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THEORY AND INTERPRETATION OF MAGNETIC LOGGING

TEORIE A INTERPRETACE MAGNETICKÉ KAROTÁŽE

František Ryšavý [1]

Abstract

This paper is about recording of the magnetic susceptibility in boreholes there. It proceeds from the magnetic potential. Its first derivative in vertical direction is the change of intensity of the magnetic field. This change of this factor is dependent on the change of magnetization of rocks and, further, on the change of the magnetic susceptibility. It tends to relation between the change of the apparent magnetic susceptibility and the change of the real magnetic susceptibility. Information about magnetic susceptibility of rocks and ores are important mainly for construction the borehole section with the help of independent software systems.

Abstrakt

Tato práce pojednává o registraci magnetické susceptibility ve vrtech. Vychází se z magnetického potenciálu. Jeho prvá derivace ve vertikálním směru je změna intensity magnetického pole. Právě tato změna tohoto faktoru je závislá na změně magnetizace hornin a dále na změně magnetické susceptibility. To vede ke vztahu mezi změnou zdánlivé magnetické susceptibility a změnou skutečné magnetické susceptibility. Informace o magnetické susceptibilitě hornin a rud jsou důležité zejména při sestavování profilu vrtu prostřednictvím nezávislých softwarových systémů.

Keywords

magnetic field in borehole, magnetic susceptibility, calibration of logs, well-logging

Klíčová slova

magnetické pole ve vrtu, magnetická susceptibilita, kalibrace záznamů, karotáž

1. Introduction

Two kinds of magnetic measurement are made in boreholes, magnetic field and magnetic susceptibility. The magnetometers used in a magnetic field are fluxgates because they give continuous readings; by measuring three perpendicular components the total field can be calculated in direction as well as strength.

Magnetic susceptibility logs can also be made continuously a hole, using a coil system similar that in the induction logging tool. The log may be used to quantify the nickel content, or the estimation of the grade of iron ore deposits and also determining high susceptibilities in the mafic and ultramafic rocks and low in the felsic.

Now, you can lay a question why to incorporate magnetic logging into group measuring methods for sedimentary rocks. Magnetic measurements were always reserved for ore prospecting. However, new age offers evaluation based on sophistic higher evaluation results of measurements. They are various methods of analysis as factor analysis, regression analysis, analyses based on mathematical logic and next ones are. Fundamental input for such analyses is table as matrix having group physical characteristics in columns versus group the depth points in rows. The more characteristics are the better and more varied the offered borehole section is. Computer offers always virtual model of borehole section being constructed all exactly after characteristics on input. Each of new physical characteristic means more correct information. Quite small differences of magnetic properties in sediments can present significant change in variability of sedimentary rocks after physical properties. The model constructed all after well - logging measurements the interpreter can compare to geological borehole section. It is after me big contribution for geologists.

In the hydrocarbon prospecting is big problem how to prevent eruptions of gas/oil on the earth surface within drilling and well-logging. Into mud is added weighting material what present materials having high density. Substance must be almost powdered and well-soluble. These materials as a loaded mud penetrates into invasion zone where fill in pores and push father away hydrocarbons from the borehole wall.

From point of time consequence the first was barite. Barite has high density being 4500 kg/m^3. As a weighting material very well filled pore space. However, was totally insoluble. Perspective deposits were thanks this totally destroyed. Unfortunately, it happened too in The Czech Republic. Barite was eliminate as perspective weighting material and was finding a new substance. It was iron sawdust. Iron has very high density presenting 7800 kg/m^3. Iron is also well-soluble. As a weighting material it was an excellent substance. However, problems were with well-logging. The iron sawdust in invasion zone created highly electrically-conductive ring that made impossible make electrical logging. So was finding a better substance. Such material has happened powdered limestone having density 2930 kg/m^3. It is an excellent weighting material being suitable for well-logging too, however, for deposit with very high pressure it is not enough. In present time exist new additives, very expensive; iron sawdust, however, are not fully out of play. Big drilling corporations use modern expensive additives; but small firms drilling in remoted regions their using not exclude. In present time electrically-conductive iron ring does not present any obstacle for logging methods registered on basis of the focused electrical field. And this was why I decided to write chapter 4.

2. Classification of substances from point of view of magnetic properties

After JAVORSKIJ and DETLAF (1965) magnetic substances are classified into three main groups:

- Diamagnetic substances
- Paramagnetic substances
- Ferromagnetic substances

The diamagnetic substances are distributed into three subgroups:

- The group of classical substances
- The group of anomalous substances
- The group of superconductive substances (superconductors)

The classical diamagnetic substances are typical for inert gases, further, for metals as Zn, Au and Hg are, and for elements having non-metallic character like Si, Ph and also for some organic compounds. Their magnetic susceptibility is negative and its values are tiny. They are not dependent on temperature. The anomalous diamagnetic substances present element like Bi, Ga, Sb, C and some other. Their magnetic susceptibility is also negative, but, higher than it was in the before case and changes with temperature. Into superconductive substances there belong such elements like Pb, and Al are; some compounds of elements as Bi and Au are belong there and carbides of Mo and W, as well. What is characteristic for them is zero resistivity for certain temperature denoted like the transition temperature.

