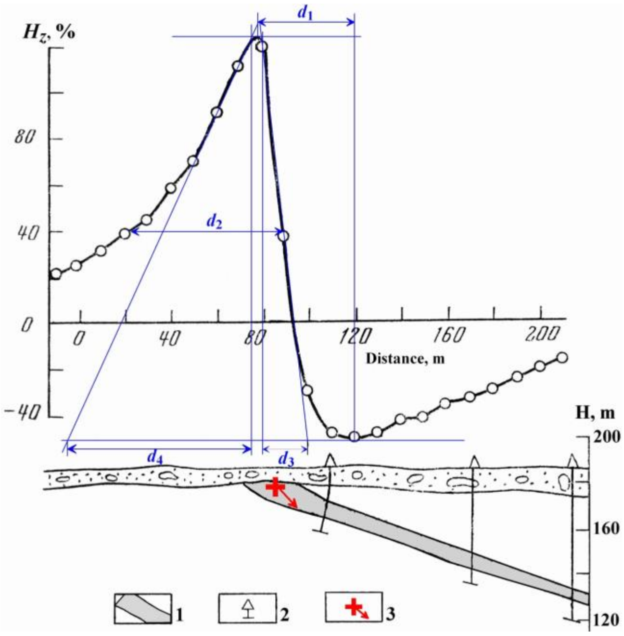

Fig. 7. Quantitative analysis of the vertical magnetic component H_z of the electromagnetic VLF field in the copper-nickel deposit (Kola Peninsula, Russia) using the improved tangent and characteristic point methods (observed curve and geological section after (Гордеев и др., 1981)).
1) copper-nickel ore body, 2) location of drilled boreholes, 3) results of quantitative analysis: cross indicates position of the upper edge of the ore body and arrow shows its dip direction

Fig. 8 illustrates the interpretation results for the H_φ curve (*f* = 19.6 kHz) along the profile across the Gyzylbulagh gold-pyrite deposit (Lesser Caucasus, Azerbaijan). The VLF anomaly over the ore object exposed by the prospecting boreholes is shown in the central portion of the profile. In the southwestern portion other VLF anomaly over an anticipated object is marked. In the both cases the approximation model was represented by an inclined thin bed.

