J. Geophys. 41, 23—41, 1975

Shock Magnetization and Demagnetization of Basalt by Transient Stress up to 10 kbar

J. Pohl, U. Bleil, and U. Hornemann

Institut für Angewandte Geophysik der Universität München

Received March 4, 1974

Abstract. The effect of stress waves on the magnetization of basalt was studied. The stress waves were generated by impacting cylindrical basalt samples with aluminium projectiles. The 3 mm thick aluminium plates were accelerated in a non-magnetic compressed air gun accelerator to velocities ranging from 20 to 160 m/s, corresponding to peak stresses in the basalt between 2.5 and 10 kbar. The duration of the stress impulse was about several micro-seconds. For the experiments a basalt with well-known magnetic properties was used (Rauher Kulm, Germany). — The magnetizing effect of the stress waves was determined as a function of the number of impacts, the intensity and direction of the applied magnetic field (<10 Oe) and the peak stress amplitude. In the used stress range the measured shock remanent magnetization (SRM) tends to a final steady value after 5 or 6 impacts. This value is proportional to the intensity of the applied field and increases with the peak stress applied. The produced SRM can be erased with maximum ac-fields of about 150 to 200 Oe. Any dependance of SRM on the direction of the applied magnetic field could not be recognized within the accuracy limits of the experiments. — The demagnetizing effect of stress waves on the high-field (1000 Oe) isothermal remanent magnetization, the low-field (1 Oe) thermoremanent magnetization and the natural remanent magnetization was studied as a function of the number of impacts and the peak stress. A final steady state of magnetization is generally obtained after 4 or 5 impacts. With increasing peak stresses increasingly harder remanent magnetizations can be demagnetized, with stresses of 2.5 kbar corresponding to coercive forces of about 75 Oe, 5.5 kbar to about 125 Oe and 8 kbar to about 175 Oe.

Key words: Rock Magnetism — Piezomagnetic Effect — Dynamic Magnetization — Shock Demagnetization — High Pressures — Meteorite Impacts — Nuclear Explosions — Lunar Magnetism.

1. *Introduction*

Effects of static and transient stresses on magnetic properties of rocks are of importance in numerous natural and man-made phenomena such as the seismomagnetic effect (Stacey, 1964; Rikitake, 1968; Talwani and Kovach, 1972; Abdullabekov *et al.*, 1972), the volcano-magnetic effect (Stacey, Barr and Robson, 1965; Johnston and Stacey, 1969), the dam-magnetic effect (Davis and Stacey, 1972), the magnetic effects associated with chemical (Barsukov and Skovorodkin, 1969) and nuclear explosions (Short, 1966;

Hargraves and Perkins, 1969; Hasbrouck and Allen, 1972) and with meteorite impacts on Earth and on the Moon (Hargraves and Perkins, 1969; Pohl, 1971).

The effects of static uniaxial stress on magnetic properties of rocks, mainly reversible changes of susceptibility and reversible and irreversible changes of remanent magnetizations, have been studied by many authors. The remanent magnetization produced by static stresses is called piezoremanent magnetization (PRM). The demagnetizing effect of stresses is called stress demagnetization. A review on this subject was given by Nagata (1970).

The effect of transient stresses on magnetic properties of rocks has been studied much less. It is well known that shocks can change the remanent magnetization of ferromagnetic materials. Systematic investigations of the effect of repeated shocks on nickel were made for example by Gerlach (1949). The demagnetizing effect of intense stress waves on iron has been used in a technique for generating high electric current impulses of short duration (Kultermann, Neilson and Benedick, 1958). — At the beginning of rock magnetic research many investigators suspected that shocks could also change the remanent magnetization of rocks. They studied this effect by giving different types of rocks numerous consecutive shocks with automatic hammering devices, but they generally found only minor changes in remanence (e.g. Koenigsberger, 1932, 1936; Schmucker, 1957) and concluded that the effect is negligeable for paleomagnetic research.