The paramagnetic substances are differed on:

- Normal substances
- The metal substances having their magnetic susceptibility independent of temperature
- Anti-ferromagnetic substances

The normal paramagnetic substances are gases like O_2, NO and metallic elements like Pt; further, chemical salts of Fe, Ni and Co and some next substances. All these have positive magnetic susceptibility and they are dependent on temperature. The metal paramagnetic substances are presented by alkaline metals like Li, Na and K are. What is characteristic for them is their magnetic susceptibility is positive and, in comparison to the former group, does not dependent on temperature. The anti-ferromagnetic substances have crystals of elements of transient groups, their compounds and alloys. They have anti-parallel orientation of magnetic moments for adjoining atoms of the crystal lattice. Here belong halogen salts of Fe, Cr and Mn.

The ferromagnetic substances are those having high magnetic susceptibility like elements Fe, Co and Ni. Their inner magnetic field is many-times higher than the generating outer magnetic field has. They have parallel orientation of magnetic moments for adjoining atoms of the crystal lattice. They are similar to anti-ferromagnetic substances; however, orientation of magnetic moments is different. If Curie-temperature is overcome, such substances will get paramagnetic. We have to distinguish the soft and hard ferromagnetic substances.

3. Magnetic fields in the borehole

Within derivation formulas of magnetic field I strictly respected way published by DACHNOW (1967), pages 294–299. The above author derived formulas for the change of magnetic potential in direction of z-axis. It is about measuring of gradient of the magnetic potential ΔZ what presents measuring difference being between two coins. In present time on ore deposits is measured the total vector of magnetic field.

Next proceeding presents transformation from ΔZ to Δ κ* what is the change of the apparent magnetic susceptibility of rocks. All adjustment is made again after formulas published by DACHNOW (1967). Adjustment tends to formula (18). In this formula important is function denoted as the characteristic function. This function determines theoretical form of curve over bed. It is determined with technical factors of tool and geological factors of borehole and bed. The function presents mathematical model making possible depict how well-logging curve will be look for different values of factors.

I shall investigate the change of magnetization of rocks denoted as ΔM [A/m]. It is a vector acting in the plane denoted as O_{xz}. It means that $\Delta M_x \neq 0$, $\Delta M_z \neq 0$, however, $\Delta M_y = 0$. The scalar magnetic potential denoted as U (magnetic voltage) is following:

$$U = \frac{1}{4} \times (\Delta M_x) \times \int_0^{2\pi} \int_{(z-h/2)}^{(z+h/2)} \int_{r_0}^{\infty} \frac{\rho^2 \times \cos\phi}{\left(\rho^2 + z^2\right)^{\frac{3}{2}}} \, d\rho \, dz \, d\varphi + \frac{1}{4} \times (\Delta M_z) \times \int_0^{2\pi} \int_{(z-h/2)}^{(z+h/2)} \int_{r_0}^{\infty} \frac{\rho \times z}{\left(\rho^2 + z^2\right)^{\frac{3}{2}}} \, d\rho \, dz \, d\varphi . \qquad (1)$$

Formula (1) was published by DACHNOW (1967) there. The first part of formula (1) is zero. It holds that:

$$\frac{1}{4} \times (\Delta M_x) \times \int_0^{2\pi} \int_{(z-h/2)}^{(z+h/2)} \int_{r_0}^{\infty} \frac{\rho^2 \times \cos\varphi}{\left(\rho^2 + z^2\right)^{\frac{3}{2}}} \, d\rho \, dz \, d\varphi = 0 . \qquad (2)$$

You receive this expression:

$$U = \frac{1}{4} \times (\Delta M_z) \times \int_0^{2\pi} \int_{(z-h/2)}^{(z+h/2)} \int_{r_0}^{\infty} \frac{\rho \times z}{\left(\rho^2 + z^2\right)^{\frac{3}{2}}} \, d\rho \, dz \, d\varphi , \qquad (3)$$

$$r_0 = \left(\frac{d}{2}\right) \times \left[\left(\frac{2\Delta}{d}\right) \times \cos\varphi + \sqrt{1 - \left(\frac{2\Delta}{d}\right)^2 \times \sin\varphi^2} \right], \qquad (4)$$

where Δ … eccentricity of tool presenting the distance between axis of tool and axis of borehole [m],
d … the diameter of borehole [m], and
U… the scalar magnetic potential [A].