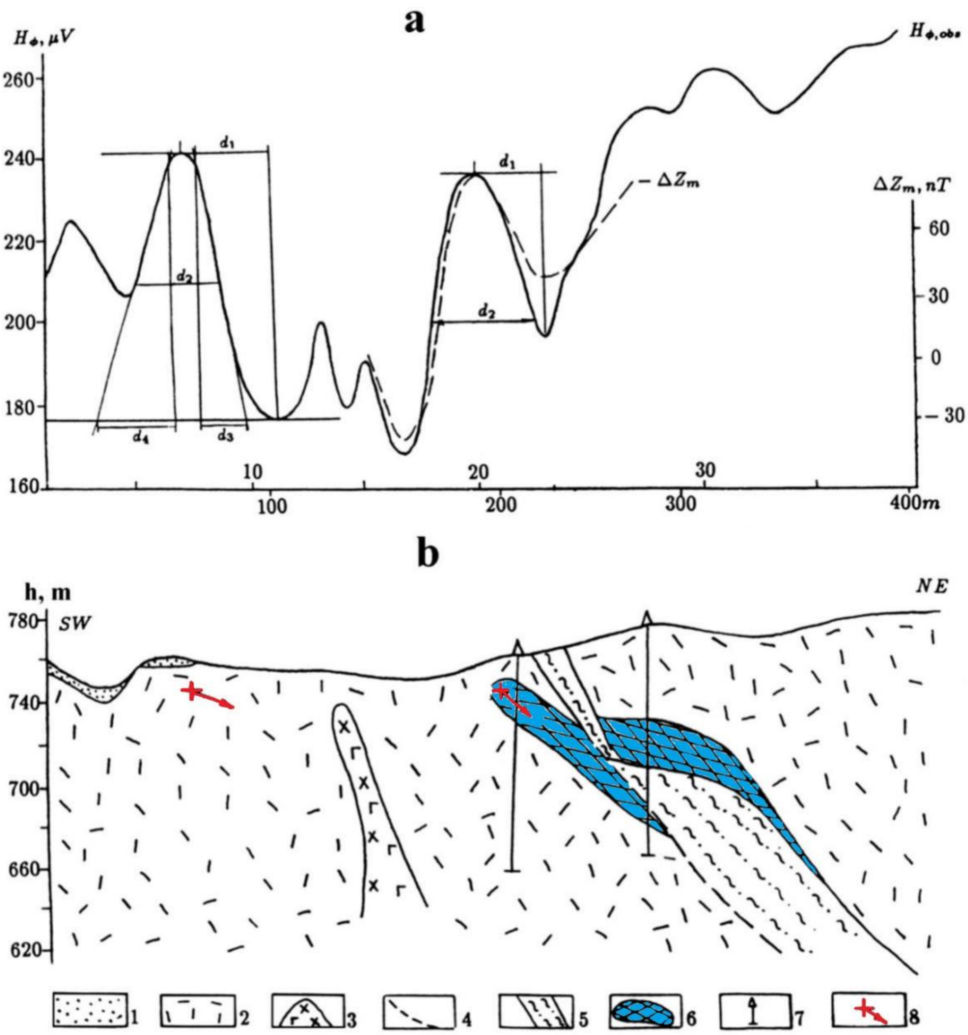

Fig. 8. Quantitative interpretation of the H_φ field in the area of the Gyzylbulagh gold-pyrite deposit (Lesser Caucasus, Azerbaijan): a) the plots of H_φ and model magnetic field ΔZ_m, b) geological section 1) loose deposits; 2) tuffs of liparite-dacitic porphyrites; 3) dike of andesite-basalts; 4) disjunctive dislocation; 5) ore body; 6) zone of boudinage; 7) prospecting wells; 8) location of the conductive bodies' upper edge and direction

As it was earlier shown, the magnetic field ΔZ was an analogue of H_x and H_φ components in the VLF method for the case of an inclined thin bed. A model magnetic field ΔZ_m due to the host medium and near-surface ore body is computed for the central part of the profile. For modeling purposes the following parameters were used: magnetization value: 300 mA/m for the host medium, and 1,000 mA/m for the anomalous (ore) body; the vector of magnetization was assumed to be vertical for the host medium (since in the VLF-method we have the quasi-vertical EM wave arrivals) and along the dipping for the orebody (VLF vector is oriented along the long body's axis). The magnetic azimuth of the selected profile was assumed to be 70°, which corresponds to the angle between the incoming VLF field and the real azimuth of the profile. It is clear from the figure that the H_φ and ΔZ_m curves are in good agreement. These calculations provided the additional proof of the similar nature of these fields.

Fig. 9 displays interpretation results in other portion of the Gyzylbulagh gold-pyrite deposit where simultaneously H_φ and H_x components (f = 19.6 kHz) were observed. The results are agreed both between themselves (H_φ and H_x) and with the available geological data obtained from "Azerbaijan Geological Assoc.".

6. Geological, environmental and other applications of VLF studies

6.1. Delineation of archaeological targets

Let us consider the following example. A detailed VLF survey was carried out near Alcala de Henares, a small town situated 20 km east of Madrid, Spain (Ogilvi et al., 1991). The main aim of this survey was localization of the air-filled underground galleries of comparatively small size occurring in the clastic sediments. One of the observed profiles is shown in Fig. 10. The underground gallery is approximated by the HCC model inscribed to the upper part of this target.

