PUBLS. INST. GEOPHYS. POL. ACAD. SC., C-99 (398), 2007

Experimental Modeling of Impact Effects on the Magnetic Susceptibility of Geological Materials

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A b s t r a c t

It is known that magnetic susceptibility of ferromagnetic materials changes if mechanical stress is applied. Various magneto-mechanic interactions can contribute to this variation. Elsewhere, it has been recognized, physically, that magnetostriction and magnetic hysteresis are intrinsically coupled phenomena. This study examined the hysteresis loops of shocked geological materials with different magnetic mineralogy. We calculated the differential magnetic susceptibility from hysteresis loops obtained from rock specimens after they were impacted using high-order explosives (penthrite). Maximum pressure is about 20 GPa. The experimental setup and procedure are described and a large number of the obtained experimental results are presented and discussed.

1. Introduction

The physical mechanism of the driven shock effect on magnetic properties of rocks is still not very well understood. Magnetic susceptibility is one of the most important of these magnetic properties within a given magnetic mineralogy. On the other hand, a number of authors found experimental evidence that shock pressures on the order of only 1 GPa or less can remove magnetic remanence, while even a few MPa can reduce it (Hargraves and Perkins 1969, Pohl *et al*. 1975, Cisowski and Fuller 1978, Pohl *et al*. 1981).

The studies carried out on the pressure effect on magnetic susceptibility are rather scanty. If we intend to determine the bulk susceptibility under pressure conditions, the measurements can only be performed using a special equipment involving pressure cells (Kapicka *et al*. 2003). Similarly, other experimental processes and systems were developed to measure reversible magnetic susceptibility under high pressures (Gilder *et al*. 2002). Such measurements find also their interest in the investigation of magnetic properties modification of the ribbons with tape recording under stress of hauling and efforts exerted by the read heads (Hug *et al*. 1994, Radwan 2002).

Previous studies show that impact structures (meteoritic craters or nuclear explosion sites) are characterized by a reduction in magnetic susceptibility (Pilkington *et al*. 1992, Ugalde *et al.* 2003). Additionally, the studied magnetic properties (susceptibility, NRM intensity and Koenigsberger ratio) of the rocks sampled outside the Lappajärvi impact structure are very different from the targeted rock (Pesonen *et al*. 1992). Hence, the effects of shock waves on the intrinsic magnetic properties are frequent phenomena in geological or industrial materials. Furthermore, the interpretation of the paleomagnetic signals of most meteorites depends on these phenomena. Similarly, the remagnetization patterns associated with impact basins on Mars, the Moon or asteroids cannot be interpreted with certainty if one neglects this aspect (Rochette *et al*. 2001, Halekas *et al*. 2002, Hood *et al*. 2003, Rochette *et al*. 2003, Hart *et al*. 200, and Kletetschka *et al*. 2004).

In order to highlight the laboratory pressure-induced changes in magnetic susceptibility, we calculated the differential magnetic susceptibility from hysteresis loops obtained from rocks impacted using high-order explosives (penthrite). The shock wave is modeled numerically with maximum pressure reaching 20 GPa. In this paper, the assumptions on the variation of magnetic susceptibility under pressure were presented by referring to the previous works on the physical theory of magnetostriction. An expression for the magnetostriction is derived from minimization of the internal energy with respect to strains, which is necessary for mechanical equilibrium, after domain wall motion or wall bowing.

2. Main Theory

When exposed to an external field (H), a ferromagnetic substance acquires a magnetic moment (M), which varies nonlinearly until saturation. The value of M depends on whether H is increasing or decreasing: the curve $M(H)$ defines a hysteresis loop whose derivative dM/dH is the differential susceptibility (X_{diff}). In other words, X_{diff} changes as a function of H whose integral Eq. (1) defines a hysteresis loop

$$M(H) = C + \int_{H_0}^{H} H_{diff}(H)\,dH \;. \qquad (1)$$

The initial susceptibility is measured in a low AC or DC field (< 1 mT) and is defined as the ratio M/H. The initial susceptibility is due to reversible displacements of mobile domain walls in multidomain (MD) particles or moment rotation in single-domain (SD) particles. In the latter case, low fields are not very effective in rotating SD moments. Therefore, susceptibilities in SD and pseudo-single-domain (PSD) grains are usually lower than that of MD grains. However, what is actually measured in the laboratory is the apparent susceptibility, χ_o, not the intrinsic susceptibility, χ_i. The difference is due to the effects of self-demagnetization. One should remind that inside a grain, the applied field, *H*, is modified by the demagnetizing field resulting from surface charges (Dunlop and Özdemir 1997, Hunt *et al*. 1995, and references therein).