After integration of variable ρ you shall get this double integral:

$$U = \frac{1}{4\pi} \times \left(\Delta M_z \right) \times \int_0^{2\pi} \int_{(z-h/2)}^{(z+h/2)} \frac{z}{\sqrt{r_0{}^2 + z^2}} \, dz \, d\varphi. \tag{5}$$

You register, however, the change of potential in direction of z-axis.

$$\Delta Z = -\frac{dU}{dz}. \tag{6}$$

Formula (5) needs to be differentiated. We attain the following formula:

$$\Delta Z = -\frac{1}{4\pi} \times \left(\Delta M_z \right) \times \int_0^{2\pi} \left\{ \frac{\left(2\bar{z} + \bar{h} \right)}{\sqrt{\left(2\bar{z} + \bar{h} \right)^2 + \left(2 r_0 \right)^2}} - \frac{\left(2\bar{z} - \bar{h} \right)}{\sqrt{\left(2\bar{z} - \bar{h} \right)^2 + \left(2 r_0 \right)^2}} \right\} d\varphi, \tag{7}$$

$$\bar{z} = \frac{z}{d}, \tag{8}$$

$$\bar{h} = \frac{h}{d}, \text{ and} \tag{9}$$

$$\bar{\Delta} = \frac{\Delta}{d}. \tag{10}$$

If I substitute from formula (4) for r_0 and I use formula (10), I shall receive this expression:

$$\begin{aligned} \Delta Z = &-\frac{1}{4\pi} \times \left(\Delta M_z \right) \times \int_0^{2\pi} \frac{\left(2\bar{z} + \bar{h} \right)}{\left\{ \left(2\bar{z} + \bar{h} \right)^2 + \left[\left(2\bar{\Delta} \right) \times \cos\varphi + \sqrt{1 - \left(2\bar{\Delta} \right)^2 \times \left(\sin\varphi \right)^2} \right]^2 \right\}^{\frac{1}{2}}} \, d\varphi \\ &+ \frac{1}{4\pi} \times \left(\Delta M_z \right) \times \int_0^{2\pi} \frac{\left(2\bar{z} - \bar{h} \right)}{\left\{ \left(2\bar{z} - \bar{h} \right)^2 + \left[\left(2\bar{\Delta} \right) \times \cos\varphi + \sqrt{1 - \left(2\bar{\Delta} \right)^2 \times \left(\sin\varphi \right)^2} \right]^2 \right\}^{\frac{1}{2}}} \, d\varphi. \end{aligned} \tag{11}$$

If you suppose that:

$$K = \left(2\bar{z} \pm \bar{h} \right), \tag{12}$$

you shall solve this integral:

$$\int_0^{2\pi} \frac{K}{\left\{ K^2 + \left[\left(2\overline{\Delta}\right)\times\cos\varphi + \sqrt{1-\left(2\overline{\Delta}\right)^2\times\left(\sin\varphi\right)^2} \right]^2 \right\}^{\frac{1}{2}}}\, d\varphi = = 2\int_0^{\pi} \frac{K}{\left\{ K^2 + \left[\left(2\overline{\Delta}\right)\times\cos\varphi + \sqrt{1-\left(2\overline{\Delta}\right)^2\times\left(\sin\varphi\right)^2} \right]^2 \right\}^{\frac{1}{2}}}\, d\varphi . \tag{13}$$

You have to use substitution t = tg (φ/2) and you shall get the integral:

$$4\int_0^{\infty} \frac{K}{\left\{ K^2 + \left[\left(2\overline{\Delta}\right)\times\cos\varphi + \sqrt{1-\left(2\overline{\Delta}\right)^2\times\left(\sin\varphi\right)^2} \right]^2 \right\}^{\frac{1}{2}}} \times \frac{dt}{1+t^2} . \tag{14}$$

This integral has been solved with the help of the complex variable. Result of integration is presented like this:

$$\Delta Z = (\Delta M_Z) \times f\left(\overline{z}, \overline{h}, \overline{\Delta}\right), \quad \text{and} \quad f\left(\overline{z}, \overline{h}, \overline{\Delta}\right) = -\frac{1}{2} \times \left\{ \frac{\left(2\overline{z}+\overline{h}\right)}{\sqrt{\left(2\overline{z}+\overline{h}\right)^2 + \left(2\overline{\Delta}+1\right)^2}} - \frac{\left(2\overline{z}-\overline{h}\right)}{\sqrt{\left(2\overline{z}-\overline{h}\right)^2 + \left(2\overline{\Delta}+1\right)^2}} \right\}, \tag{15) (16}$$

where $f\left(\overline{z}, \overline{h}, \overline{\Delta}\right)$ … the characteristic function for the case having no invasion zone; it holds that $D_i = d$, i.e., $\overline{D}_i = 1$,

ΔM_z … the change of magnetization of rocks in direction of z-axis [A/m], and

ΔZ … the change of intensity of the induced magnetic field in direction of z-axis, [A/m].

You can use the next formula:

$$(\Delta M_z) = (\Delta \kappa) \times H_z , \tag{17}$$

where $\Delta\kappa$ … the change of the real magnetic susceptibility of rocks, and

H_z … the normal component of intensity of the earth magnetic field for non-magnetic surroundings directed in z-axis, [A/m].

The component of the earth magnetic field is registered on the free surface of the earth at the position where the borehole is located. The trouble is that the drilling tower presents gigantic accumulation of iron material; therefore factor H_z is taken away of the maps of magnetic field for the mentioned area or the earth magnetic field is gauged in the place where influence of the drilling tower is zero.

