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Effects of and methods for determination of induced magnetic anisotropy of igneous and metamorphosed rocks

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ABSTRACT

The phenomena of the magnetic memory of rocks associated with paleointensity, paleotemperature, and paleostress are reviewed and discussed here. The methods for the determination of the paleointensity and the paleoconditions are described and discussed in terms of their sensitivity and applicability. The determination of paleoconditions (stress and temperature) is essential for understanding rock mineral formation and rock history. Such knowledge is applicable also in ore deposit geology and geophysics. The phenomena of the magnetic memory manifest themselves through the constriction and asymmetry in the hysteresis loops, as well as through a nonlinear pattern in the anhysteretic magnetization curve, both being due to the induced magnetic anisotropy. The pros and cons of some applied methods are reviewed. The superposition of several paleotemperatures (re-heatings of the rock) and/or paleostresses is studied also. Under certain conditions, a rock can remember information on several paleotemperatures (paleo-heating events), as well as the respective intensities of the geomagnetic field of the past.

Keywords: paleomagnetism, rock magnetism, magnetic memory, paleointensity, paleostress, paleotemperature, hysteresis loop, multi-domain

1. INTRODUCTION

The origin of deep-seated physical processes leading to the formation of various minerals cannot be studied without the knowledge of petrophysical properties of rocks. The ability of magnetic rock-forming minerals to store information about the conditions at their formation and during their existence is of particular importance among petrophysical properties. Here we focus on one particular aspect of rock magnetism - the magnetic memory of rocks in terms of paleointensity and paleotemperature. Attention is paid also to the role of paleostress as associated with the magnetic memory of rocks. The magnetic memory discussed here is related to the magnetic fabric (structure, arrangement) of the

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rock. By magnetic fabric we mean the configuration of magnetic domains in the magnetic minerals of the rock and the distribution of the energy gradient of the domain boundaries (*Vetchfinskii, 1992*). It is important to understand that the magnetic fabric of ferrimagnetic minerals stores not only the paleo-conditions of the distant past (at the origination of the rock), but also relatively recent effects of various factors acting on the rock during the course of its existence. For example, during intense volcanic (intrusions/extrusions) or tectonic activity rocks are subjected to the effects of variations in both temperature and stress. In the presence of the geomagnetic field, the whole set of varying external factors (pressure, high temperatures, and so on) can change the magnetic fabric of a ferrimagnetic mineral in such a way that all of these effects will be recorded by its magnetic memory. The presence of a constant geomagnetic field is the most crucial condition of the magnetic fabric formation.

Among major factors determining the mineral composition and structure of rocks are the paleotemperature and the paleopressure. The terms paleotemperature and paleopressure refer here to the temperature of the secondary heating of a rock in a certain (possibly quite recent) geological period of its existence (after its formation) and the pressure that acted on the rock during the same time period. The study of the ability of rocks to store information on the paleotemperature and paleopressure is a way of understanding the formation mechanism of minerals and of predicting their position within rocks. The reconstruction of paleopressures and paleotemperatures is of importance in ore geophysics both theoretically and practically - in developing mineralization criteria - and in studies of deep-seated processes.

Various methods for the determination of paleointensity and paleotemperature have been developed (*Aabdulwahab and Coe, 1976*; *Banerjee and Mellema, 1974*; *Coe and Gromme, 1973*; *Domen, 1977*; *Kono and Ueno, 1977*; *Markert and Heller, 1972*; *McClelland, 1981*; *McClelland and Druitt, 1989*; *Nagata, 1961*; *Shaw, 1974*; *Vilson, 1961*, and others). We discuss here only the determination of paleointensity and paleotemperature based on the magnetic memory of rocks, not based on studying the remanent magnetization. The effects of the magnetic memory are directly associated with the so-called induced magnetic anisotropy (IMA) of rocks. When heated (or re-heated) to temperatures below the Curie temperature (T_C) and subsequently cooled in a constant magnetic field, it has been shown that rocks, which contain magnetic minerals, acquire an induced magnetic anisotropy. The IMA is capable of retaining information on the paleointensity of the geomagnetic field and the paleotemperature of the heating. The impact of paleostress on the magnetic memory, and the possibility of its determination are investigated also. Compared for instance to the Thellier method (e.g., *Kono and Ueno, 1977*) that is commonly applied in order to determine the paleointensity of rocks possessing thermoremanent magnetization, which works well on rock samples containing single-domain grains of ferromagnetic minerals, but may fail on rocks with multidomain mineral grains (*Shashkanov and Metallova, 1972*), the determination of the paleointensity based on the IMA-related magnetic memory is free of heating the rock sample, and works well for samples with multidomain magnetic composition.

Among the studies devoted to rock magnetic anisotropy we refer to *McFadden (1981)*, *Nagata (1970)*, and *Saratiri and Kino (1980)*. The phenomenon of the magnetic memory based on IMA is, however, a special case of magnetic anisotropy, and publications on this topic are sparser. In the 1920s investigators observed constricted loops of magnetic hysteresis in nickel and cobalt alloys subjected to thermal treatment in a zero magnetic field (*Elmen, 1929*). These "sausage-type" magnetization hysteresis loops were observed in the region of a zero magnetic field. In ferrite compositions $Fe_{3-x}Co_xO_4$ such loops were first found by Kato and Takey in the 1930s (see *Krupička, 1969, 1973*). Theoretical validations of this effect were reported later by *Néel (1954)*, and by *Taniguchi and Yamamoto (1954)* and *Taniguchi (1955)*, as well as by others, see *Krupička (1969, 1973).* There are several types of magnetic anisotropy known to the physics of magnetic materials (*Krupička, 1969, 1973*). Out of these, the IMA is one particular type. Constricted minor hysteresis loops for rocks were first observed by Radhakrishnamurty in basaltic lavas (*Runcorn, 1970*). Most recently, numerical modelling of constricted hysteresis loops was performed by *Tauxe et al. (1996)*. Constricted (or "wasp-waisted") loops were recently analyzed also by *Roberts et al. (1995)*.

Much of the work on the IMA as related to the magnetic memory of rocks was carried out in the former Soviet Union and Russia over the last 30 years. The findings we present here are to a great extent a review of those experimental and theoretical investigations, published prevailingly in Russian (*Bol'shakov and Vinogradov, 1986*; *Ershov, 1998*; *Ershov et al., 1999*; *Shashkanov, 1985*; *Shashkanov and Metallova, 1977, 1982*; *Shashkanov et al., 1975*; *Vetchfinskii, 1992, 1994*; *Vetchfinskii and Fillin, 1987*; *Vetchfinskii and Tselmovitch, 1992*; *Vetchfinskii and Vajda, 1998*; *Vetchfinskii et al., 1983, 1984, 1986, 1989, 1999*).