3. Experimental Procedure

Experimental procedures were described in Lamali *et al*. (2005) and are summarized briefly here. The blocks of rocks are arranged in a rubber container filled with sand and gravel. A stick of explosive is stuck vertically on the flat surface of the sample. The blocks are oriented according to the local field declination with an average angle of 90° regarding to the direction of their natural remanent magnetization (NRM), in order to distinguish the overprint magnetization acquired during the shock. The container is maintained closed by a heavy wood cover. With the aim of targeting well the part that is most affected by the shock wave propagation, we carried out an in-depth millimeter-length sampling around the point of impact using the diamond wire saw. We obtained ten (10) specimens for each block of impacted rock which corresponds to "3 cm" in depth from the impacted area. The specimens have parallelepiped shape with a volume of $4\times4\times3$ mm^3. With this geometric form, we are sure that the total magnetization intensity of each specimen largely exceeds the background noise of the cryogenic magnetometer and is directly measurable with the vibrating sample magnetometer (VSM). Before all measurements, each specimen was weighed. The same sampling procedure is followed for non-impacted rock.

In order to determine the shock effect on different magnetic mineralogy, we chose four types of rocks (microdiorite, basalt, rhyolite and schist). Thermomagnetic curves carried out with KLY2 suggest the presence of magnetite in microdiorite, titanomagnetite in basalt, hematite in rhyolite and pyrrhotite in schist. A number of rock-magnetic experiments (NRM analysis, hysteresis, anisotropy of magnetic susceptibility) have also been carried out for all impacted and non impacted specimens (Lamali *et al*. 2005).

4. Results and Interpretation

In this paper, we focused on the hysteresis loops measurement where the differential magnetic susceptibility is calculated according to equation Eq. (1). On the other hand, we showed (Lamali *et al*. 2005) that measured magnetic susceptibilities for all impacted specimens and their magnetic anisotropy factor are strongly modified by the shock wave in the first centimeter of the impact point. Furthermore, we also showed that shock wave imparted a magnetic foliation with a minimum susceptibility axis parallel to the direction of impact. On the other hand, the unshocked specimens have homogeneous magnetic susceptibilities and hysteresis parameters (see Table 1, showing remanence, coercivity, saturation, and other parameters). We show in Figs. 1-3 the obtained curves of the differential magnetic susceptibility from hysteresis loops, respectively, for the shocked basalt, microdiorite and schist samples. Unfortunately, we could not represent the curves relating to the rhyolite specimens while the measured magnetic signal by the VSM apparatus is too noisy. It is often the case when the major carrier of magnetization in the sample is the hematite.

Table 1

Hysteresis parameters of shocked and unshocked materials
(For each parameter, the number of measured specimens is n = 10)

Hysteresis parameters	Basalt		Microdiorite		Schist	
	Unshocked	shocked	Unshocked	shocked	Unshocked	shocked
Mr (Am^2kg^{-1})	9.78±0.67 10^{-2}	1.08±0.16 10^{-1}	2.38±0.20 10^{-2}	5.35±4.98 10^{-2}	4.48±2.90 10^{-2}	7.20±4.5 10^{-2}
Ms (Am^2kg^{-1})	6.22±0.46 10^{-1}	6.41±0.21 10^{-1}	1.28±0.14 10^{-1}	1.84±0.26	9.14±6.02 10^{-2}	1.43±0.9 10^{-1}
Mr/Ms	1.57±0.03 10^{-1}	0.17±0.03	1.39±0.07 10^{-2}	0.03±0.03	4.99±0.28 10^{-1}	0.51±0.03
Bc (mT)	5.19±0.16	5.05±0.89	1.86±0.08	4.05±4.12	23.8±5.9	26.79±12.16
Bcr (mT)	18.4±1.1	16.20±1.81	19.1±0.7	20.5±5.82	31.3±11.7	32.59±15.38
Bcr/Bc	3.54±0.14	3.24±0.17	10.3±0.4	7.34±2.76	1.29±0.12	1.21±0.06