Relation (17) can be implemented in formula (15) and then you attain these formulas:

$$\left(\Delta \kappa^*\right) = (\Delta \kappa) \times f\left(\overline{z}, \overline{h}, \overline{\Delta}\right), \text{ and} \tag{18}$$

$$\left(\Delta\kappa^{*}\right)=\frac{\Delta Z}{H_z},\tag{19}$$

where $\Delta\kappa^{*}$ … the change of the apparent magnetic susceptibility of rocks and

$\Delta\kappa$ … the change of the real magnetic susceptibility of rocks.

Both characteristics are dimensionless. This is relation for the case having no invasion zone. In most cases the beds with invasion zone are presented like the magnetically-homogeneous surroundings and therefore it is possible to use formulas (18) and (16) for calculation. However, if you use iron powder/sawdust like one of additive component for heavy mud which invades into beds, there will be situation all other. Magnetic material invaded in beds makes change surroundings on the magnetically-inhomogeneous one. Such porous bed saturated with iron material has its invasion zone and behaves like the vein of magnetic ore. Formula for the characteristic function must be adjusted to reflect this new fact.

4. Invasion zone and its influence

Invasion zone that under ordinary conditions is not magnetic behaves as bed without invasion. But if you use iron powder /sawdust it will get visible. The deeper invasion is the stronger magnetization will be. Such inhomogeneous magnetic bed looks then as real ore or mafic rock. With the help of the characteristic function you can make various models of theoretical curve. It is important for changes being close to thickness of bed and position of tool in the borehole. It is clear for registering thin beds is better the centred tool than the pressed tool to the borehole wall. It is clear in fig.3.

Inhomogeneous magnetic bed is directed by the following formula valid for the characteristic function:

$$\mathrm{f}\left(\bar{z},\bar{h},\bar{\Delta},\bar{D}_i\right)=-\frac{1}{2}\times\left\{\frac{\left(2\bar{z}+\bar{h}\right)}{\sqrt{\left(2\bar{z}+\bar{h}\right)^2+\left[2\bar{\Delta}+(\bar{D}_i)^{-1}\right]^2}}-\frac{\left(2\bar{z}-\bar{h}\right)}{\sqrt{\left(2\bar{z}-\bar{h}\right)^2+\left[2\bar{\Delta}+(\bar{D}_i)^{-1}\right]^2}}\right\}.\tag{20}$$

Note, please, that the term denoted as $\left(2\bar{z}\pm\bar{h}\right)$ presents acting of factors $\bar{z}$ and $\bar{h}$ in vertical direction, whereas, the term $\left(2\bar{\Delta}+1/\bar{D}_i\right)$ reflects acting of factors $\bar{D}_i$ and $\bar{\Delta}$ in horizontal direction. We can analyse this formula to reach an imagination about action of those characteristics on recording.

4.1 Centred tool

The axis of tool and the axis of borehole are identical. Here holds condition that $\bar{\Delta}=0$. Then formula (20) attains this form:

$$\mathrm{f}\left(\bar{z},\bar{h},\bar{D}_i\right)=-\frac{1}{2}\times\left\{\frac{\left(2\bar{z}+\bar{h}\right)}{\sqrt{\left(2\bar{z}+\bar{h}\right)^2+(\bar{D}_i)^{-2}}}-\frac{\left(2\bar{z}-\bar{h}\right)}{\sqrt{\left(2\bar{z}-\bar{h}\right)^2+(\bar{D}_i)^{-2}}}\right\},\ \text{and}\tag{21}$$

$$\overline{D}_i = \frac{D_i}{d}, \tag{22}$$

where D_i = the depth of invasion zone.

Formula (21) does not distinguish whether the tool is thick or thin. Factor $\overline{D}_i$ varies in the following interval:

$$1 \leq \overline{D}_i < \infty. \tag{23}$$

If it is no invasion zone on condition that $\overline{D}_i$ = 1, you will obtain the form of the characteristic function being identical with the characteristic function of SP-potentials when it is the centred tool; only the sign is inverse.

$$f\left(\overline{z},\overline{h}\right) = -\frac{1}{2} \times \left\{ \frac{\left(2\overline{z}+\overline{h}\right)}{\sqrt{\left(2\overline{z}+\overline{h}\right)^2+1}} - \frac{\left(2\overline{z}-\overline{h}\right)}{\sqrt{\left(2\overline{z}-\overline{h}\right)^2+1}} \right\}, \ \ldots \text{for } \overline{D}_i = 1. \tag{24}$$

If it is valid that $\overline{D}_i \neq 1$, there will hold equation (21). In the case that $\overline{D}_i = \infty$ it is valid that its reciprocal value is zero. In such case holds $f\left(\overline{z},\overline{h}\right) = 0.$ It is then independent of characteristics $\overline{z}$ and $\overline{h}$. Such case is however only theoretical.