Constriction in the zero magnetic field is due to the independence (or weak dependence) of the initial magnetic susceptibility on the magnetization field. This phenomenon, referred to as perminvar effect, is caused by diffusion-induced stabilization of the domain boundaries (DBs). This stabilization results in "gigantic" potential barriers on the DB motion path. A DB gets into a potential energy well, while IMA develops in ferrimagnetic materials.

Investigations, to be reviewed and discussed, have revealed that cooling of ferrimagnetic specimens in a constant magnetic field (H_T) from temperatures T_x lower than the Curie temperature (T_C) to room temperature (T_r) can result in extraordinary constricted minor magnetization hysteresis loops. The constriction is a manifestation of the IMA. These constrictions are observed at the values of the magnetization field close to or equal to that of the field strength H_T (see Fig. 1). Subsequent heating of the specimens from room temperature causes the constriction to disappear at the temperature T_x. By the constriction in the hysteresis loop, the magnetic fabric of these ferrimagnetic materials, formed in the course of thermomagnetic treatment, can identify and store information about the magnetic field and the temperature at which this ferrimagnetic material was treated. In this case, a special type of IMA develops.

In Section 2 we describe natural and synthetic samples, as well as equipment, used in studying the magnetic memory of rocks due to IMA. Section 3 deals with the effects of the magnetic memory manifested in hysteresis loops as constrictions and asymmetry, in induced anhysteretic magnetization as non-linearity, and in magnetic susceptibility as an anomaly. Various hysteresis loops are treated there with due attention. Section 4 is devoted to giant Barkhausen jumps as to the cause of the IMA constrictions. In Section 5 we review the previous and discusses the recent results of investigations of IMA. In

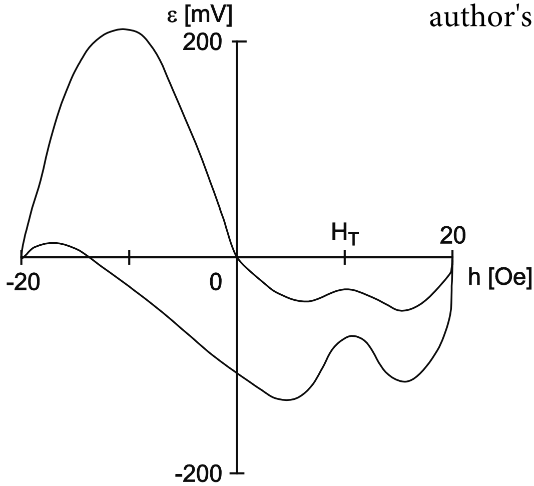

Fig. 1. Illustration of the manifestation of magnetic memory by the constriction in the compensated differential minor hysteresis loop (CDHL), T_X= 250°C, H_T= 10 Oe. ε means electromotive force (e.m.f.) in mV, which corresponds to magnetization.

Section 6 we discuss the physics behind the processes responsible for the magnetic memory of rocks due to IMA. In Section 7 we summarize and conclude the presented work.

2. SAMPLES, EXPERIMENTAL WORK, AND EQUIPMENT

The properties of the IMA magnetic memory were studied on samples of rocks ranging in age from a few tens of years (for example lavas of the latest eruption of the Tolbachik volcano) to 100–200 Ma (Cretaceous–Jurassic). Samples of lavas and tuffs of Armenia, Scotland, Mongolia, the Far East, Kamchatka, the Kurile Islands, the Yana-Kolyma fold area, and the Mid-Atlantic Ridge were investigated. The majority of these rocks contained magnetite and titanomagnetite with Curie points ranging from 170 to 570°C. Some pyrhotite-bearing rocks and synthetic samples of magnetite and titanomagnetites with various Ti contents were also studied. Polycrystalline magnetite (Fe_3O_4) and titanomagnetite specimens with different content of titanium ($Fe_{3-x}Ti_xO_4$, $0 < x < 0.4$) were investigated, too. Also, specimens with $Fe_{3-x}Co_xO_4$ ($x = 0.01$ and 0.0005) were used in the experiments. For more details on the micro-structure, composition, and grain sizes of the natural samples we refer to *Vetchfinskii and Tselmovitch (1992)*, *Vetchfinskii et al. (2000, Chapter 1B)*, and *Vetchfinskii et al. (2004, Section 2)*. Synthetic magnetite samples were used to optimize the parameters of the anhysteretic magnetization method. The samples contained 5% of magnetite grains of various sizes subdivided into fractions 102–120 μm, 75–88 μm, and 40–50 μm (*Vajda, 1992*).

In the case of the anhysteretic magnetization method the induced magnetization was measured on the spinner magnetometer JR-4. At each step also the magnetic susceptibility was measured with the kappa-bridge KL-2 in a 920 Hz field with amplitude of 5 Oe, see also *Vajda (1992)*, and *Vetchfinskii et al. (2000, Chapter 2)*.

For studying the IMA effects on hysteresis loops, compensated differential hysteresis loops (CDHLs) have to be produced (*Vetchfinskii et al., 2004, Chapter 2*), since the constrictions and asymmetry due to the magnetic memory are too small to be observed on a standard minor hysteresis loop. Therefore, a special method of observing this effect was developed, its principle being based upon standard hysteresis loop measurements in an alternating magnetic field. A sine-shaped magnetic field is created using a solenoid with the sensor for measuring the electro-motive force (e.m.f.) within the solenoid consisting of two equal coils wound in opposite directions. The sensor is wound on a water jacket under which a furnace for heating the samples is placed. The position of the sensor within the solenoid is such that the total e.m.f. is equal to zero. Inserting a sample into one of the two coils causes an e.m.f. signal proportional to magnetic susceptibility of the sample.

