Second-order magnetic phase transition in the Earth

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[1] It is known that second-order magnetic phase transition, the transition between ferromagnetic (ferrimagnetic) and paramagnetic states of the material at the Curie temperature, is accompanied by a sharp (theoretically infinite) enhancement of the magnetic susceptibility. A second-order magnetic phase transition within the Earth (usually at mid-crustal depths, depending on geothermal conditions and on the type of magnetic material) is assumed to produce extremely high susceptibility zones of a thickness of a few hundreds of meters. Such strongly magnetized zones may be sources of well-known but not-yet explained geomagnetic anomalies, and at the same time, they may produce complicated electrical conductivity anomalies, as well. The second-order magnetic phase transition should be taken into account as one of the possible sources of geomagnetic and magnetotelluric anomalies. **Citation:** Kiss, J., L. Szarka, and E. Prácser (2005), Second-order magnetic phase transition in the Earth, *Geophys. Res. Lett.*, *32*, L24310, doi:10.1029/2005GL024199.

1. Introduction

[2] In 1885 Hopkinson [*Hopkinson*, 1889] discovered a sharp increase in magnetic susceptibility of iron at temperatures just below the Curie temperature. In 1907 Pierre-Ernest Weiss provided the first explanation (the so-called Curie-Weiss law) for the magnetic susceptibility at the Curie point. In the 20th century several important theoretical results were obtained in the field of critical phenomena [e.g. *Landau and Lifshitz*, 1960; *Wilson*, 1993]. Relevant current research related to this so-called second-order magnetic field transition can be found in the physics literature [*Poulopoulos et al.*, 2000; *Rüdt et al.*, 2002] and in the mineral physics literature [*Ferré et al.*, 1999; *Kontny et al.*, 2000; *Hrouda*, 2003; *Kontny et al.*, 2003; *Just*, 2004].

[3] In this paper, after briefly describing the second-order magnetic phase transition, we discuss the potential consequences of its occurrence in the Earth. On basis of the aforementioned new results in physics we assume much higher Hopkinson peaks in the Earth's natural laboratory, than were given by *Dunlop* [1974]. Geothermal, geomagnetic and magnetotelluric considerations are discussed, and the results are illustrated by using model calculations.

2. Second-Order Magnetic Phase Transition

[4] The ferromagnetic-paramagnetic phase transition is a so-called critical phenomenon. It is a "continuous" or "second-order" phase transition, and the Curie temperature itself is a critical point. At the critical point the magnetization of ferromagnetic materials disappears, but in the absence of an external magnetic field $\mathbf{H}_E$ the magnetic susceptibility is theoretically infinite. Figure 1 shows the schematic behavior of remanent magnetization M_r, magnetic susceptibility X and specific heat c. As summarized by *Kittel* [1996], the magnetization of ferromagnetic materials, approaching the Curie temperature T_c, disappears as $(T_c - T)^{\alpha}$, and the magnetic susceptibility varies as $|T_c - T|^{-\beta}$; α and β are the so-called critical exponents.

[5] *Hopkinson* [1889] observed a 30 times susceptibility increase in the presence of a weak (appr. 24 A/m) external field. Recent experiments carried out on very thin layers (see Figure 2a [after *Rüdt et al.*, 2002]) do not exclude a hundred times (or even higher) increase of the ferromagnetic (ferrimagnetic) susceptibility in a very narrow (5–10 degrees wide) temperature interval, just below the Curie temperature.

3. Second-Order Magnetic Phase Transition in the Earth

[6] *Dunlop* [1974], as a result of the Hopkinson effect, assumed a susceptibility enhancement factor of about 3. Recent, much more precise laboratory experiments on Earth materials have revealed the characteristics and physical conditions of the Hopkinson peak of the most relevant minerals: e.g., pyrrhotite [*Kontny et al.*, 2000], shown in Figure 2b, magnetite [*Kontny and de Wall*, 2000], and titanomagnetite [*Kontny et al.*, 2003], and various further Earth materials such as cataclasites [*Just*, 2004]. The observed Hopkinson peaks are higher than obtained by *Dunlop* [1974], but they are still smaller than in the experiments by *Rüdt et al.* [2002]. It should be noted that the physical conditions (pressure, intensity, and frequency of the external magnetic field, heating rate, homogeneity of physical conditions) in the laboratory are not the same as in the crust. Considering (a) the theory and (b) the experimental results both in physics and magnetic mineralogy (but with emphasis on the first), then for ideal homogeneity conditions in the Earth's crust, we assume that the second-order magnetic phase transition in the Earth, might be intense as is described in section 2.