If it is that the value in the centre of bed is zero, $\overline{z}$ = 0, and $\overline{D}_i < \infty$ from equation (21) you will receive that:

$$f\left(\overline{h},\overline{D}_i\right) = \frac{\overline{h}}{\sqrt{\left(\overline{h}\right)^2 + \left(\overline{D}_i\right)^{-2}}}. \tag{25}$$

If it holds that $\overline{D}_i \rightarrow \infty$, you will get this relation:

$$\lim_{\overline{D}_i \to \infty} f\left(\overline{h},\overline{D}_i\right) = 1. \tag{26}$$

This is very important relation saying that the characteristic function on condition that the depth of invasion zone is infinite **is independent of thickness** of bed. The deflections are always very high for **both thick and thin beds together**; it is important not only for location of magnetic veins formed as stringer set, but too for basic volcanic material in form of gravels or pebbles as basalts, phonolites and others are.

This fact is better evident when you compare that with the case when it will hold that $\overline{D}_i$ = 1. From equation (24) it results that for $\overline{z}$ = 0 you will get this expression:

$$f\left(\overline{h},\overline{D}_i\right) = \frac{\overline{h}}{\sqrt{\left(\overline{h}\right)^2 + 1}}. \tag{27}$$

This will be all other case. Here you have to distinguish; for thick bed it holds that $\overline{h} \rightarrow \infty$ and there is valid that

$$\lim_{\overline{h} \to \infty} f\left(\overline{h},\overline{D}_i\right) = 1. \tag{28}$$

However, for thin bed there exists all other condition:

$$\lim_{\bar{h}\to 0} f(\bar{h},\bar{D}_i) = 0 . \tag{29}$$

Thus you can expect that the veins of the magnetic ore presented like thin beds with infinitely deep invasion will have for the centred tool very high and narrow deflections. Such deflections can be highly interesting for interpretation. It can be said that in the nature environment ore sets being well-branched into thin ore veins are nothing special. That is true too for magnetic ores.

It was said yet that the characteristic function of centred tool, if there is no invasion, is identical to the characteristic function of SP-potentials; except the sign. It holds that vertical component ΔZ of the magnetic field and SP-potentials USP have the same characteristic function. Dachnow (1967) explained this fact by that the distribution of the magnetic field in the borehole is for the centred tool fully identical with distribution of the electric field of SP-potentials. However, the magnetic field has contradictory orientation than it is for the field of SP-potentials; the lines of force of the induced magnetic field in bed are inversely oriented to those lines of the earth magnetic field.

The change of the real magnetic susceptibility has positive and negative values; it depends on redundancy or deficit of the real magnetic susceptibility. As the characteristic function is negative the registered values of the apparent magnetic susceptibility will have inverse sign in comparison to those real. The continuous curve of the apparent values will oscillate around zero line; the recorded data will be positive and negative.

4.2 Pressed-to tool

This event is dependent on the diameter of tool. This presents condition that there holds this relation:

$$\bar{\Delta} = \frac{1}{2}\times\left(1-\bar{d}_s\right), \text{ and} \tag{30}$$

$$\bar{d}_s = \frac{d_s}{d}, \tag{31}$$

where d_s = the diameter of tool [m].

Factor $\bar{d}_s$ varies in the interval as follows:

$$0 < \bar{d}_s \le 1 . \tag{32}$$

Both limits of the interval present two extreme cases; for $\bar{d}_s \to 0$ it is thin tool, whereas, for $\bar{d}_s \to 1$ it is thick tool filling up all borehole diameter.

The tool is pressed on the wall of borehole. If you substitute this condition (30) for $\bar{\Delta}$ into equation (20), you will receive the following formula:

$$f\left(\bar{z},\bar{h},\bar{d}_s,\bar{D}_i\right) = -\frac{1}{2}\times\left\{\frac{\left(2\bar{z}+\bar{h}\right)}{\sqrt{\left(2\bar{z}+\bar{h}\right)^2+\left[1-\bar{d}_s+(\bar{D}_i)^{-1}\right]^2}} - \frac{\left(2\bar{z}-\bar{h}\right)}{\sqrt{\left(2\bar{z}-\bar{h}\right)^2+\left[1-\bar{d}_s+(\bar{D}_i)^{-1}\right]^2}}\right\}. \tag{33}$$

If $d_s = d$ it means that $\bar{d}_s = 1$. You attains again formula (21), because the tool is simultaneously pressed-to and centred. Condition when holds $\bar{d}_s = 1$ is the case of thick tool. In contrary, if it holds that $d_s << d$, it presents that $\bar{d}_s \rightarrow 0$. It is case of thin tool. Then equation (33) will take this form:

$$f\left(\bar{z},\bar{h},\bar{D}_i\right)=-\frac{1}{2}\times\left\{\frac{\left(2\bar{z}+\bar{h}\right)}{\sqrt{\left(2\bar{z}+\bar{h}\right)^2+\left[1+(\bar{D}_i)^{-1}\right]^2}}-\frac{\left(2\bar{z}-\bar{h}\right)}{\sqrt{\left(2\bar{z}-\bar{h}\right)^2+\left[1+(\bar{D}_i)^{-1}\right]^2}}\right\}. \tag{34}$$

If there is no invasion it is valid that $\bar{D}_i = 1$. You obtain the formula being identical again to the characteristic function of SP-potentials when the thin tool is pressed on the wall of borehole.