It seems that in these early investigations rock types with quite stable remanent magnetizations were used, because more recently it was found that shocks can cause appreciable changes of magnetic properties of many rock types. Demagnetized rocks can acquire a remanent magnetization in the presence of a magnetic field under the effect of shocks. This phenomenon has been called dynamic magnetization or shock magnetization. The remanent magnetization produced by this procedure is called shock remanent magnetization (SRM, Nagata, 1971). On the other hand a remanent magnetization can also be destroyed by shocks (shock demagnetization).

The shocks or stress waves used in these experiments were generated by automated hammering devices (Shapiro and Ivanov, 1966, 1967), by falling masses (Domen, 1961; Nagata, 1971) and by explosives (Pohl, 1967; Hargraves and Perkins, 1969). The effect of shocks was measured as a function of the number of repeated shocks, of the intensity of the shock (kinetic energy of the impacting hammer, momentum of the falling mass) and of the applied magnetic field in the case of a production of remanent magnetization. Nagata (1971) gave also some information about the duration of the used stress impulse. The stability of shock remanent magnetizations was measured by Shapiro and Ivanov (1966). — In the above cited experiments either very low or very high stresses were used. Generally the stress amplitudes did not exceed several hundred bar. In cases where explosives were used, the stresses were estimated to be of the order of several tens of kbars (Pohl, 1967; Hargraves and Perkins, 1969).

Static experiments with uniaxial stress without a confining hydrostatic pressure are limited to stresses of about 2 kbar, where the samples generally crash. With stress waves of short duration much higher stresses can be used. A limit is given also in these experiments by the pulverization of the sample.

The aim of the present study was to investigate the effect of stress waves up to about 10 kbar on a basalt with well-known magnetic properties. Different results of experiments with static uniaxial compressive stress on the same basalt, which can be usefully compared with dynamic experiments, are shown in the corresponding sections.

It should be noted that the expression "shock waves" is not appropriate to describe these experiments, although the expressions shock remanent magnetization and shock demagnetization are used. The term "shock wave" is applied to a compressional wave having an amplitude exceeding the Hugoniot elastic limit. The shock front is characterized by a discontinuity in pressure, density, energy and particle velocity. In the used stress range the compressional waves in solids have a comparatively long rise time, particularly in inhomogeneous materials such as rocks. In a first approximation the state of strain behind the wave front is uniaxial and the stress distribution is anisotropic.

2. *Experimental Method*

The stress waves are generated by the impact of aluminium projectiles (30 mm diameter, 3 mm thick) on an aluminium driver plate (3 mm thick) which is in contact with the cylindrical basalt sample (25 mm in diameter and 25 mm high). The projectiles are accelerated in a compressed-air gun accelerator (Hornemann, Pohl and Bleil, 1975). The peak stress is derived from the impact velocity, using Hugoniot-data for aluminium and basalt, and from direct measurements with piezo-ceramic transducers. The length of the stress pulse increases from about 8 μs at the impact side of the basalt sample to about 25 μs at its back side. The amplitude of the stress wave decreases by about 20% within the specimen. The magnetic field at the place of the sample is controlled by a triple set of Helmholtz coils. The remanent magnetization of the samples is measured with a Digico flux-gate spinner magnetometer.

The measuring procedure is as follows. For magnetizing experiments the samples are placed at the end of the launching tube, a magnetic field is applied and an impact is given to the sample. Then the remanent magnetization is measured in the Earth's magnetic field. For demagnetizing experiments the sample with a remanent magnetization is impacted in magnetic zero-field. The measurement of the residual remanent magnetization is also made in the Earth's magnetic field.

Nagata (1971) has introduced the following notation for the description of static and transient stress experiments in rock magnetism: H^+ = application of a magnetic field, H^0 = removal of a magnetic field, P^+ = application of static stress, P^0 = removal of static stress, S = application of a shock. It seems convenient to add the notation H^e indicating that the Earth's magnetic field is applied and to restrict the notation H^0 to the meaning of the removal of any applied field, e.g. cancellation of the Earth's magnetic field. With these notations the remanent magnetization J_r produced in the magnetizing experiments described above after n impacts is given by

$$J_r(H^+S_1H^e,\ H^+S_2H^e,\ \ldots,\ H^+S_nH^e)$$

Similarly the demagnetizing experiments can be described by

$$J_r(\mathrm{TRM},\ H^0S_1H^e,\ H^0S_2H^e,\ \ldots,\ H^0S_nH^e)$$

where TRM means that the original remanence was a thermoremanent magnetization which must however be specified.