3.1. Depth and Thickness Estimation

[7] In a steady-state situation the temperature-depth profile is usually estimated from the shallow-level geothermal gradient $g_t = dT/dz$. For continental crust it is about 30 degrees Celsius/km. In the case of high (100 mW/m^2) heat flow and relatively low thermal conductivity values (e.g., due to sediments), the geothermal gradient may be doubled.

[8] Properties of magnetic Earth materials, among others the Curie/Néel temperatures of various ferrimagnetic-anti-

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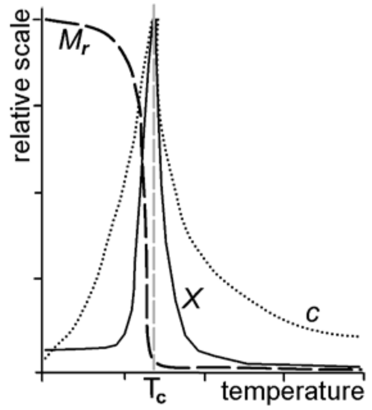

Figure 1. Schematic behaviour of remanent magnetization M, magnetic susceptibility X and specific heat c around the Curie temperature T_c.

ferromagnetic minerals (denoted as T_c) are well known from rock physics [e.g., *Carmichael*, 1982]. The magnetization of rocks depends first of all on their iron oxide (mainly magnetite) content, occurring mostly in mafic igneous rocks, but it is also known that the Curie temperature is dramatically decreased in case of titanomagnetite content. Lithostatic pressure has also a slight effect on the Curie temperature, which we take into account as a Curie temperature gradient $g_c = (dT_c/dp)(dp/dz) = dT_c/dz$. Thus, after *Fowler* [2005], we estimate the Curie depth as $z_c = (T_c - T_0)/(g_t - g_c)$, where T_0 is the surface temperature. The critical temperature interval, where susceptibility is expected to become very high, is denoted by ΔT_c, and the depth interval of the magnetic phase transition Δz_c is given by $\Delta z_c = \Delta T_c/(g_t - g_c)$. ΔT_c, on the basis of Figure 2, is about 5–10 degrees Celsius.

[9] In Figure 3, on the basis of data by *Carmichael* [1982], both z_c (the geothermally estimated Curie depth values) and Δz_c (the estimated critical depth interval) are presented for several minerals and rocks, including titanomagnetite-magnetite mixtures.

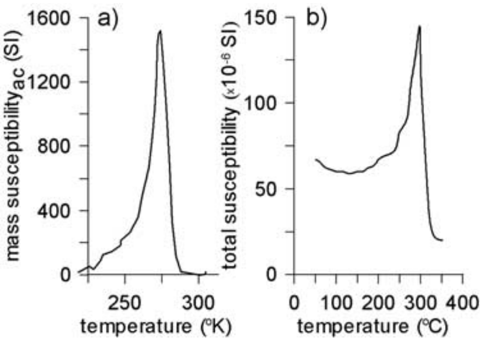

Figure 2. X(T) laboratory results in physics and in mineralogy (a) Hopkinson peak of an ultra-thin (5 ML) Ni layer (after C. Rüdt and K. Baberschke, Sfb290 TP A2 UP II: ac-susceptibility in UHV, available at http://www.physik.fu-berlin.de/~ag-baberschke/sfb290/TPA2up2.html). The low T_c values are exclusively due to the extra-thin sample thickness (Lenz, personal communication, 2005). (b) Hopkinson peak in a Weiss-type pyrrhotite (after *Kontny et al.* [2000]).