To magnify the investigated IMA effects, even spectral harmonic decomposition has to be used (*Vetchfinskii et al., 2004, pp. 366–370)*. In the region of low magnetic field (Rayleigh region) the e.m.f. signal can be represented by a sum of harmonics (*Vetchfinskii et al., 1984*), $\varepsilon = -mSf\,h\left(A\cos\left(ft\right) + B\sin\left(2ft\right) + C\cos\left(3ft\right) + \ldots\right)$, where m is the number of windings of the sensor coil, S is the sensor-coil area, h and f are the amplitude and frequency of the alternating magnetic field, respectively, t is time and A, B, C are constants which depend on the magnetic properties of the sample (magnetic susceptibility, Rayleigh's constants, etc.). The frequency of the alternating field used in most experiments was 1 kHz. In low magnetic field the induced magnetization can be 100 times greater than the remanent magnetization. This means that the first harmonic, $A\cos\left(ft\right)$, which is associated with the induced magnetization, is much higher than the remaining harmonics. The most important information on the constriction of hysteresis loop is carried by higher harmonics. When measuring minor hysteresis loops, the first harmonic can be suppressed using a special filter or using a special method of measurement. As a result, the CDHL is measured, consisting of only harmonics higher than the first order. For more details on the apparatus, observation procedures, and how they evolved over a couple of decades of the experimental investigations devoted to IMA magnetic memory effects we refer to *Vetchfinskii (1992)* and *Vetchfinskii et al. (1984)*.

3. OBSERVABLE IMA PHENOMENA AND METHODS OF DETERMINATION OF PALEOFIELD PARAMETERS

3.1. Observable IMA phenomena

The magnetic memory effect due to IMA is so small that it can be observed only on CDHLs, as described above. Our experiments have shown that the phenomenon of magnetic memory of IMA occurs in polycrystals and in rocks containing multi-domain magnetic minerals, while it was not observed on rocks that only contain single-domain particles. Therefore, it is the IMA in multidomain grains which carries the information on temperature T_X, at which heating or reheating occurred, and the information on field H_T.

The first discovered effect was the nonlinearity of the dependence of the partial anhysteretic magnetization on the constant magnetizing magnetic field $I_{rpi} = f\left(H\right)$, cf. Fig. 2a (*Shashkanov and Metallova, 1977*). The nonlinearity of the dependence $I_{rpi} = f\left(H\right)$ arose in thermally magnetized rocks at the constant field intensity $H \approx H_T$. Later, in Geophysical Institutes of the Slovak and Czech Academies of Sciences, specific behavior of the magnetic susceptibility was discovered in thermally magnetized magnetite samples after their acquisition of I_{rpi} in various constant fields *H*, namely, kinks were observed in the plots $\Delta\kappa_{rpi} = f\left(H\right)$ at field intensities close to H_T (Fig. 2b), see *Vajda (1990, 1992), Vetchfinskii and Vajda (1998*). The $\Delta\kappa_{rpi}$ is the susceptibility increment due to the acquisition of the anhysteretic partial magnetization.

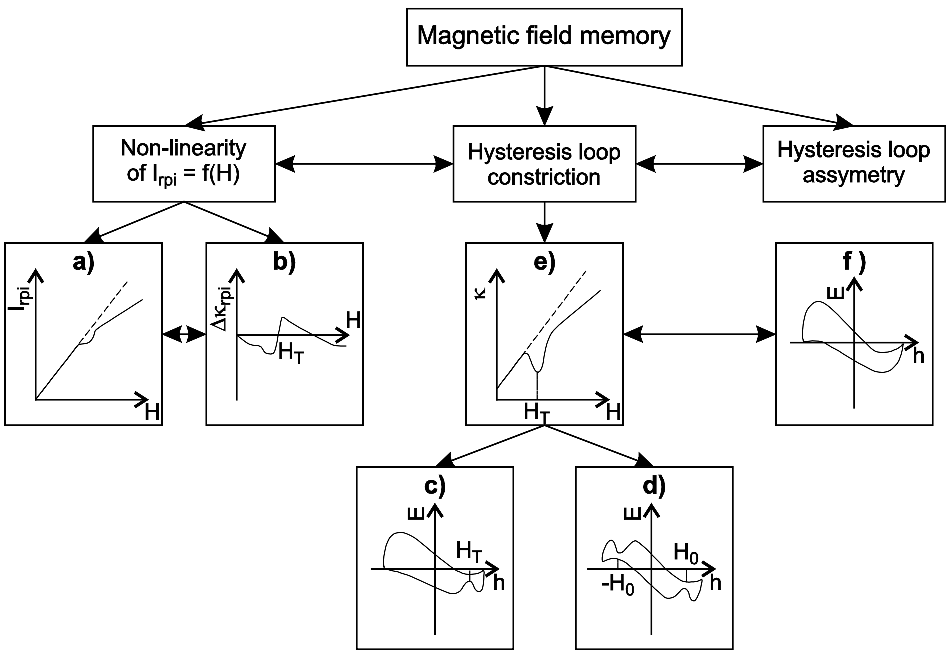

Fig. 2. Schematic illustration of the main effects/manifestations of the IMA magnetic memory. **a)** and **b)** IMA effects manifested during anhysteretic magnetising, where *H* is the direct (magnetising) magnetic field, I_{rpi} is the induced anhysteretic magnetization, $\Delta\kappa_{rpi}$ is the increment of the magnetic susceptibility acquired (and measured) at each incremental step of the anhysteretic magnetising (at each value of *H*). In all plots H_T is the intensity of the paleofield. **c)–f)** IMA effects manifested in hysteresis loops, where *h* is the amplitude of the alternating magnetic field, ε (or *E*) is the e.m.f. of the CDHL observed on the oscillograph, and κ is magnetic susceptibility. Constrictions in the CDHLs, plots c) and d), are due to the behaviour of the magnetic susceptibility as shown in plot e).

Later, constrictions of a special type in minor hysteresis loops of magnetization were discovered from CDHL measurements at amplitudes of alternating fields $h \approx H_T$ (Fig. 2c) in rock samples thermally magnetized in the field H_T. Furthermore, if a rock sample containing ferrimagnetic minerals is held for a few minutes at a constant temperature (for example at room temperature T_r) in an alternating sinusoidal magnetic field of a fixed amplitude H_0, after which the amplitude h is abruptly increased, two constrictions symmetrical with respect to $h = 0$ arise in the CDHL of the sample (Fig. 2d). Constrictions in the hysteresis loops in rocks possessing the IMA are due to a magnetic susceptibility decrease in fields close in intensity to the IMA acquisition field (Fig. 2e). The behavior of such dependences $\kappa = f(H)$ in thermally magnetized magnetite was studied by *Bol'shakov and Vinogradov (1986)*.

Asymmetric incremental hysteresis loops are observed in thermally magnetized rock samples (Fig. 2f), see *Vetchfinskii et al. (2000, 2004)*. The degree of asymmetry increases with the intensity H_T.

The e.m.f. signal producing a CDHL can be expanded into harmonic components, and their behavior can be studied as a function of the temperature and the magnetic field. This makes it possible to focus on specific CDHL distortions unnoticeable in the hysteresis loop as a whole. Methods of higher harmonics significantly enhance the effectiveness of the study of IMA effects. Various IMA manifestations of the temperature magnetic memory are shown schematically in Fig. 3.