In order to determine the remanence it is necessary to preserve the samples after each impact in the original form. Since the used peak stresses highly exceed the breaking strength of the rock material, the samples were embedded with an epoxy resin in thin aluminium rings. At a peak stress of about 2 kbar small cracks begin to appear on the impacted surface of the samples. The number of cracks increases with higher impact velocities and repeated impacts. At a stress of about 10 kbar the sample is strongly brecciated after a few impacts. Measurements of the effect of repeated shocks are therefore limited at this stress level. However single shot experiments can be made with the available apparatus up to stresses of about 20 kbar, as the remanent magnetization can be measured as long as the sample is recovered approximately in its original form.

There is suspicion that the strong brecciation could modify the coercivity spectrum of the basalt by the development of cracks and/or lattice defects in the ferrimagnetic minerals. Therefore the coercivity spectra of the isothermal remanent magnetization (IRM) produced in a 1000 Oe field were measured before and after repeated impacts. As they were almost identical we conclude that such brecciation effects can be neglected in this study. Other macroscopic magnetic properties have not yet been investigated in this respect. It would be interesting for example to consider irreversible changes of the initial susceptibility and to measure the rotational hysteresis and the susceptibility anisotropy before and after impacting.

Table 1. Magnetic properties of the Rauher Kulm basalt

Compositional Curie point	T_c	245	°C
Measured Curie point	T_c	220	°C
Susceptibility (low field)	χ	$4 \cdot 10^{-3}$	emcgs
Saturation magnetization (20 °C)	J_s	4	G
Saturation remanent magnetization (20 °C)	J_{sr}	0.5	G

Ferrimagnetic ore: Homogeneous titanomagnetite, oxidation class I. $x\mathrm{Fe_3O_4} \cdot (1 - x)\mathrm{Fe_2TiO_4}$, x = 0.46.
Ore content: 4 Vol%
Grain size distribution:

Size (μm)	Vol%
30 — 50	24.5
10 — 30	60
5 — 10	12
1 — 5	3.15
< 1	0.35

The decrease of the peak stress intensity and the increase of the pulse length within the sample could produce an inhomogeneous remanent magnetization which can easily be detected by a simple flux-gate measuring arrangement (Helbig, 1965). No indications for any inhomogeneity in magnetization were however found within the accuracy limits of the method (3%). This may be due to the fact that an increase in pulse length leads to a higher remanence whereas a decrease in stress amplitude causes a lower remanence and that both effects cancel each other more or less.

3. Magnetic Properties of the Basalt from Rauher Kulm (RK), Germany

Basalts having acquired a SRM in low fields (<10 Oe) and in the stress range lower than 10 kbar can be demagnetized with peak ac-fields of about 100 to 200 Oe. Therefore a basaltic material with a coercivity spectrum having a maximum at coercive forces below 100 Oe was selected for this study. The used basalt comes from the Tertiary "Rauher Kulm", Germany. Magnetic and mineralogical properties of this basalt have been described by Refai (1960); Petersen (1966); Soffel (1968); Creer and Petersen (1969); Creer, Petersen and Petherbridge (1970). Investigations of static uniaxial compression effects on magnetic properties of the RK-basalt have been carried out by Schmidbauer and Petersen (1968) and Zinsser (1970). Some additional measurements have been made in this study. A summary of different magnetic and mineralogical properties is given in Table 1 and in Figs. 1 and 2.