[10] As shown in Figure 3, the Curie depth generally occurs at mid-crustal depths (in the 9–30 km range); in the case of high titanomagnetite content it may be expected (especially in areas having high geothermal gradients) even at upper crustal depths. The thickness of the magnetic phase transition zone is about a few hundred meters: it is thinner for small Curie depth (e.g., where the geothermal gradient is high), and it is thicker for large Curie depth (e.g., where the geothermal gradient is low).

3.2. Bulk Susceptibility in State of Magnetic Phase Transition

[11] Because Earth's magnetic field $\mathbf{H}_E$ (app. 40 A/m) is weaker than the magnetic field usually used in laboratory experiments, and the temperature profile within the Earth is continuous, a relatively high increase can be easily assumed for the magnetic susceptibility in the magnetic phase transition state. (Theory suggests the highest peaks occur in zero field.) Although it is not yet supported by rock physics experiments, on the basis of theoretical results and physical experiments (see Figures 1 and 2a) for the critical susceptibility $X^* = \frac{1}{\Delta T_c} \int_{T_c - \Delta T_c}^{T_c} X(T)\,\Delta T$ we postulate $X^* = 100X$. Because the relation between magnetic susceptibility X (given in SI units) and relative magnetic permeability μ_r (where $\mu_r = \mu/\mu_o$, where $\mu_o = 4\pi 10^{-7}\,\frac{\mathrm{Vs}}{\mathrm{Am}}$ is magnetic permeability of vacuum) is as follows: $\mu_r = 1 + X$, a 100 times susceptibility enhancement in case of pure magnetite ($\mu_r = 5$) would mean a critical permeability value of $\mu_r^* = 401$. In the case of a basalt with 3% magnetite content (where $\mu_r = 1.12$) it would result in a critical value of $\mu_r^* = 13$. A more detailed list is given in Table 1. The increase in terms of magnetic permeability is relatively high, certainly exceeding the limits where μ_r can be considered as 1.

[12] Magnetization of a ferromagnetic material ($\mathbf{M}_{\mathrm{total}}$) is given as a sum of remanent and induced magnetizations $\mathbf{M}_r$ and $\mathbf{M}_i$. In this way $\mathbf{M}_{\mathrm{total}} = \mathbf{M}_r + \mathbf{M}_i \sim \mathbf{M}_r(\mathrm{T}, \mathbf{0}) + \mathbf{H}_E \sum \underline{X}$, where (T, $\mathbf{0}$) means time dependence, when $\mathbf{H}_E = \mathbf{0}$. The tensorial susceptibility $\underline{X}$ should be taken into account. As

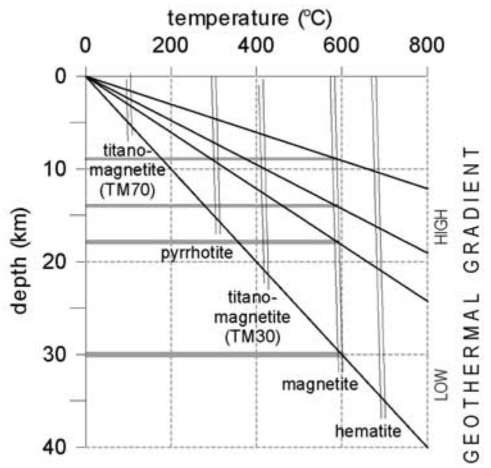

Figure 3. Geothermal estimation for depth and thickness of subsurface zones in state of second-order magnetic phase transition. ΔT_c intervals for various Earth magnetic minerals are shown.

Table 1. Relative Magnetic Permeabilities of Several Earth Materials in Normal (μ_r) and in Hypothetical Critical (μ_r^*) State, Assuming a 100 Times Increase in the Susceptibility

Minerals		μ_r	μ_r^*
Quartz (diamagnetic)		0.999985	-
Calcite (diamagnetic)		0.999987	-
Rutile (paramagnetic)		1.0000035	-
Pyrite		1.0015	1.15
Hematite		1.053	6.3
Ilmenite		1.55	56
Pyrrhotite		2.55	156
Magnetite		5.0	401
	% magnetite		
Rocks	0	~1.0	
Granites	0.2	1.006	1.6
	0.5	1.017	2.7
	1.0	1.04	5
Basalts	2.0	1.08	9
	3.0	1.12	13
	5.0	1.18	19
Iron ore	10.0	1.34	35
	20.0	1.56	57

shown in Figure 1, on approaching the Curie temperature, the induced magnetization has a sharp enhancement, and the remanent magnetization quickly disappears.