If a hysteresis loop became constricted or asymmetric after a rock sample was cooled from a temperature $T_X < T_C$ in a magnetic field (Figs 3a and 3b, solid line), these distortions disappear at the temperature T_X during subsequent heating of the sample, and the loops become ordinary symmetrical loops (Figs 3a and 3b, dotted line).

All of the aforementioned IMA effects were observed within the Rayleigh range of a given ferrimagnetic mineral in the rock, i.e., the ordinary hysteresis loops had a typical Rayleigh shape before the IMA acquisition by the magnetic particles. The Rayleigh range of the studied materials varied from several Oe to hundreds of Oe.

Markov (1986) observed distortions in the temperature dependences of the remanence and the initial magnetic susceptibility of thermally magnetized magnetite-bearing rocks, i.e., in the plots $I_{rpt} = f(H)$ and $\kappa_H = f(H)$, κ_H being the initial susceptibility. These distortions arise at temperatures close to T_X from which the rocks cooled in the magnetic field (Figs 3c and 3d). Later, it was established that this effect is related to the IMA acquisition by thermally magnetized rocks (cf. e.g., *Vetchfinskii et al., 2000*).

The pressure effect on the CDHL constriction is illustrated in Fig. 4, where $\Delta\varepsilon$, Δh, and ΔS are the depth, the width, and the area of the constriction, respectively (cf. *Vetchfinskii et al., 2004, Fig. 8*). *Ershov et al. (1999)* showed that, in rocks acquiring the IMA, these constriction parameters decrease with increasing pressure. The impact of pressure on CDHL constrictions is not understood completely yet, and has not been investigated in full yet. In *Vetchfinskii et al. (2004)* the effect of stress on the IMA phenomena is investigated in more detail for acquisition at various temperatures or during cooling starting from various temperatures. Here we show a general character of the stress effect on IMA acquired at room temperature (Figs 4a–c). When the IMA is acquired by

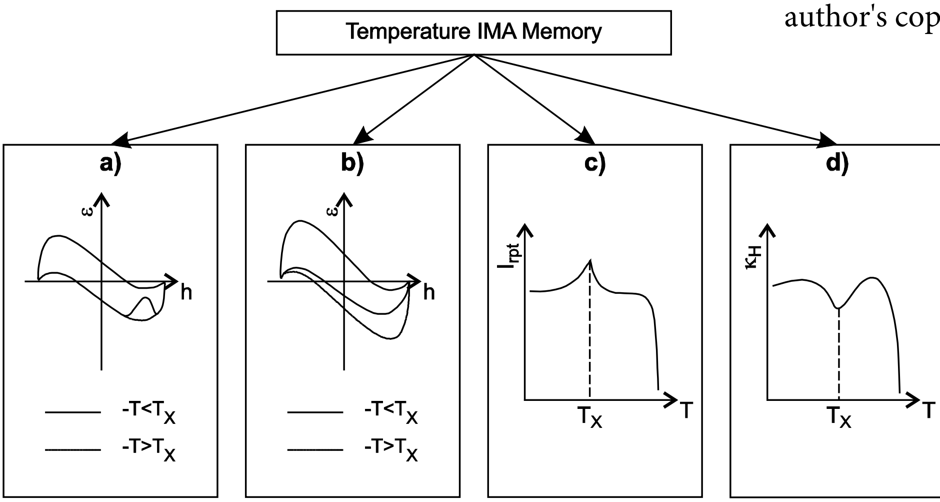

Fig. 3. Schematic illustration of the main temeperature effects on the IMA and of the temperature memory of IMA. Temperature is denoted by T, T_X stands for temperature at which the rock started acquiring thermal magnetization while cooling, ε (or E) is the e.m.f. of the CDHL observed on the oscillograph, I_{rpt} is the remanence, and κ_H is initial magnetic susceptibility. **a)** Constrtiction and **b)** assymetry of a hysteresis loop (solid curve) that disappear upon heating to T_X (dotted curve). **c)** IMA temperature memory phenomena in the thermal remanence, **d)** IMA temperature memory phenomena in the initial susceptibility.

a sample cooling from various temperatures, the dependence of the constriction parameters on the acquisition is very complex and varies from sample to sample. When the IMA is acquired at a pressure, the dependence of the constriction value on the acquisition temperature weakens with increasing pressure (Fig. 4d).

3.2. Methods of determination of paleofield parameters based on IMA

Methods used for the determination of the paleo-magnetic field intensity, paleotemperature, and paleostress, based on the IMA acquisition by rocks, can be briefly characterized as follows.

Shashkanov et al. (1975) introduced a new heating-less method for the determination of paleointensity and named it “the incremental remagnetization method” (*Shashkanov and Metallova, 1977, 1982*). The method is based on the phenomenon discovered by the authors that for thermally magnetized (in field H_T) rocks, the dependence of partial anhysteretic magnetization (I_{rpi}) on the constant magnetic field (H), in which it is produced, is non-linear at (or in proximity of) H_T. They assumed that this non-linear effect has the same origin as those responsible for the appearance of constrictions in minor hysteresis loops. Later, this hypothesis was confirmed (*Vetchfinskii et al., 1983, 1984*; *Shashkanov, 1985*; *Vetchfinskii, 1992*). This stepwise AF remagnetization method for determining the paleointensity H_T based on the IMA magnetic memory is illustrated in

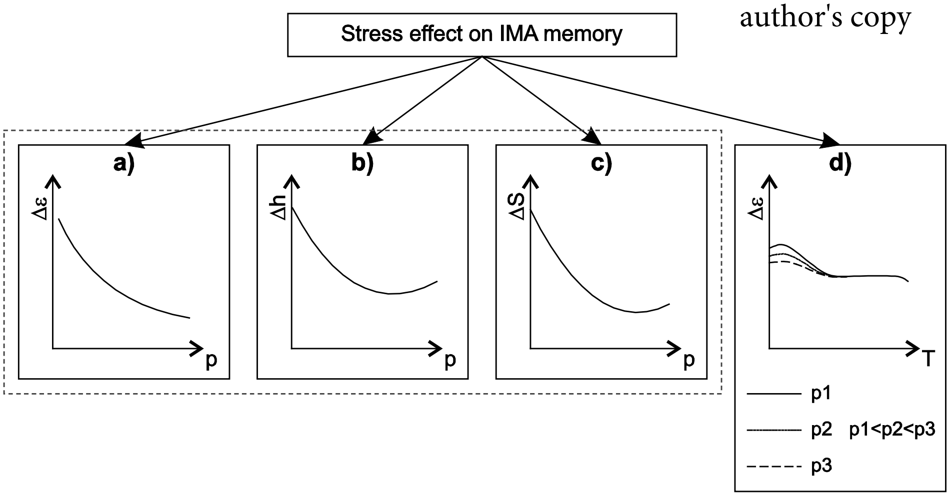

Fig. 4. Schematic illustration of the effect of stress (pressure) *p* on the IMA magnetic memory acquired at room temperature, for **a)** depth $\Delta\varepsilon$, **b)** width Δh and **c)** area ΔS of the constriction on the CDHL. **d)** Effect of various values of pressure, denoted as p_i (i = 1, 2, 3), on the dependence of the depth of the constriction $\Delta\varepsilon$ on temperature.