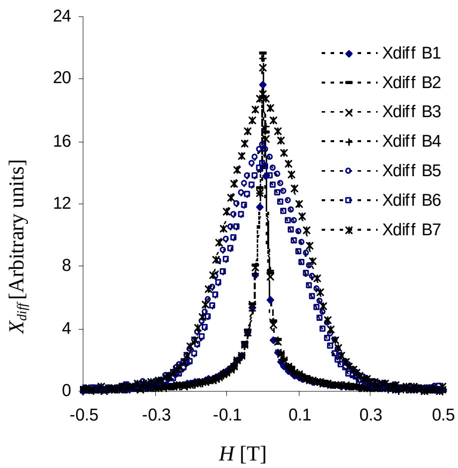

Fig. 1. Microdiorite X_{diff} curces (E1 to E7: distance from impact).

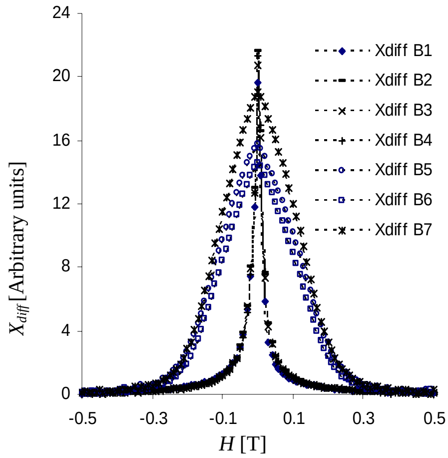

Fig. 2. Basalt X_{diff} curves (B1 to B7: distance from impact).

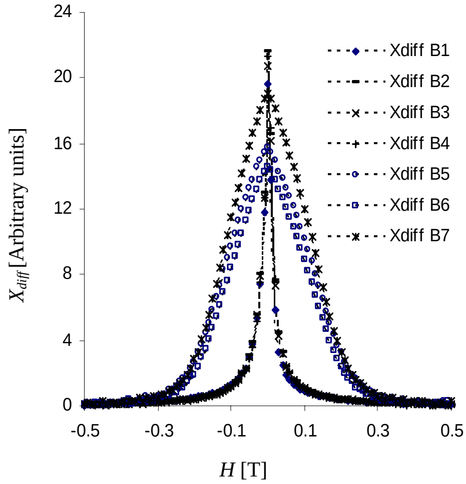

Fig. 3. Schist X_{diff} curves (S1 to S7 distance from impact).

Pressure-induced changes in magnetic parameters have been studied on a large set of rock samples. The modification of these parameters is noticeable in the rock with ferrimagnetic minerals. We examined here the changes in the differential magnetic susceptibility parameter. We observe in Figs. 1-3 that this parameter is strongly affected by the shock wave in the first centimeter of the all impacted rocks. Here we focus on the major peak. This peak grows as the pressure decreased from its maximum at first relevant shocked specimens. For impacted microdiorite specimens, these peaks reach a pronounced minimum at the first few steps of shock wave propagation (Fig. 1). Otherwise, at this stage of propagation, the impacted basalt specimens present a considerable peak with a delimited narrow area (Fig. 2) and this confirms that the coercivity was strongly affected. These observations concern microdiorite and basalt, with magnetite and titanomagnetite bearing mineralogy, respectively, rather than pyrrhotite present in schist where the peaks show a chaotic evolution towards the shock wave propagation (Fig. 3). The presence of pyrrhotite under its two crystallographic phases (monoclinic and hexagonal) in schist specimens may be the cause of this behavior. We can deduce that the magnetic mineralogy behaves differently under pressure.