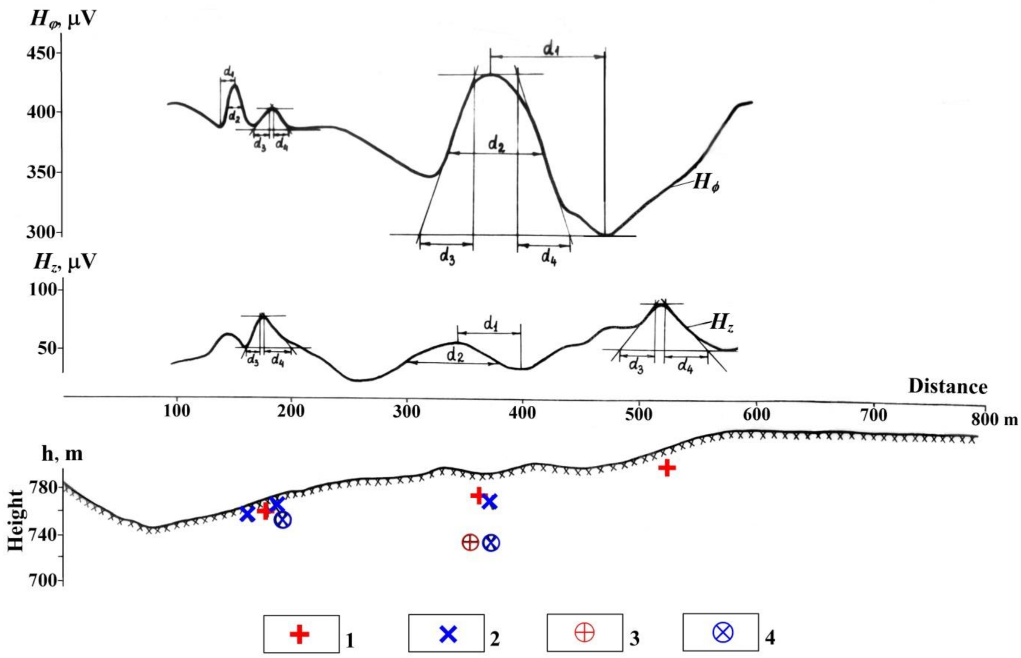

Fig. 9. Quantitative analysis of the total horizontal component H_φ and vertical component H_z of the magnetic field of VLF anomalies in the area of the Gyzylbulagh gold-pyrite deposit (Lesser Caucasus, Azerbaijan) (revised after Eppelbaum and Khesin, 2012) Positions of thin bed upper edge center by the data of H_z 1) and H_φ 2), positions of the centers of the horizontal circular cylinder by the data of H_z 3) and H_φ 4)

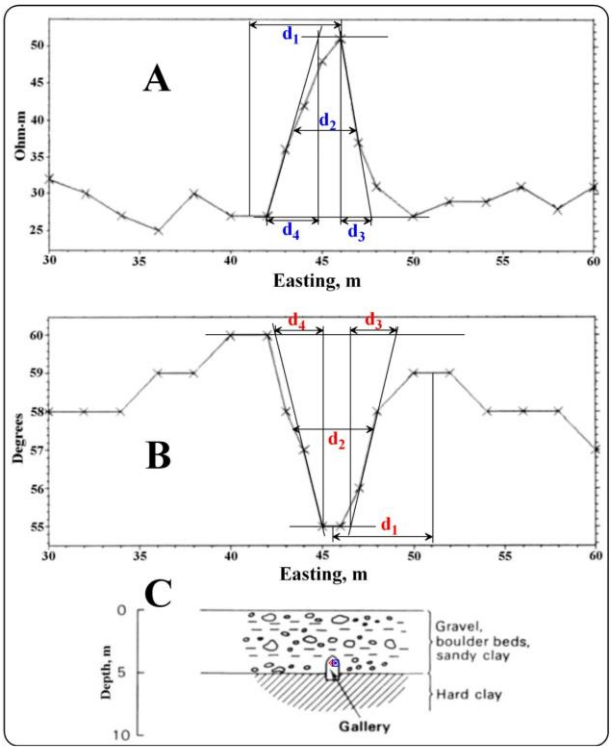

Fig. 10: Quantitative interpretation of VLF-R apparent resistivity and phase profiles, NAA transmitter (Gutler ME, USA), 24 kHz[1]. A – apparent resistivity, B – phase anomaly, C – geological section. Symbols ◈and ▣designate the determined position of HCC center for phase anomaly and apparent resistivity, respectively. Observed curves and geological section are taken from Ogilvi et al. (1991), interpretation after Eppelbaum (2007b).

Results of quantitative examination of the phase anomaly and apparent resistivity curves indicate that the obtained results have enough accuracy.

6.2. Geological mapping

6.2.1. Ring targets as example

It is well-known that interpretation of VLF data strongly depends on the kinds of geological noise in the areas under study (Jeng et al., 2007). So, here arises a problem of development of methodologies enabling to recognize the VLF signals against the strong noise background.

One of key problems of geophysical prospecting (including VLF method) is the delineation of the typical *buried* objects of various size and origin. The ways of revealing such buried objects with an *a priori* shape are illustrated below through example of identification of the ring (circular) buried targets.

The ring structures (RS) are omnipresent in the Earth's environment (Fig. 11). RS are generally classified as *Terrestrial* and *Extraterrestrial* (natural RS) or *Archaeological and Military/Engineering* (artificial RS) (Eppelbaum, 2007a). Thus, problems sometimes arise not only of the RS identification, but also of the correct target classification. A greater accuracy can be achieved by collecting more comprehensive geological (geochemical), geophysical, archaeological and engineering (military) data. In the flow chart (Fig. 11) natural RS are classified using Khain's (1995) scheme and the author's supplements and extensions (Eppelbaum, 2007a). The *Extraterrestrial* RS are associated with dropping of the

[1] In the modern Reference Handbook the NAA transmitter is presented with the frequency of 25.3 kHz

cosmic bodies. The *Terrestrial* RS are divided to tectonic, magmatic, metamorphic and erosional with the following specification. The *Archaeological* RS are presented as the buried caves, ancient squares and circus rings, the remains of fortresses and towers, the tailings of detritus and religious edifices. The detection should be coordinated with the other geophysical methods, morphological characteristics, etc. The *Military* RS are displayed as the rocket shafts, command posts and defensive installations (obviously, kinds of these RS may be significantly extended). In the latter case the VLF Remote Operative Vehicles (ROV) application has clear advantages over other identification methods.