Fig. 5a. A closely related method, called the anhysteretic magnetizing method, based on the first derivative of I_{rpi} with respect to *H* (*Vetchfinskii et al., 1983*; *Vajda 1992*; *Vetchfinskii and Vajda, 1998)* is presented in Fig. 5b. These methods are based on the appearance of a nonlinear pattern with an onset at H_T. In both methods the paleointensity (H_T) is determined from the onset of the non-linear pattern. In the latter method the pattern is more pronounced due to the use of the first derivative. The advantage of these methods is that the sample does not have to be heated and the primary remanent magnetic polarization (primary RMP) does not have to be investigated. However, the success of the these methods crucially depends on setting up the proper parameters, when executing the anhysteretic magnetizing, such as the angle between the constant magnetizing field *H* and the RMP, the selection of the values of *H*, the initial and final amplitudes of the alternating demagnetizing field *h*, the decrease of amplitude of *h* per half cycle, as well as the duration of applying *h* (*Vajda 1990, 1992*).

It is very difficult to determine the IMA acquisition temperature from the CDHL constriction variation during heating. The magnetic paleo-geothermometer method (*Vetchfinskii, 1994*) has been developed for the determination of the magnetic field intensity H_T. This method is based on the analysis of the temperature dependence of the amplitudes of CDHL harmonics, see Fig. 5c showing the fifth harmonic (its amplitude A_5). Certain CDHL harmonics are more sensitive to constriction variations. The temperature T_X is determined from local maxima and minima in the experimental plots $A_n = f(T)$, where *n* is the *n*-th harmonic and *A* is its amplitude.

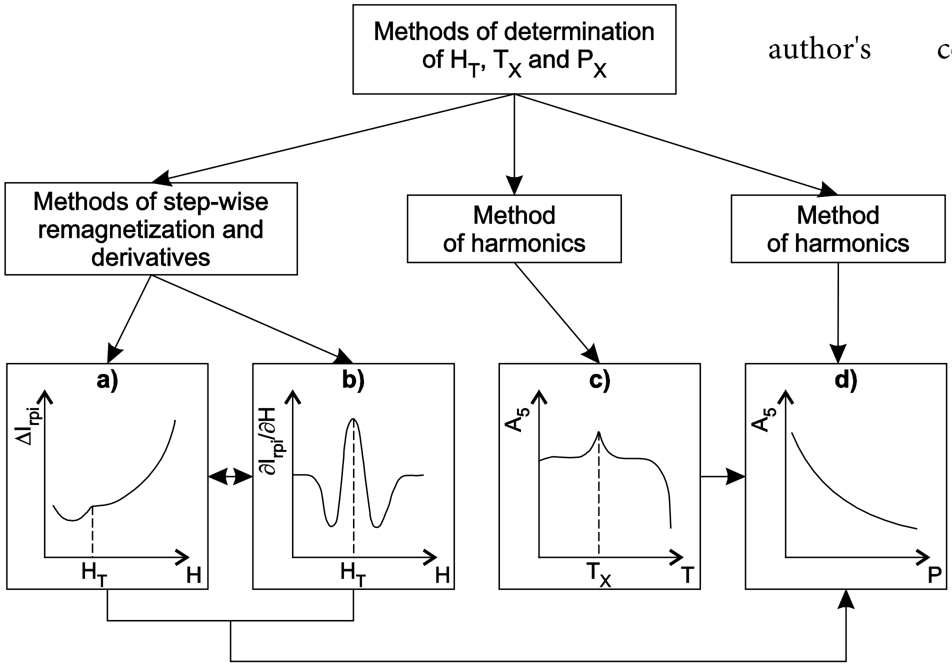

Fig. 5. Schematic illustration of the main methods used for the determination of H_T, T_X, and P_X. **a)** Vertical axis is the increment of anhysteretic magnetization. **b)** Vertical axis is the first derivative of the anhysteretic magnetization with respect to the constant magnetising field. **c)** and **d)** Amplitude of the fifth harmonic (A_5) of the ε of the CDHL. The meaning of remaining symbols is the same as in Figs 3 or 4.

The effects of pressure on IMA have not been adequately explored yet. However, experiments and physico-chemical models indicate that the IMA of rocks carries information on the pressure P_X present at the IMA acquisition (*Ershov et al., 1999*; *Vetchfinskii et al., 2004*). Fig. 5d shows a plot of the amplitude of the fifth harmonic of the e.m.f. responsible for a constricted CDHL as a function of the IMA acquisition pressure. This curve illustrates the method used for the determination of the pressure at which a rock cooled in a magnetic field.

The presence of pressure during the IMA acquisition by a rock hampers the determination of T_X by the method of a magnetic geothermometer, i.e., the temperature memory is pressure dependent. For this reason, new local extrema arise in the dependences $A_3/A_5 = f(T)$, where A_3 and A_5 are the amplitudes of the third and fifth CDHL harmonics, at temperatures close to T_X. The IMA-related distortions in these dependences are observed over a larger temperature range. Moreover, if the IMA is acquired at pressure, constriction values decrease with increasing pressure P_X and the amplitudes of harmonics associated with the memory effects attenuate.

However, the IMA acquisition temperature determined from extrema of the plots $A_3/A_5 = f(T)$ differs little from the T_X value even if the magnetic anisotropy is induced at a pressure close to the sample fracture (failure) value. Thus, the IMA in even deep-seated rocks should fix a temperature very close to the rock heating temperature, but its determination is a considerably more difficult task compared to rocks occurring at shallow depths.

4. GIANT BARKHAUSEN JUMPS IN BASALTIC LAVAS

The IMA constrictions are due to large Barkhausen jumps (*e.g., Dunlop and Özdemir, 1997*) in multidomain grains of ferrimagnetic minerals of rocks (*Vechfinskii et al., 2008*). However, giant Barkhausen jumps can be observed in some rocks regardless of the intensity of the thermal magnetization field or even of whether these rocks are magnetized at all.