We can put forward several hypotheses which could explain these pressure-induced changes referring to previous works. The shock wave affects differently the intrinsic magnetic properties, owing to differences in mineralogical composition, texture, porosity, grain size and alteration degree (Pesonen *et al*. 1992). Previous studies show that magnetostriction coefficients in magnetite increase with increasing titanium concentration which makes titanomagnetite more stress-sensitive than pure magnetite, where the bulk volume decreases 1% to 2% [GPa], and closer atomic distances should result in heightened superexchanging interaction and thus influence the magnetostriction (Gilder *et al*. 2002, 2004 and references therein). Referring to the micromagnetism theory, it is known that the number of dislocation increases with stress which acts to reduce domain size, inhibit wall motion and/or physically create single or sub-volumes that take on single domain properties (Gilder *et al*. 2005). Additionally, under great deformations, the important density of fixed dislocations and their strongly heterogeneous walls distribution anchor and curve the principal walls very easily (Hug *et al*. 1994). Intergown phases and local stress field around may serve, in addition to lattice defects, as a strong pinning sites for domain walls and also magnetic interactions may not be negligible (Kapicka *et al*. 2003). In conclusion, the decrease of mean susceptibility under uniaxial stress is related to the decreased mobility of the domain walls or to qualitatively different behavior of the changes of directional susceptibilities of orientations different with respect to the applied stress (Kapicka 1990, 1992).

Finally, it is noteworthy that these observed pressure-induced changes are irreversible and not annealed for temperature up to 580°C. Similar irreversible changes in magnetic properties have been observed in magnetite under hydrostatic pressures up to 6 GPa (Gilder *et al*. 2004) and in hematite powder subjected to shocks between 8-27 GPa (Williamson *et al.* 1986).

5. Conclusions

Laboratory pressure treatment results indicate that the intrinsic magnetic properties (hysteresis, susceptibility) of the magnetite-, titanomagnetite- and pyrrhotite-bearing rocks are permanently modified by a shock wave generating a peak pressure greater than a few GPa. Many factors cited above may be responsible for these modifications. We recommend additional laboratory measurements which are ineluctable to investigate the real origin of these pressure-induced changes.

Acknowledgments. This study is a detailed interpretation of the hysteresis loops obtained during my training in rock magnetism laboratory at CEREGE (University Aix-Marseille 3 and CNRS), in order to obtain the master2 research diploma under the direction of Pr. Pierre Rochette. We acknowledge Fabienne Vadeboin at CEREGE who kindly contributed to carry out all our measurements.

References

Cisowski, S.M., and M. Fuller, 1978, *The effects of shock on magnetism of terrestrial rocks*, J. Geophys. Res. **83**, 3441-3458.

Dunlop, D.J., and Ö. Özdemir, 1997, *Rock magnetism*, Cambridge Univ. Press, Cambridge, 573 p.

Gattacceca, J., M. Boustie, B.P. Weiss, P. Rochette, E. Lima, L.E. Fong and F. Baudenbacher, *Investigating impact demagnetization through laser impacts and SQUID microscopy*, Geology (in press).

Gilder, S., and M. LeGoff, 2005, *Pressure dependence on the magnetic properties of titanomagnetite using the reversible susceptibility method*. **In:** J.H. Chen, Y.B. Wang, T.S. Duffy, G.Y. Shen and L. Dobrzhinetskaya (eds.), “Advances in High-Pressure Technology for Geophysical Applications”, Elsevier, Chapter **15**, 315-335.

Gilder, S., M. LeGoff, J.C. Chervin and J. Peyronneau, 2004, *Magnetic properties of single and multi-domain magnetite under pressures from 0 to 6 GPa*, Geophysical Research Letters **31**, L10612, doi:10.1029/2004GL019844.

Gilder, S., M. LeGoff, J. Peyronneau and J.C. Chervin, 2002, *Novel high pressure magnetic measurements with application to magnetite*, Geophysical Research Letters **29**, 10.1029/2001GL014227.

Halekas, J.S., D.L. Mitchell, R.P. Lin, L.L. Hood, M.H. Acuña and A.B. Binder, 2002, *Demagnetization signatures of lunar impact craters*, Geophys. Res. Let. **29**, doi: 10.1029/ 2001GL013924.

Hargraves, R.B., and W.E. Perkins, 1969, *Investigations of the effect of shock on natural remanent magnetism*, Journal of Geophysical Research **74**, 2576-2589.