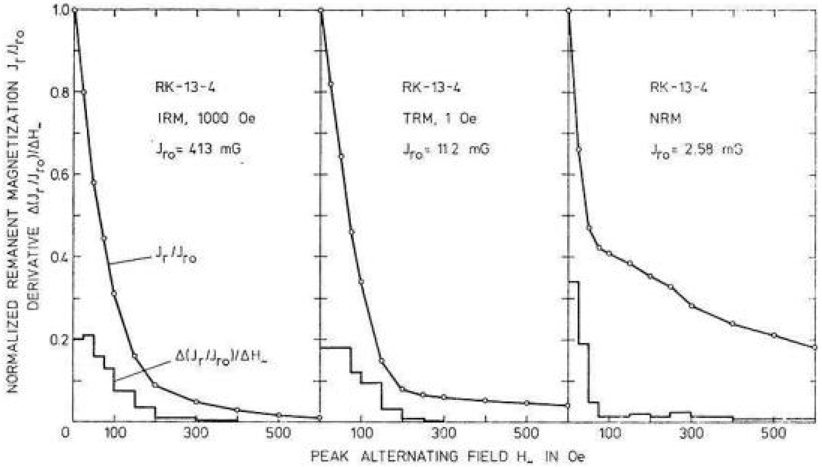

Fig. 1. Ac-demagnetization and coercivity spectra of the strong field isothermal remanent magnetization (IRM), the weak field thermoremanent magnetization (TRM) and the natural remanent magnetization (NRM, see also Fig. 11) for the Rauher Kulm (RK) basalt

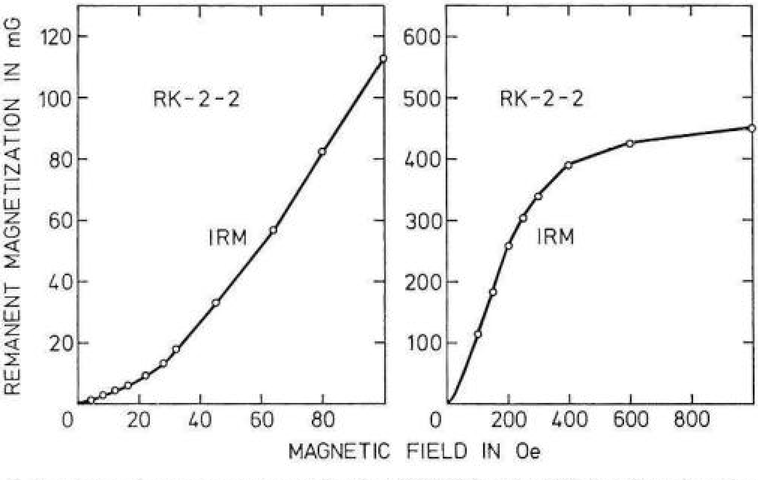

Fig. 2. Isothermal remanent magnetization (IRM) for the RK-basalt as function of the applied magnetic field

The carriers of remanence in the RK-basalt are both single domain (SD) and multi-domain (MD) grains. The mixed SD and MD behaviour was investigated by microscopic analysis of the magnetic domain structure by Soffel (1968). He showed that remanent magnetizations with coercive forces H_c smaller than about 200 Oe are located in MD grains and that remanent magnetizations with coercive forces higher than about 200 Oe, especially the stable TRM component, are located in SD grains. The mixed SD and MD behaviour is also suggested by applying the Lowrie and Fuller (1970) criterion (see also Dunlop, Hanes and Buchan, 1973). The normalized ac-demagnetization curves of low field TRM and high field IRM (Fig. 1) are nearly identical for $H_\sim < 200$ Oe. For $H_\sim > 200$ Oe the TRM curve is above the IRM curve indicating a SD behaviour in this H_c-region. The ac-demagnetization of natural remanent magnetization (Figs. 1 and 11) also shows that the NRM of the RK-basalt consists both of an unstable, probably viscous component (Creer, Petersen and Petherbridge, 1970) and a stable TRM component (Soffel, 1968). The samples used in this study were taken from unoriented boulders which have probably been lying in the Earth's magnetic field with an orientation different from their original in situ orientation for several hundred years.

4. *The Effect of Repeated Impacts*

A characteristic feature of shock magnetization and demagnetization is that for a given peak stress intensity a final steady state of magnetization is not achieved by a single impact but that it is gradually approached with an increasing number of shocks. For low stresses this was shown by Gerlach (1949), Shapiro and Ivanov (1966) and Nagata (1971). The experimental results of magnetizing igneous rocks by repeated stress waves can empirically be represented in exponential laws (Shapiro and Ivanov, 1966). The remanent magnetization obtained in low magnetic fields after n impacts is given by

$$J_r(n) = J_r(\infty)\,(1 - e^{-\alpha n})\,. \tag{1}$$

$J_r(\infty)$ denotes the resulting final state of magnetization after a great number of impacts. The residual remanent magnetization after n impacts in non-magnetic space is given by

$$J_r(n) = J_r(\infty) - (J_r(\infty) - J_0)\,e^{-\alpha n} \tag{2}$$

J_0 denotes the initial remanent magnetization.