Narrow constrictions were observed in Quaternary samples of Kamchatka lava (Mutnovskii volcano) containing multidomain grains of low-Ti titanomagnetite (with a Curie point T_C of 520–570°C). Minor hysteresis loops were measured in samples possessing natural remanent magnetization (*NRM*). The same samples were then thermally magnetized when cooled from T_C to room temperature in constant magnetic fields of H_T= 1–2 Oe. This was followed by heating the samples to T_C and their cooling in a nonmagnetic space. An absolute zero state was created in their ferrimagnetic minerals. The samples were also demagnetized by an alternating magnetic field of industrial frequency, typically 1 kHz, see also *Vetchfinskii et al. (2000, Chapter 2D)*, with an amplitude of 500 Oe. The demagnetization was performed along three axes of a 1-cm cubic sample. In this way, at least a partial (if not absolute) zero state was created in the sample.

The same behavior with very similar minor hysteresis loops was found in samples with *NRM* and a thermoremanent magnetization, in samples in an absolute zero state, and in those demagnetized by an alternating magnetic field. Constrictions were observed at approximately the same values of the magnetizing field (5–10 Oe) regardless of the sample prehistory. Fig. 6 presents the minor hysteresis loop of one of these samples.

Using formulae presented in *Vechfinskii et al. (2000)* we calculated theoretical hysteresis loops under the condition that moving domain walls encounter giant potential barriers. It is found that the energy of these giant barriers should be no less than 100 times higher than the potential barrier energy of magnetic minerals yielding ordinary hysteresis loops, and about 10 times higher than the energy of barriers responsible for loop constrictions carrying information on the field value H_T.

During 1925–1933 several researchers conducting experiments with ferrimagnetic wire samples observed jump-wise magnetization changes in hysteresis loops (*Krupička 1969, 1973*, and references therein). The value of these jumps attained one tenth of the saturation induction. The samples were short fragments of wire made of Ni and Permalloy alloys. The samples were pre-treated both mechanically (extension and compression) and thermally. Recently, materials having hysteresis loops similar to the one shown in Fig. 6 have been applied in the technology of ferrimagnetic materials. These ferrites have

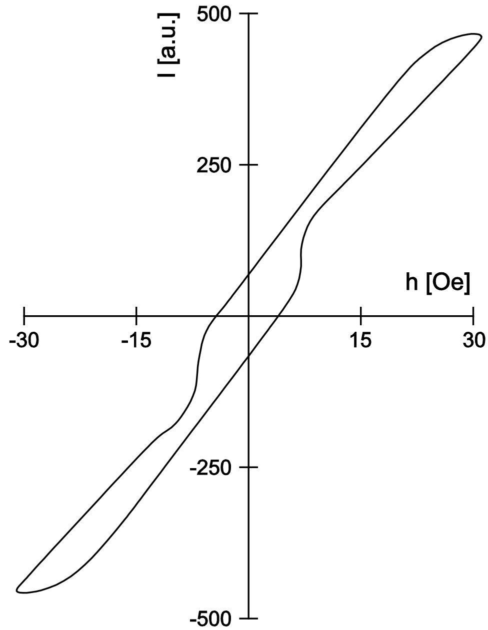

Fig. 6. An example of a minor integral hysteresis loop of basaltic lavas from Kamchatka. On vertical axis *I* is magnetization (in arbitrary units).

a complex composition and the technology of their production is complicated. Hysteresis loop constrictions of such materials are also observed at the same values of the magnetizing field. It is characteristic that hysteresis loops similar to that presented in Fig. 6 are observed in materials that were subjected to elastic deformation caused by external pressure. Natural rocks also experience the effect of pressure exerted by surrounding rock masses. Our experiments have shown that ferrimagnetic materials required in engineering and produced by special, complicated, and therefore expensive, technologies exist under natural conditions.

5. MULTI-EVENT MEMORY OF IMA

Experiments showed that the magnetic fabric of a rock can record the intensities of several magnetic fields (even of various origins) and several respective temperatures of the thermal magnetization. This fact is demonstrated by the following experiments. A sample cooled in the field $H_T = 5$ Oe. A constriction of its CDHL was observed in fields $h \approx 5$ Oe. The sample was then kept for a few days in a nonmagnetic space, which gave rise to a zero-field constriction of the CDHL due to dis-accommodation of the initial susceptibility. Another two constrictions were created after the sample was kept in an alternating magnetic field with an amplitude of 8 Oe. The resulting CDHL is shown in Fig. 7a. As clearly seen from the figure, the rock magnetic fabric recorded both the intensity of the thermal magnetization field and the amplitude of the alternating field.

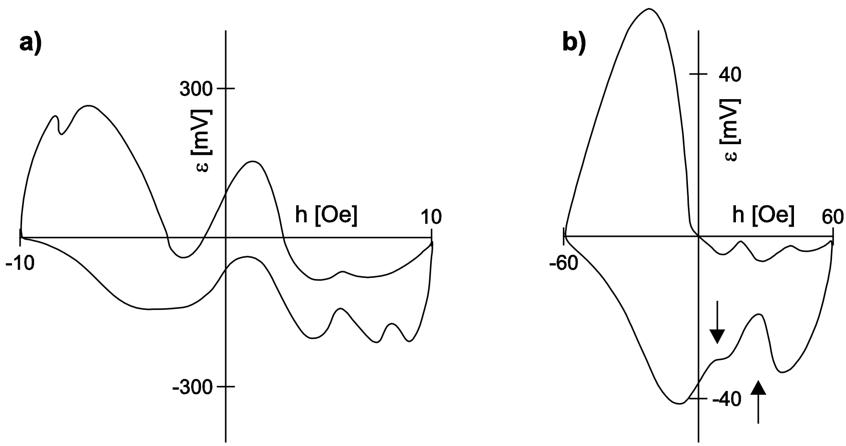

Fig. 7. An example of multi-event IMA magnetic memory manifested in minor CDHLs of basaltic lavas from the Kamchatka Peninsula in terms of two distinctive constrictions. **a)** IMA memory recording both the intensity of the thermal magnetization field (5 Oe, bottom-right branch) and the amplitude of the alternating field (8 Oe, bottom-right and upper-left branches). **b)** IMA memory remembering two field intensities (10 and 30 Oe depicted by arrows) recorded at two different temperatures (150°C and 250°C). The individual constrictions disappear at heating to the respective individual acquisition temperatures, therefore the IMA serves as a memory of those two temperatures, as well.