Hart, R.J., S.H. Connell, M. Cloete, L. Mare, M. Drury, and M. Tredoux, 2000, *Super magnetic' rocks generated by shock metamorphism from the centre of the Vredefort impact structure*, South African Journal of Geology **103**, 151-155.

Hood, L., N.C. Richmon, E. Pierazo and P. Rochette, 2003, *Distribution of crustal magnetic fields on Mars: shock effect of bassin-forming impacts*, Geophys. Res. Let. **30**, 10.1029/2002GL016657.

Hug, E., M. Kant and M. Clavel, 1994, *Influence de l'écrouissage sur les propriétés magnétiques d'alliages Fe-3%Si non orientés*, Journal de Physique III **4**, **7**, 1267-1284.

Hunt, C.P., B.M Moskowitz and S.K Banerjee, 1995, *Magnetic properties of rocks and minerals*. **In:** T.J. Ahrens (ed.), “Rock physics and phase relations”, AGU, Washington DC, 189-204.

Kapicka, A., V. Hoffmann and E. Petrovsky, 2003, *Pressure instability of magnetic susceptibility of pyrrhotite bearing rocks from the KTB borehole*, Studia Geophysica Et Geodaetica **47**, 2, 381-39.

Kapicka, A., 1992, *Magnetic susceptibility under hydrostatic pressure of synthetic magnetite samples*, Physics of the Earth and Planetary Interiors **70**, 248-252.

Kapicka, A., 1990, *Variations in mean susceptibility of rocks under hydrostatic and non-hydrostatic pressure*, Physics of the Earth and Planetary Interiors **63**, 78-84.

Kletetschka, G., J.E.P. Connerney, N.F Ness and M.H Acuna, 2004, *Pressure effects on Martian crustal magnetization near large impact basins*, Meteoritics & Planet. Sci. **39**, 11, 1839-1848.

Lamali, A., J. Gattacceca, P. Rochette and M. Boustie, 2005, *Magnetic effects of explosive driven shocks on geological materials*, AGU San Francisco Dec. 2005.

Pesonen, L.J., N. Marcos and F. Pipping, 1992, *Palaeomagnetism of the Lappajärvi impact structure, western Finland*, Tectonophysics **216**, 1-2, 123-142.

Pilkington, M., and R.A.F. Grieve, 1992, *The geophysical signature of terrestrial impact craters*, Reviews of Geophysics **30**, 161-181.

PohI, J., U. Bleil and U. Hornemann, 1975, *Shock magnetization and demagnetization of basalt by transient stress up to 10 kbar*, J. Geophys. **41**, 23-41.

Pohl, J., and A. Eckstaller, 1981, *The Effect of Shock on Remanence in Multi-Domain Iron Grains and Implications for Palaeointensity Measurements*, Lunar and Planetary Science **XII**, 851-853.

Radwan, M.M., 2002, *Magnetostriction Properties of* $Fe_{40}Ni_{38}B_{18}Mo_4$ *Amorphous Alloy*, Egypt. J. Sol. **25**, 1.

Rochette, P., J.P Lorand, G. Fillion and V. Sautter, 2001, *Pyrrhotite and the remanent magnetization of SNC meteorites: A changing perspective on Martian magnetism*, Earth Planet Sci. Let. **190**, 1-12.

Rochette, P., G. Fillion, R. Ballou, F. Brunet, B. Oulladiaf and L. Hood, 2003, *High pressure magnetic transition in pyrrhotite and impact demagnetization on Mars*, Geophys. Res. Lett. **30(13)**, 1683, doi:10.1029/2003GL017359.

Ugalde, H.A., N. Artemieva and B. Milkereit, 2003, *Numerical Modelling and Petrophysical Constraints the Magnetic Signature of Impact Structures*, Expanded Abstracts, 3rd International Conference in Large Meteorite Impacts, Noerdlingen, Germany, Abstract 4017.

Williamson, D.L., E.L Venturini, R.A. Graham and B. Morosin, 1986, *Morin transition of shock-modified hematite*, Phys. Rev. B **34, 1**899-1907.

Accepted March 22, 2007