4. Geophysical Consequences

[13] If such a sharp enhancement in the magnetic permeability occurs at the estimated depth and in the assumed depth interval, it may lead to measurable geomagnetic and electromagnetic (magnetotelluric) anomalies.

4.1. Magnetotelluric Anomalies

[14] Faraday's induction law shows that in a subsurface conductor the voltage varies not only with the rate of change of magnetic field, but also with the magnetic permeability of the conductor, so induced currents are simply enhanced by a factor of μ. In magnetotellurics (also in most electromagnetic geophysical methods) it is usual to assume $\mu = \mu_0$, because the magnetic permeability of rocks rarely is appreciably greater than μ_0. However, an exceptional enhancement of magnetic permeability (as we assume it at Curie depth) would dramatically change the situation. Consequently, a traditional inversion of apparent resistivity and phase curves, when only electrical conductivity values and the corresponding geometries are varied, could lead to false results. Ignoring the variation of magnetic permeability, the complex induction number k, describing the electromagnetic induction process (where $k^2 \sim \omega\mu\sigma$; ω is angular frequency, and σ is conductivity) would suggest high-conductivity magnetotelluric anomalies in any case. Nevertheless, the magnetotelluric consequences of the second-order magnetic phase transition are due to both the electromagnetic diffusion process in the piecewise homogeneous medium, and the boundary conditions. The tangential magnetic field ($\mathbf{H}_t$) and the normal magnetic induction vector should be continuous along the corresponding surfaces. In effect, the continuity of $\mathbf{H}_t$ directly leads to the continuity of k/μ, that is to the continuity of σ/μ. As a consequence, different boundary conditions may easily lead to paradoxical results. Thus, for a half-space, which is homogeneous in terms of resistivity ($\rho = 1/\sigma = 100\ \Omega$.m), and has a three-layered character in terms of relative magnetic permeability ($\mu_r = 100$ between 8 km and 8.5 km), a traditional inversion results in a fictitious high-resistivity layer (9930 Ω.m between depths 8 km and 58 km and an RMS misfit of only 0.000043). A more complex (two- or three-dimensional) geometry would lead to a more complex but fictitious ensemble of high-resistivity and high-conductivity zones, and the effect is significant.

[15] Many conductivity anomalies are known from mid-crustal depths [*Jones*, 1992]. Although we think that all interpretations of crustal conductivity anomalies [e.g., *Shankland and Ander*, 1983; *Ádám*, 1987; *Jones*, 1992] are reasonable, in cases of magnetotelluric anomalies where high-conductivity and high-resistivity zones occur together, the second-order magnetic phase transition must be considered a possible cause.

4.2. Magnetic Anomalies

[16] A classical spectral depth estimation method [*Spector and Grant*, 1970] of sources of a ΔZ magnetic anomaly map of Hungary [*Kiss*, 2005] shown in Figure 4 provides 15 km as the largest source depth. Along the four South-Transdanubian profiles in Figure 4, the following estimated source depth values were obtained: 8 km, 6 km, 8 km and 8 km. *Kis et al.* [1999] also found maximum source values (in their terms: the depth of Curie isotherm) in Hungary between 6 and 16 (exceptionally, 25) km. The sources of these anomalies are not known. Curie isotherm calculations carried out in other regions (e.g., *Dolmaz et al.* [2005] for Turkey; *Hemant et al.* [2005] for Europe) also give larger maximum depth values of magnetic sources in colder crust, and smaller depth values in hotter crust.

[17] All these authors assume large-size magnetic bodies extending down to the Curie depth. In contrast to the present paradigm, we think that some magnetic anomalies may be caused by induced magnetization due to very sharp susceptibility increase just at the Curie depth.