6.2.2. Methodology of RS Delineation

The first problem in the RS analysis is to differentiate the targets from the background geological noise. Very frequently it is difficult to single out the RS in complex geological-geophysical environments, especially when the typical rectangular network of geophysical observations is used. In addition, anomalies caused by the RS can be distinguished from other geophysical field features by their location on the periphery of the anomalous bodies. For this purpose a special method has been devised to distinguish the RS structures by computing the sums of the horizontal gradients of geophysical fields and their differences (Khesin et al., 1996). It should be noted that the ROV application makes it possible to observe geophysical fields at different levels and compute difference of the horizontal gradients between them, which might be employed as an additional searching indicator (Eppelbaum, 2016).

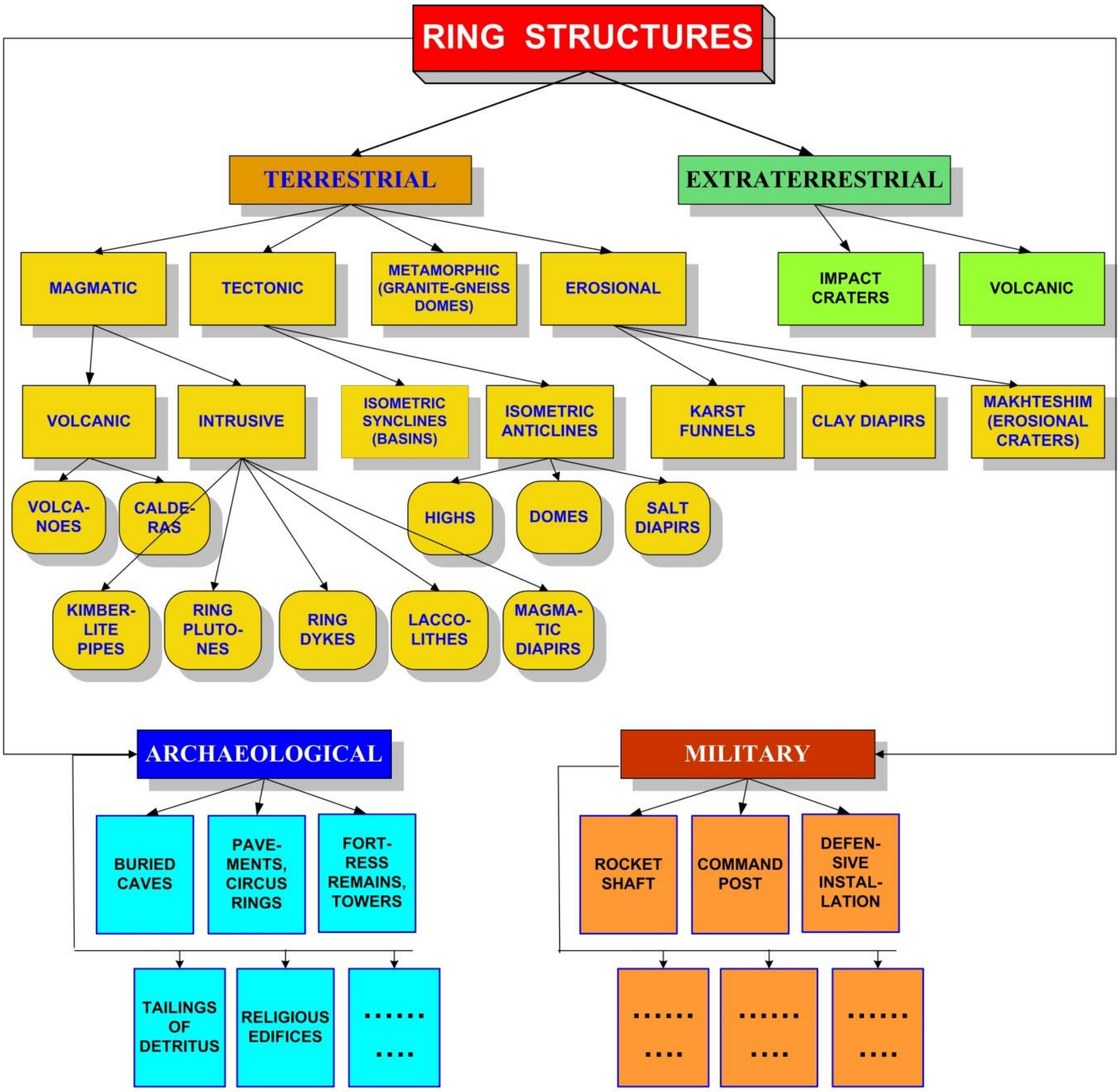

Fig. 11. Classification of ring structures in the Earth's environments (after Eppelbaum et al., 1998 and Eppelbaum, 2007a, revised and supplemented)