$$f\left(\bar{z},\bar{h}\right)=-\frac{1}{2}\times\left\{\frac{\left(2\bar{z}+\bar{h}\right)}{\sqrt{\left(2\bar{z}+\bar{h}\right)^2+4}}-\frac{\left(2\bar{z}-\bar{h}\right)}{\sqrt{\left(2\bar{z}-\bar{h}\right)^2+4}}\right\},\ \ldots \text{for } \bar{D}_i=1 \text{ and } \bar{d}_s=0. \tag{35}$$

If it holds $\bar{D}_i \neq 1$ there have you equation (34). If you implement condition that $\bar{z} = 0$, you will attain relation as follows:

$$f\left(\bar{h},\bar{D}_i\right)=\frac{\left(\bar{h}\right)}{\sqrt{\left(\bar{h}\right)^2+\left[1+(\bar{D}_i)^{-1}\right]^2}}. \tag{36}$$

When it is valid that $\bar{D}_i \rightarrow \infty$, then you receive that:

$$\lim_{\bar{D}_i\rightarrow\infty} f\left(\bar{h},\bar{D}_i\right)=\frac{\bar{h}}{\sqrt{\left(\bar{h}\right)^2+1}}.$$

This is, however, relation (27). That is why you have to distinguish again thick and thin beds; compare relation (28) for thick ones and relation (29) for thin ones. You see distinctly that for the case when the tool is pressed-to **you cannot determine so well** thin beds presenting **the veins of magnetic ore**. Therefore the tool should be always centred for recording.

It ought to be added more, if you have the known fixed value of the real magnetic susceptibility from samples denoted as κ_0, then it is possible to determine all continuous curve of the magnetic susceptibility with depth after this formula:

$$\kappa_{i+1}=\kappa_i+\Delta\kappa_{i+1} \quad , i=0,1,2,3\ldots,(n-1). \tag{37}$$

The constructed continuous curve of κ will have negative and positive values again. After DOBRYNIN (1988) the real magnetic susceptibility of rocks and minerals varies in the interval $-200\times10^{-6}\,\mathrm{SI} \le \kappa\times10^{6} \le +20\,\mathrm{SI}$; it is evident that the magnetic susceptibility expressed in units SI – it is its value multiplied by 10^6, i.e., $(\kappa\times10^6)$. The same holds for the change of the magnetic susceptibility; it holds that $(\Delta\kappa\times10^6)$. The diamagnetic rocks have $\kappa < 0$, the paramagnetic ones have $\kappa > 0$ and the ferromagnetic ones have $\kappa >> 0$. Data usually vary around zero level.

For counting of the change of real magnetic susceptibility you will use relation from equation (18):

$$(\Delta\kappa) = (\Delta\kappa^{*}) \,/\, \mathrm{f}\left(\bar{z}, \bar{h}, \bar{\Delta}\right) \text{ for } \bar{z} = 0 . \tag{38}$$

Fig.1 presents three characteristic functions for the pressed-to tool, whereas, fig.2 depicts three characteristic functions for the centred tool on condition that it is thin tool. Both figures are for no invasion zone when holds that $\bar{D}_i = 1$. Note, please, the centred position of tool is much marked than state when the tool is pressed to wall of borehole. It holds namely for those beds being thin and very thin.

It is better depicted in next figure. Fig.3 compares differences between the centred and pressed-to tools for various thicknesses of beds. For depiction of thin volcanic rocks as basalts, phonolites and as well as for thin veins of magnetic ores containing Fe, Co and Ni the position of the centred tool ought to be almost absolutely imperative.