The capability of the rock IMA to record several (re-)heating temperatures was demonstrated in experiments similar to that described below. A sample was heated to T_{T1} = 250°C and cooled in the field H_{T1} = 30 Oe. The same sample was then heated to T_{T2} = 150°C and cooled in the field H_{T2} = 10 Oe. As a result, two constrictions of the sample CDHL arose at fields of 10 and 30 Oe. The CDHL of a sample treated in this way is presented in Fig. 7b, the arrows showing the positions of the constrictions. Subsequent heatings to 150 and 250°C eliminated the respective constrictions at 10 and 30 Oe. If the temperature of the second heating exceeded that of the first heating ($T_{T2} > T_{T1}$), a constriction caused by the field H_{T2} arose in the CDHL. Thus, the rock can record a few temperatures and thermal magnetization fields only if the temperature of repeated heatings does not exceed the preceding temperatures.

The capability of the rock magnetic fabric to preserve information on several thermal magnetization fields and temperatures is very important in paleomagnetic studies.

6. PHYSICS OF SOME PROCESSES PRODUCING IMA

We shall consider the properties of the investigated IMA type. Physical processes causing the constriction effect that bears the information on the field of the thermal reheating are similar to those causing a “normal” (ordinary) constriction in the zero field. Nevertheless, there are essential differences between these two constrictions. Firstly, the constriction remembering the H_T field is weaker (by an order of magnitude or even more) than the normal constriction in the zero field. Secondly, the zero field constriction is observed when measuring the hysteresis loops along any axis of the cube sample, while the H_T field constriction is anisotropic - it is most apparent when hysteresis loops are measured along the direction of the field that generated it. However, this anisotropy is unmistakable. Thirdly, the alternating sinusoidal magnetic field with an amplitude up to 100 Oe can itself generate HL constrictions.

It was unclear until now, why effects associated with IMA are by two orders of magnitude weaker than the normal constrictions in zero field, while showing a clearly pronounced anisotropy. In this study we propose an explanation of some IMA properties.

As noted earlier, when a ferrimagnetic material is held in a constant field H_T under a given temperature T_X , then some part of its domain boundaries (DBs) becomes stabilized and giant potential barriers arise subsequently resulting in HL constrictions.

The stabilized DBs are significantly wider then the usual ones. They have a complicated structure, which is characterized not only by magnetic properties of the individual ferrimagnetic material, but also by the neighboring (and enveloped by the boundary) defects of the crystalline lattice, or even by trace amounts of admixtures of other materials. The wide DBs comprise Bloch lines, which are like those that can be observed in some ferrimagnetic materials. *Vlasko-Vlasov et al. (1976)* have shown that the change of internal stress in a ferrimagnetic material can result in a dramatic redistribution of magnetization inside such a boundary. If temperature of the ferrimagnetic material changes, its crystallographic anisotropy constants change, too, i.e., its internal stresses change. Then the wide and complex DBs are likely to become an origin of embryonic formation of domains of a new phase. If IMA is produced under temperature T_X and stabilized DBs are formed, then at the subsequent cooling some portions of these boundaries, divided by Bloch lines, can over-grow into new domains.

Figure 8 schematically shows the ferrimagnetic structures with domain boundaries divided by Bloch lines. The dashed and light portions are related to different magnetization orientation inside the DBs (or more exactly to different spin orientation).

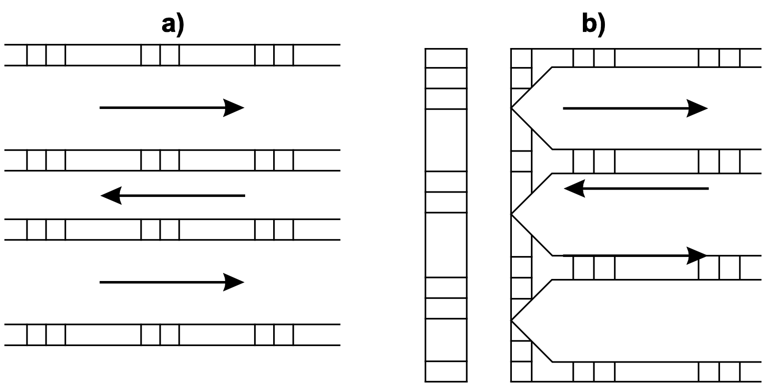

Fig. 8. Structures of a ferrimagnetic material with domain boundaries divided by Bloch lines. **a)** Domain structure (DS) stabilized at T_X and **b)** DS after cooling at room temperature in the absence of magnetic field. Arrows represent the spontaneous magnetization.

The arrows show spontaneous domain magnetization (I_S). Fig. 8a is respective to a domain structure (DS) that stabilized at temperature T_X. Fig. 8b shows the structure of the same ferrimagnetic material this time after cooling to room temperature T_r at the absence of the magnetic field. A constriction in CDHL is observed at T_X when measuring on ferrimagnetic samples with stabilized domain structure.

Due to restructuring of the DS and to appearance of new domains, after cooling to the room temperature, the correlation between DBs with "giant" potential barriers created in places of boundary stabilization is disturbed. As a result the constriction in CDHL does not occur. After a repeated heating to T_X the domain structure returns to the initial state and the constriction in hysteresis loops re-occurs. At additional heating (above T_X) the diffusion disintegration of "giant" barriers takes place.

Paulus and Simonet (1971) investigate changes due to varying temperature of constrictions generated in zero magnetic field in ferromagnetic alloys $Ni_xFe_{3-x}O_4$ with an admixture of cobalt. They demonstrate that on the DS stabilized at some temperature in the zero magnetic field constriction occurs in partial HLs. When the temperature is lowered the constriction disappears. The authors believe that in the process of temperature decrease, because of changes in the spontaneous magnetization and the constants of the crystallographic anisotropy, a change of the dimensions of the domains takes place, as the internal stresses change. In such a case, in the wide DBs, a change of the vector direction I_S takes place in neighboring domains, by turning to the angle of $k\pi$ ($k = 0, 1, 2, \ldots$). During the process of cooling, the stabilized boundaries can release boundaries of higher mobility, their width being significantly less than that of the original boundaries (*Krupička, 1969, 1973*). Fig. 9 schematically shows the stabilized DS (Fig. 9a) and the structure occurring as a result of appearance of mobile boundaries (dotted lines in Fig. 9b). "Pseudoboundaries" can also occur, which are the DS portions, where spontaneous magnetization, due to some reason (including stabilization processes on defects), deviates from the normal I_S direction. In this case the DS portions divided by these "pseudoboundaries" look like individual domains with parallel magnetization directions. Such "pseudoboundaries" can further divide and give birth to new domains. When changing temperature and internal stresses, a drift may occur of the mobile part of defects of crystallic lattices, at which the deviation of the magnetization direction took place. This drift looks like a release of a narrow boundary from a wide one. The