The apparent graticule radii drawn an interval of 45° determine the horizontal gradients (Fig. 12c). The sum of the gradients should be higher in the presence of circular features, and other signals should remain constant (an example from the magnetic prospecting is demonstrated). Here the correlation of the sum of gradients (or the average gradient) for a circle with a radius R_n, and a ring external to this circle limited by R_n and R_{n+1} radii makes it possible to determine whether the circular feature reflects ring structure (Fig. 12d). The sum of gradients inside the circle tends to zero in the absence of a centric texture. An application of this method is depicted on a model of an quasi-circular body magnetized along its dipping (Fig. 12a,b). It should be noted that this method demonstrated a better efficiency compared to other sophisticated approaches where the derivatives of high orders were calculated.

6.4. Indicators of dangerous geodynamic events at a depth

Electrical anomalies in the Earth's atmosphere have been observed many times before significant earthquakes (e.g., Pierce, 1976; Pulinets and Boyarchuk, 2004; Kachakhidze et al., 2009; Harrison et al., 2010).

Perturbations in the VLF phase and amplitude have been reported to occur before the large earthquakes (Kushida Y. and Kushida R., 2002; Hayakawa et al., 2010; Moriya et al., 2010; Rozhnoi et al., 2013). One of first studies of this effect reported about the use of the Omega navigation transmitters and claimed that 250 out of 350 earthquakes with the magnitude *M* greater than 4 were associated with phase and/or amplitude variations (Gokhberg et al., 1989).