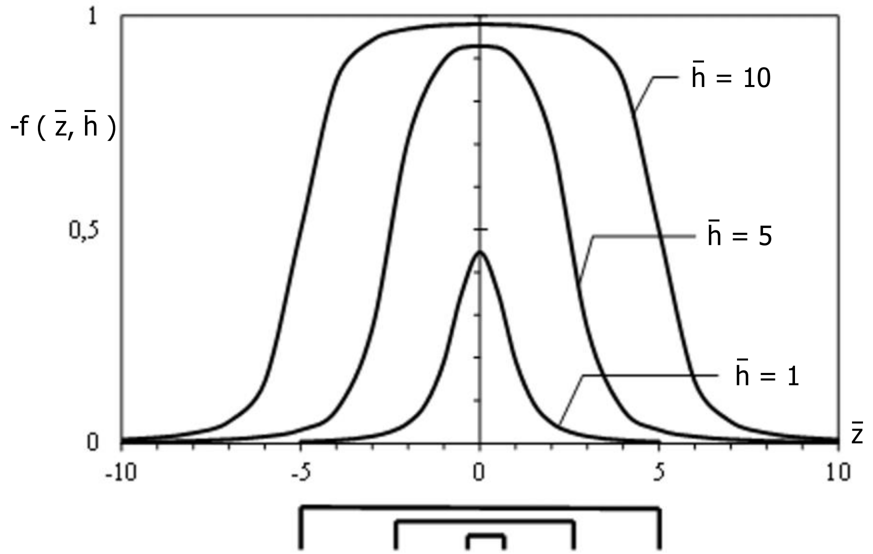

Fig. 1 Depiction of the characteristic function for pressed-to tool

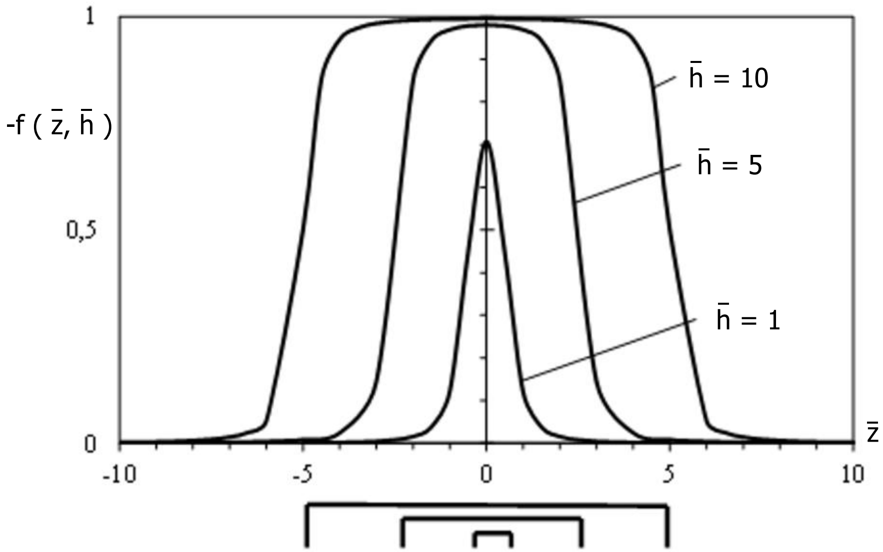

Fig. 2 Depiction of the characteristic function for centred tool

5. Calibration of Magnetic Log

We register either characteristic ΔZ, or rather characteristic denoted as κ^*. Thus, we can suppose that the deflection being on output of equipment is the change of the apparent magnetic susceptibility. Calibration of magnetic logs presents relation $I = f(\Delta\kappa^*)$, when reflection denoted as I reflects ratio of two independent factors. There exist double way of calibration: with outer standards and with inner standards. It is encouraged to make controlling of inner standards with the help of outer ones.