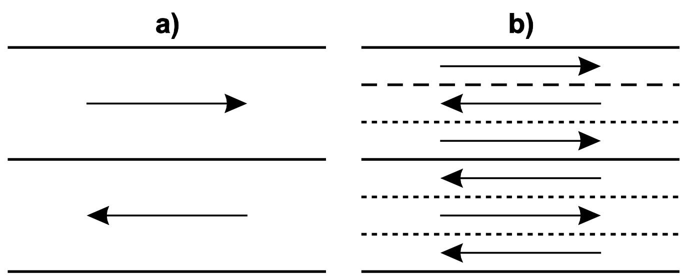

Fig. 9. **a)** The stabilized domain structure and **b)** the structure formed as a result of formation of the mobile boundaries.

occurrence of mobile boundaries and the "fractioning" of domains lead to the disappearance of the constriction. The subsequent heating results in mobile DBs being overtaken by the stabilized DBs and the original DS obtained under the T_X temperature gets revealed.

Both mechanisms of the DS reconstruction are of similar nature. In both cases the complex stabilized boundaries are the cause of formation of new domains. However, in the first case, the turn angle between magnetization directions in original and newly formed domains is about 90°, while in the latter case it is equal $k\pi$.

When the ferrimagnetic material placed in the permanent magnetic field cools down from temperature T_X, the reconstruction of the DS is prevented by this magnetic field. If the temperature is lower than T_X, the stabilized DBs are formed. Then during the subsequent heating the constriction is observed at any temperature between the room temperature and T_X.

Let us take a look at the causes of anisotropy in the IMA memory phenomena. All the investigations indicate that a given IMA type is caused by the stabilization of boundaries with a turn angle of the spontaneous magnetization $k\pi$. Therefore, when the acting magnetizing field is parallel to the direction of H_T, the stabilized boundaries move forward most intensely, and interact more actively with potential barriers, which oppose their movement. The potential barriers themself are naturally 3D, thus can be symmetric. But the 180° boundaries, due to their nature, move in parallel to each other. Naturally, when the magnetizing field is applied perpendicularly to I_S of the stabilized domains, these domains either cannot move or their mobility is very limited. A lower mobility is likely to be preserved at the cost of a different scheme for the turn-around of magnetization inside the boundary. In any case, this is less likely, since the boundary structure itself will prevent such a process. However, this cause is already on the quantum level.

Figure 10 presents two possible schemes for the turn-around of the I_S into 180° in the boundary between two domains. The reversal of the spontaneous magnetization, shown in Fig. 10a, takes place in the plane perpendicular to the plane of the figure in a spiral way towards the $k\pi$ angles. This type of the I_S reversal, in particular, is responsible for the anisotropy of the IMA memory phenomena.

Please note that the constrictions after thermal reworking of in a zero magnetic field can be observed, when measuring the hysteresis loop, in any direction. In such cases constrictions are caused by the large Barkhausen jumps, in which the boundaries with magnetization at angle 180°, 90° or other angles take part (*Krupička, 1969, 1973*). The fact that the unidirectional IMA is due to boundaries with rotation angles divisible by 180° also explains the weakness of the memory phenomena, since those are arranged by only a small percentage of all the DBs of this ferrimagnetic sample. The DBs are of some length. Cases are possible when the "gigantic" Barkhausen jump acts only on a portion of the DB with a spiral magnetization distribution (cf. Fig. 10a). In Fig. 10b the I_S turns by 180° in the plane of the figure. Such a turn, first of all, does not lead to the anisotropy of the IMA phenomena, and, second of all, it occurs only rarely.

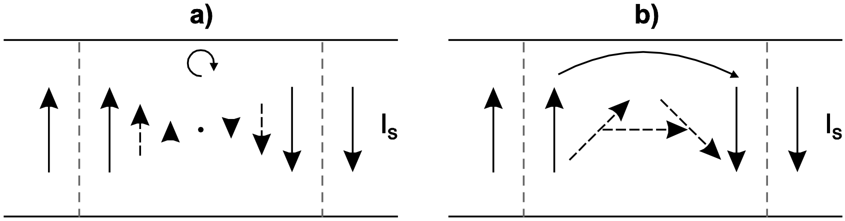

Fig. 10. Schemes of spontaneous magnetization (I_S) reversal by 180° in the boundary between two domains. **a)** Reversal in spiral way, **b)** reversal in the plane.

In addition, as mentioned earlier, stabilized boundaries are wide, and only the spiral-like rotation can lead to the I_S turns with angles divisible by $k\pi$. This also means that not all the 180° boundaries participate in forming the phenomena of a given IMA type. What was said above explains not only the anisotropy of the memory phenomena, but also the fact that the constrictions of hysteresis loops bearing the information on the magnetic field intensity and on the temperature of the thermal reworking are weaker, a few tens times, than the “ordinary” constrictions in the zero field, which are caused by disaccomodation of the initial susceptibility.

Taking into account what was described above, it is necessary to specify this type of the induced magnetic anisotropy as unidirectional IMA (UIMA). With respect to the processes and the physics associated with producing the IMA magnetic memory we refer the reader also to *Vetchfinskii et al. (2000, 2004)* for more details.

7. CONCLUSIONS

All magnetic memory effects described above were first discovered in geological objects (rocks) and only afterwards in artificial ferrimagnetic materials. Results similar to those presented in this work have repeatedly demonstrated that geophysical research in rock magnetism often not only anticipates results in the technology of ferrimagnetic materials, but also is promising for finding minerals with exotic properties in the Earth’s interior.

The capability of uni-axial induced magnetic anisotropy (UIMA) to record the rock heating temperature is applicable to the determination of paleotemperatures. The UIMA capability to preserve information on several subsequent heating temperatures and several thermal magnetization fields, i.e., on several paleotemperatures and paleointensities, has even more significant implications for paleomagnetism. In many cases, paleotemperatures are determined at a qualitative level. The metamorphism grade, rather than the rock heating temperature itself, is often determined. The method of Zijderveld diagrams is a fairly widespread method in which the paleotemperature is determined from the spatial variation in the remanence vector of a rock during its heating under laboratory conditions. This method has its own drawbacks. In particular, the remanence can strongly vary under the effect of external factors unrelated to the heating of the rock. Moreover, dealing with such complex objects as rocks, researchers should not restrict themselves to a single method of study.

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