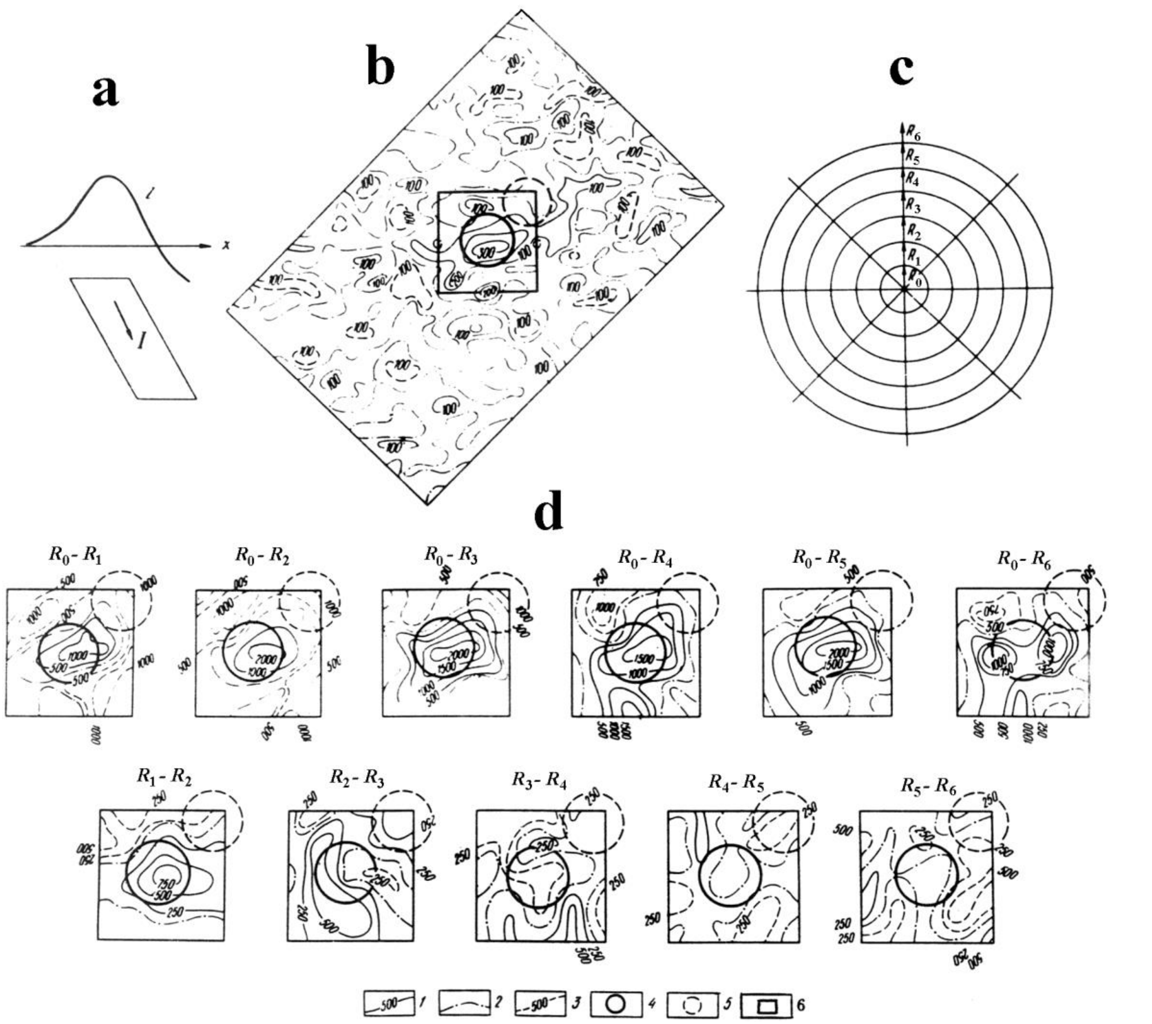

Fig. 12. Principal difference scheme for ring structure localization (on example of magnetic field processing) (modified after Khesin et al., 1996):
a) Magnetic field calculated from a model body (along profile), **b**) model field complicated by random noise (in plane), **c**) apparent graticule for ring structure selection,(**d**) singling out a model body by summing horizontal gradients of the field within apparent circular graticule zones.
Magnetic field intensity (in nanoTesla) of a model field (**b**) and the sum of its gradients (**d**) in conventional units: 1) positive, 2) zero, 3) negative; cylinder edge projection: 4) upper, 5) lower; 6) contour of the target shown in (**b**).

However, a subsequent test of the link between these variations and earthquakes concluded that the observed precursory relationship was not sufficiently statistically significant (Michael, 1997). Nevertheless, the same conclusion can be said about all other geophysical methods employed in the earthquake forecasting.

Fig. 13 indicates two negative VLF anomalies (total magnetic component H_φ was observed) at two frequencies from the VLF-transmitters occurring in Bordeaux, France (f = 15.1 kHz) (see also Table 1) and Krasnodar, Russia (f = 11.9 kHz). These observations were carried out in the Agdara area of Azerbaijan (Lesser Caucasus) before four days of earthquake with the magnitude of 4.8 with the epicenter occurring at the depth of 22 km. Besides the different employed frequencies, the VLF anomalies are characterized by the different azimuths to the transmitters, i.e. these anomalies are independent ones that increase reliability of these precursors. Interestingly to note that Smirnov's (2019) study testifies the appearing of significant *negative* Earth's electric anomalies before the dangerous geodynamic events.

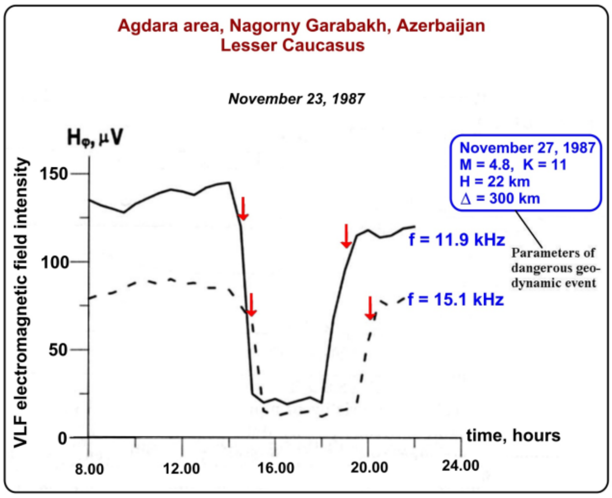

Fig. 13. VLF temporal variations as possible precursors of dangerous geodynamic events. Agdara area, Nagorny Garabakh, Azerbaijan (modified after Eppelbaum and Finkelstein, 1998)

6.5. Possible military application

An important peculiarity of a VLF ROV survey at different altitudes is the slow decrease of the VLF signal with increasing observation height over the Earth's surface (Гордеев и др., 1981; Oskooi and Pedersen, 2006; Eppelbaum and Khesin, 2012; Abtahi et al., 2016). Therefore, VLF ROV observations can effectively be applied for various military purposes (for instance, for delineation of underground tunnels and recognition of some targets shown in the right lower side of Fig. 11) (Eppelbaum, 2016).