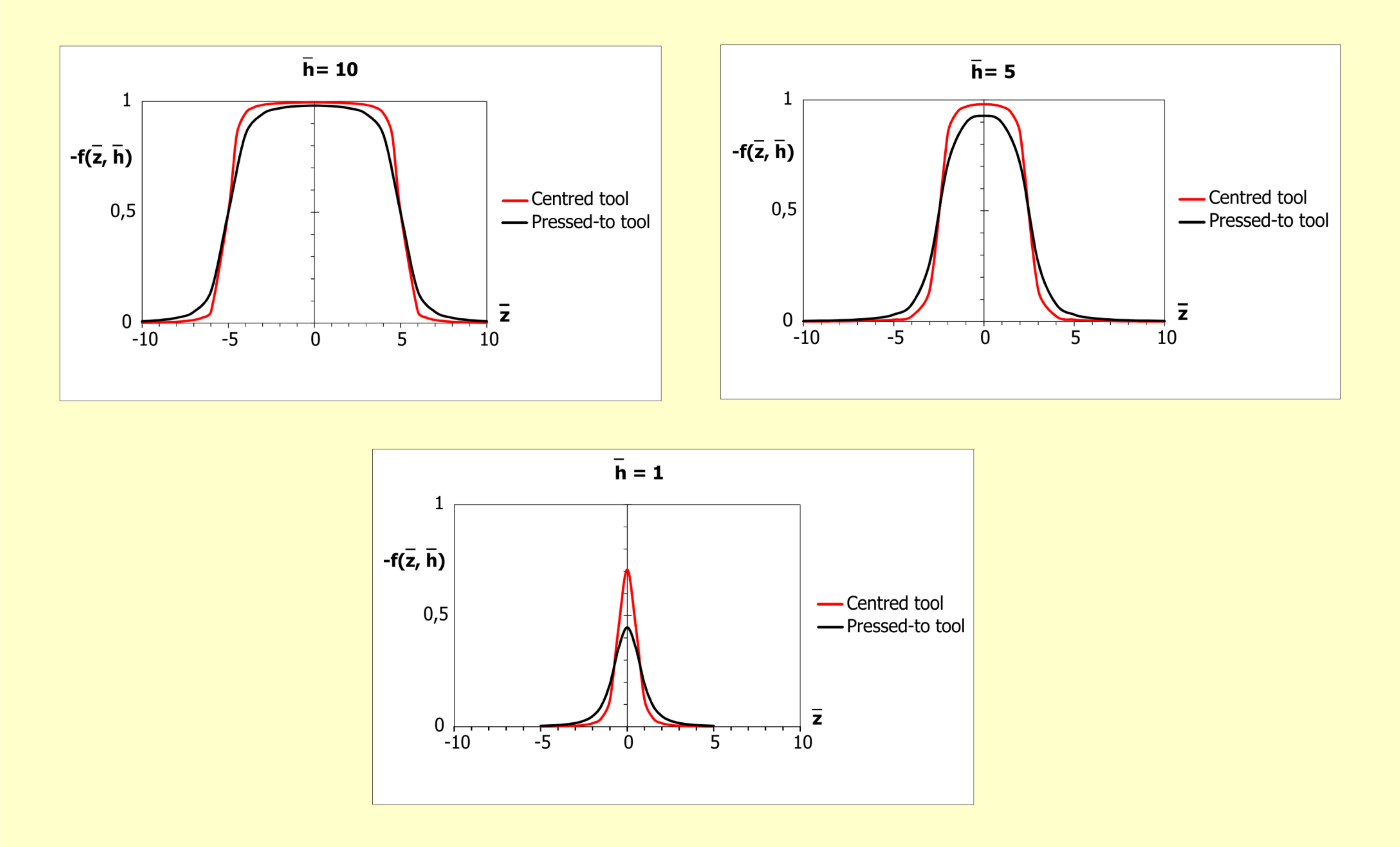

Fig. 3 Different positions of tool for thick, middle and thin beds

5.1 Outer standards

The first way needs to have two standards – simulators of susceptibility – for high and low values of magnetic susceptibility. Each of standards is presented by coaxial cylinder manufactured from magnetic substances. For high susceptibility it should be magnetic alloy like electrolytic iron, Armco and Alfenol are. For low magnetic susceptibility it can be a plaster impregnated with homogeneous powder magnetite.

The length of such cylinder presents thickness of bed being denoted as h. The tool is put into cylinder in the centred position and that means that $\Delta = 0$. Thickness of cylinder presents the characteristic D_i. The distance between the centre of cylinder and the centre of detector is denoted as z.

This distance you can change; you can have in this way arbitrary amount of data for relation $I = f(\Delta\kappa^*)$. The last characteristic is the inner diameter of cylinder denoted as d. The cylinder undoubtedly simulates the bed for the centred tool. Therefore it is possible to use this formula:

$$\left(\Delta\kappa^* \times 10^6\right) = \left(\Delta\kappa_s \times 10^6\right) \times f\left(\bar{z}, \bar{h}, \bar{D}_i\right). \qquad (39)$$

It ought to be said that characteristic $\Delta\kappa_s$ is the change of real magnetic susceptibility of standard in SI-units which is determined in laboratory and regularly inspected. With the help of both standards we get arbitrary amount of points. So you have arbitrary amount of calibration dyads for construction relation $I = f(\Delta\kappa^*)$ what means you will be able to cover all range of magnetic susceptibility from known quantity magnetic substances. In the case of the outer standards; calibration and inspection of stability of equipment is made simultaneously. It does not for the case of inner standards.

5.2 Inner standards

The second way is using inner standards. These present two independent voltage sources denoted as U_1 and U_2 having accurately calibrated values in [mV]. Accuracy of both sources must be $\Delta U = \pm 0.1$mV. By selection of values on both sources you reach arbitrary ratio which is conveyed to the scale of equipment. It is possible to do that, because the apparent magnetic susceptibility is defined in accordance to formula (19) like dimensionless ratio of two independent factors. Thus, in this way you make a calibration of the scale very easy.

The selected ratio presents value of the change of the apparent magnetic susceptibility. For linear scale it is enough only one standard. It holds that:

$$\left(\Delta\kappa_s \times 10^6\right) = \frac{U_1}{U_2} \times 10^6 \ . \qquad (40)$$

The deflection on the recorder is denoted as l_0 .It is presented by the following formula:

$$l_0 = \frac{\left(\Delta\kappa_s \times 10^6\right)}{n} \qquad (41)$$

, where n = the step of linear scale expressed in $\left[\Delta\kappa \times 10^6 / 1\text{cm}\right]$.

I should like to remark that calibration is made in SI-units; the same is valid for recording of magnetic logs. Finally, I think both ways are interesting; each of them has own positives and negatives and it will be only the producer who select this or that way.

6. Conclusions

- Magnetic Logs are well-used not only for prospecting of Fe, Co and Ni ores, but too, for location of effusive volcanic rocks in the sedimentary basins.
- Classical invasion zone without any magnetic minerals presents homogeneous non-magnetic surroundings. This case is identical to one when there is no invasion zone.
- If heavy mud has like additive iron sawdust, the homogeneous magnetic surroundings will change on inhomogeneous.
- It presents that for an extremely deep invasion both thick and thin beds have the characteristic function extraordinary high near to one for value in the centre of bed. This holds only for the centred position of tool.
- In such case there is suppressed an influence of the bed thickness and influence of the magnetic material quantity is intensifying.
- It means in practice that the stringer sets of magnetic ores and thin beds saturated with magnetic material for the tool being in the centred position will be very well-visible. It is valid for deep-invaded thin beds in case of centred position of tool.
- Deflections of such beds will be narrow and high, whereas for no-invaded thin beds holds that have small deflections.
- Calibration is made either with two outer cylindrical standards, or with one inner standard presenting two voltage sources.

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Author:
[1] RNDr. František Ryšavý, Lesní 3, 695 03 Hodonín, Czech Republic, rysavy.frantisek@seznam.cz