The experiments described in this study indicate that these relations can also be applied for stresses up to 10 kbar. Fig. 3 shows the remanent magnetization acquired by repeated impacts in a low field. Demagnetization curves are shown in Figs. 7 and 8.

The coefficient α indicates how rapidly the final steady state is approached. α can be estimated by comparing the normalized experimental curves with a set of standard curves. It is generally impossible to use numerical or geometrical methods because of the small number of experimental points and their rather high scatter. α depends on numerous parameters, such as

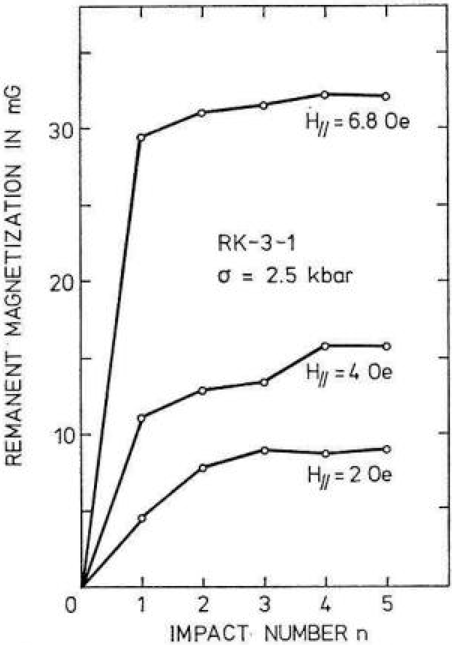

Fig. 3. Aquisition of shock remanent magnetization (SRM, $J_r(H+S_1H^e, \ldots, H+S_nH^e)$) and dependance on the number of impacts and the applied magnetic field

material properties, stress wave characteristics and intensity and direction of the applied magnetic field. In demagnetization experiments the particular type of initial remanence must also be considered. For the RK-basalt and stresses between 2.5 and 10.5 kbar, α varies from 0.8 to about 2. The final steady state of magnetization is generally approached to more than 95% after 3 or 4 shocks. Although no definite conclusions can be drawn due to the scatter of the experimental results, it seems that α increases with higher magnetic fields applied in magnetization experiments. No correlation was found between α and the peak stress intensity. The relations between α and the applied magnetic field and the peak stress intensity may be somewhat obscured by the fact that the determination of α strongly depends on the rate of the magnetization obtained after the first shock relative to the final state of magnetization after n shocks.

5. Shock Remanent Magnetization (SRM)

The relationship between the shock remanent magnetization $J_r(H+S_1H^e, H+S_2H^e, \ldots, H+S_nH^e)$, the peak stress intensity and the intensity and direction of the applied magnetic field (< 10 Oe) was investigated (Figs. 3,