7. Self-integration of different VLF frequencies and combination with other geophysical methods

It is known that such factors as the ambiguity of geophysical field examination, the complexity of geological scenarios and the low signal-to-noise ratio affect the possibility to developing reliable physical-geological models of subsurface structure. Presence of several dozens of the VLF transmitters in the world (part of these stations is shown in Table 1) allows to flexibly combine different frequencies, and these investigations can be integrated with other geophysical methods. Optimal variants of integration of VLF investigations with other geophysical methods for land and ROV variants for subsurface studying are shown in Fig. 14. It is necessary to note that employment of various VLF frequencies (they range from 10 to 30 kHz) which are characterized by different maximal depths of investigation δ gives additional possibilities to determine parameters of hidden anomalous body. Employment of VLF-transmitters located in the various regions of the world enables to utilize different azimuths from the emitting VLF stations that can also be used as an additional interpretation procedure.

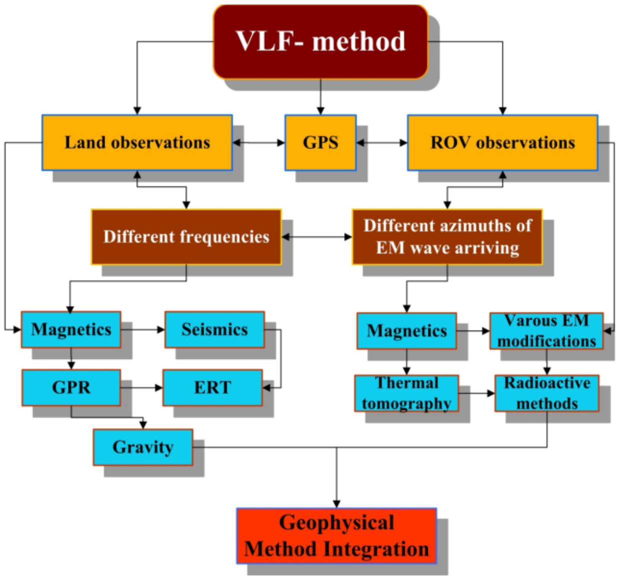

Fig. 14. Scheme of the VLF self-integration and combining with other geophysical methods

Application of the effective methodologies for geophysical method integration by the use of the theory of information and modern wavelet approach are described in detail in Eppelbaum et al. (2011), Alperovich et al. (2013), Eppelbaum (2014a, 2014b), Eppelbaum et al. (2014), Eppelbaum (2019, 2020). For instance, the modern wavelet methodologies include application of such effective procedures as 'matching pursuit combined with the wavelet packet dictionaries', 'diffusion maps', 'coherence portraits', 'complex Gaussian and Morlet wavelets', 'integrated polarization angle', 'curvelet transform', 'best classifiers' (here only a small part of the available approaches is listed). Employment of the aforementioned methodologies enables to recognize the hidden anomalous targets even under conditions of high ratios of the VLF "*noise*/*anomalous signal*".

Conclusions

It can be concluded that a successive system of the VLF method processing and interpretation has been developed. This system includes following components: removing temporal EM variations, elimination of rugged relief influence and advanced quantitative analysis of VLF anomalies observed under complex physical-environmental conditions (besides traditional parameters determined in magnetic prospecting, an angle of dipping for the anomalous bodies of non-spherical form can also be calculated). The developed system has been effectively approved on the VLF data observed in the Caucasian ore deposits (mainly in the polymetallic and gold-copper deposits of Azerbaijan). VLF investigations can also be applied for localization of archaeological targets and different types of subsurface mapping (example of ring structure delineation is shown in detail). A separate attention is paid to carrying out VLF surveys using the Remote Operative Vehicles. The possibility to utilize the VLF observations as possible precursors of the dangerous geodynamic events at a depth is displayed. Different schemes of the VLF method integration are shortly described.