[18] In a magnetotelluric field project [*Szarka et al.*, 2004], at a depth of about 8-10 km, we identified three electrical conductivity anomalies, and the most important one coincides with a moderate magnetic anomaly of unknown origin. This magnetic anomaly can be fully explained by using a 500 m times 500 m model with X =

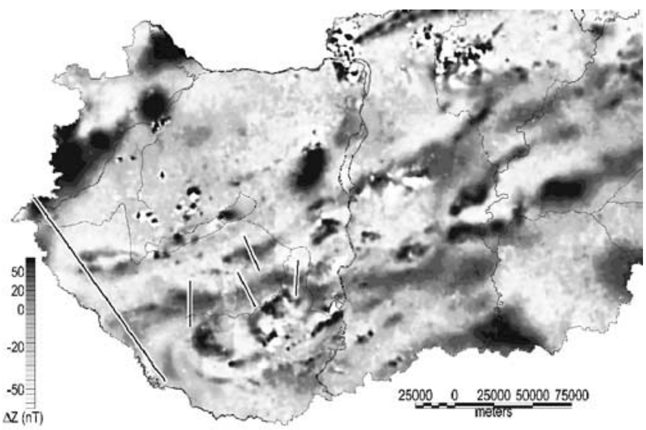

Figure 4. Geomagnetic ΔZ map of Hungary [*Kiss*, 2005], with four small sections of individual depth estimation. Location of the geomagnetic anomaly, where the model calculation in Figure 5 was carried out, is also shown.

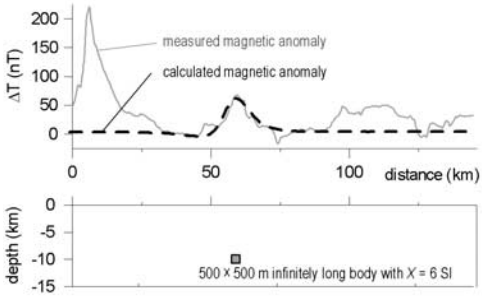

Figure 5. Measured and modeled ΔT geomagnetic anomaly along the profile shown in Figure 4, together with its possible interpretation.

6 SI (corresponding to $\mu_r^* = 7$) at a depth of 10 km (Figure 5). We think that extremely high-susceptibility small bodies may explain numerous field anomalies, which had been thought earlier to be caused by large-size bodies, having "classical" susceptibility values.

5. Conclusions

[19] In this paper we call attention to potential effects of a second-order magnetic phase transition in the Earth's crust. On the basis of the theory and recent experiments (e.g., Figure 2a) we consider this phenomenon likely to be much more significant than previously thought. Disregarding geological diversity, geophysical considerations suggest either horizontal slab- or layer (pancake) model with thickness of a few hundred meters at mid-crustal depths, depending on the occurrence of magnetic material at the critical depth. In the case of sharp (about two orders of magnitude) enhancement of the magnetic susceptibility, such zones may produce observable magnetotelluric and geomagnetic anomalies at the surface.

[20] In magnetotellurics, for various practical reasons, usually $\mu = \mu_0$ is assumed, but for a second-order magnetic phase transition this assumption is not valid. For natural conditions ("multidimensional environment"), an ensemble of high-conductivity and high-resistivity zones is expected. It cannot be excluded that some crustal anomalies revealed by magnetotellurics should be reinterpreted.

[21] A geomagnetic field anomaly can be also equally interpreted in terms of a second-order magnetic phase transition, and the deepest sources of geomagnetic anomalies are everywhere in a close relationship with Curie depth values. Therefore we suggest that many not-yet-explained magnetic field anomalies can be equally-well interpreted by relatively small sources in the second-order magnetic phase transition state.

[22] In order to test this hypothesis we recommend to carry out: a detailed magnetic studies of mineral candidates in laboratory experiments that approximate crustal conditions (pressure, magnetic field: both intensity and frequency, heating rate, homogeneity of physical conditions throughout the sample, and extremely detailed temperature sampling at the second-order magnetic phase transition). A worldwide and/or regional statistical analysis of magnetic and magnetotelluric anomalies would be useful also.

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