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МЕТОД СДВР: УЛУЧШЕННАЯ СИСТЕМА ОБРАБОТКИ И ИНТЕРПРЕТАЦИИ (ОПРОБОВАНИЕ НА РУДНЫХ МЕСТОРОЖДЕНИЯХ КАВКАЗА)

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Резюме. Исследование электромагнитных (ЭМ) полей удаленных военных передатчиков сверхнизкочастотного (СНЧ) диапазона является одним из самых мобильных и недорогих геофизических методов. В настоящее время этот метод находит применение при поисках различных месторождений, разведке приповерхностных подземных вод, археологических исследованиях и геологическом картировании. Для геофизических исследований может быть использовано несколько десятков СНЧ-передатчиков, находящихся в разных регионах мира. Различные частоты и углы прихода регистрируемого ЭМ-излучения позволяют получить дополнительные преимущества при интерпретации. При исследовании методом СДВР (в западных публикациях используется аббревиатура VLF) используются как электрическая, так и магнитная составляющие ЭМ поля. Обычно предпочтение отдается магнитной компоненте ЭМ поля (*H*). Широкое использование метода СДВР ограничивалось отсутствием надежных методов устранения временных вариаций ЭМ поля, влияния сильнопересеченного рельефа и процедур количественной интерпретации СДВР-аномалий. Эти проблемы были успешно решены и объединены в единую методическую систему. Для исключения влияния вариаций во времени была разработана специальная фильтрационная процедура. Корреляционный метод позволяет кардинально снизить влияние пересеченного рельефа местности. Для количественной интерпретации аномалий СДВР доказана возможность использования современных методов, разработанных в магниторазведке для сложных геолого-геофизических условий. Наконец, для выявления скрытых объектов на фоне интенсивных геологических помех было предложено использование оригинальных статистических, информационных и вейвлет-алгоритмов. Главные компоненты разработанной интерпретационной системы были успешно применены на полиметаллических и медных месторождениях Кавказа.

Ключевые слова*: СДВ-передатчики, устранение временных вариаций, устранение влияния пересеченного рельефа, улучшенная количественная интерпретация, рудные месторождения, геолого-геофизическое картирование, предвестники землетрясений*

FUDR METODU: İŞLƏNİLMƏ VƏ İNTERPRETASİYANIN TƏKMİLLƏŞDİRİLMİŞ SİSTEMİ (QAFQAZIN FİLİZ YATAQLARINDA SINAQLANDIRMA)

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Xülasə. İfrat aşağı tezlik (İAT) diapazonuna malik uzaqlaşdırılmış hərbi otürücü sahələrinin elektromaqnit (EM) tədqiqi ən mobil və ucuz geofiziki üsullardan biridir. Hazırda bu üsul müxtəlif yataqların axtarışında, səthəyaxın yeraltı suların kəşfiyyatında, arxeoloji tədqiqatlarda və geoloji xəritələnmədə tətbiqini tapmışdır. Geofiziki tətqiqatlar üçün dünyanın müxtəlif regionlarında yerləşmiş onlarla İAT - ötürücülərdən istifadə oluna bilər. Müxtəlif tezliklər və qeyd olunan EM – şüalanmanın gəlmə bucağı təfsirdə əlavə üstünlük əldə etməyə imkan verir. FUDR (Qərb nəşrlərində VLF abbreviaturasından istifadə olunur) üsulu ilə tədqiqatda EM sahəsinin həm elektrik, həm də maqnit tərtibçilərindən istifadə olunur

Adətən EM sahəsinin maqnit komponentinə (H) üstünlük verilir. FUDR üsulunun geniş istifadəsi EM sahəsinin müvəqqəti variasiyalarının aradan qaldırılmasının etibarlı üsulların olmaması, relyefin kəskin dərə-təpəliyinin təsiri və FUDR anomaliyaların miqdari təfsirinin proseduru ilə məhdudlaşmışdır. Bu problemlər uğurla həll edilmiş və vahid metodik sistemdə birləşdirilmişdir. Zamanda variasiyaların təsirini istisna etmək üçün xüsusı filtrasiya proseduru hazırlanmışdır. Korrelyasiya üsulu ərazinin dərə-təpəliyinin təsirini əsaslı azaltmağa imkan verir. FUDR anomaliyalarının miqdari təfsiri üçün mürəkkəb geoloji-geofiziki şəraitlərdə maqnit kəşfiyyatında hazirlanmış müasir üsullardan istifadənin mümkünlüyü sübut edilmişdir. Nəhayət, intensiv geoloji əngəllər fonunda gizlin obyektlərin aşkar olunması üçün orijinal statistik, informasion və veyvlet-alqoritmlərdən istifadə edilməsi təklif edilmişdir. Hazirlanmış interpretasiya sisteminin əsas komponentləri Qafqazın polimetal və mis yataqlarında müvəffəqiyyətlə tətbiq edilmişdir.

Açar sözlər**:** *FUD-ötürücülər, müvəqqəti variasiyalarin aradan qaldırılması, dağ-təpəli relyefin təsirinin qaldırılması, təkmilləşdirilmiş miqdari təfsir, filiz yataqları, geoloji-geofiziki xəritələnmə, zəlzələlərin müjdəçiləri*