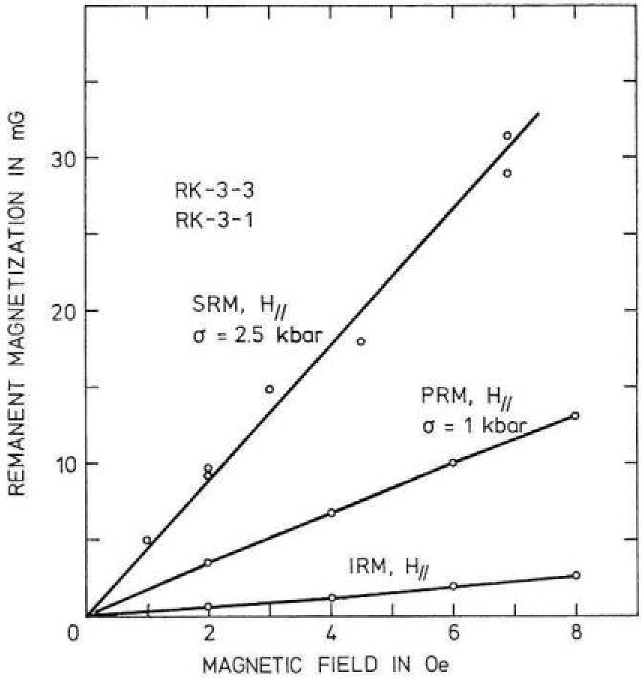

Fig. 4. Shock remanent magnetization $J_r(H^+S_1H^e, \ldots, H^+S_nH^e)$, piezo-remanent magnetization $J_r(H^+P^+P^0H^0)$ and isothermal remanent magnetization as functions of the applied magnetic field. For the SRM final steady state values obtained after several impacts are plotted

4 and 5). Prior to the magnetization experiments the samples were demagnetized in an ac-field of 1500 Oe. In the Earth's magnetic field the samples acquired a viscous magnetization of about 0.2 mG after several minutes, which is however small in comparison with the produced SRM and can therefore be neglected. The SRM is always parallel to the applied magnetic field.

Fig. 4 shows that for stresses from 2.5 to 10 kbar the SRM (final steady state values achieved after several impacts) increases almost linearly with the applied field H. These results correspond to those of Shapiro and Ivanov (1966) and of Nagata (1971) in the low stress range (<1 kbar). For comparison the dependance of a piezo-remanent magnetization J_r $(H^+P^+P^0H^e)$ and of the isothermal remanent magnetization on the applied field are also shown in Fig. 4. The PRM is proportional to H, whereas the IRM curve has a slight curvature corresponding to the Rayleigh-relationship between IRM and H ($\sim H^2$, see also Fig. 2). The magnetic field was applied parallel to the propagating direction of the stress wave (longitudinal mag-

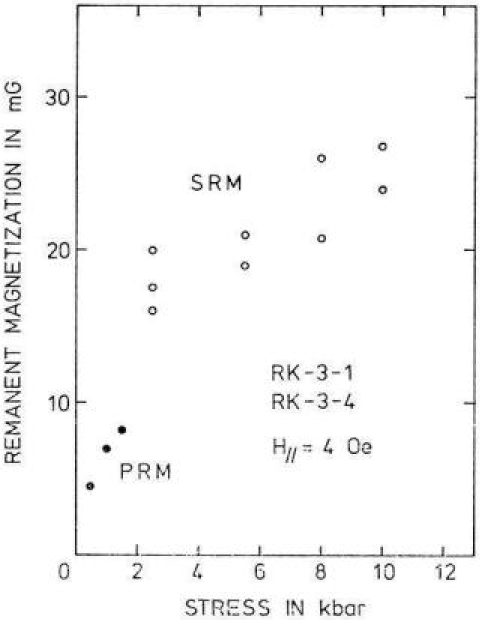

Fig. 5. Shock remanent magnetization (open circles) $J_r(H^+ S_1 H^e, \ldots, H^+ S_n H^e)$ as dependent on the stress wave amplitude and piezo-remanent magnetization (full circles) $J_r(H^+ P^+ P^0 H^0)$ as dependent on the applied uniaxial compressive stress. For the SRM final steady state values after several impacts are plotted

netization) and perpendicular to it (transverse magnetization). The longitudinal remanent magnetization was in most cases slightly higher than the transverse remanent magnetization, but the scatter of the intensities does not allow to determine a quantitative difference. The trend of the difference however confirms similar results for PRM and SRM in the lower stress range (Nagata, 1971).

The dependance of the final steady values of SRM on the peak stress is shown in Fig. 5. The remanent magnetization increases with increasing stress, but the rate of increase diminishes at higher stresses. The final SRM values may well be lying on the continuation of the curve obtained by experiments with static uniaxial compression, which is also shown in Fig. 5. The static experiments could only be made up to stresses of 1.8 kbar beyond which the samples crushed. The diminution of the rate of increase of the SRM at high stresses can in part be explained by the coercivity spectrum of the RK-basalt, if we assume that with increasing stress grains with increasing coercive forces can be magnetized. A quantitative analysis can not yet be made as the relation between the peak stress and the coercive forces is not well enough known.

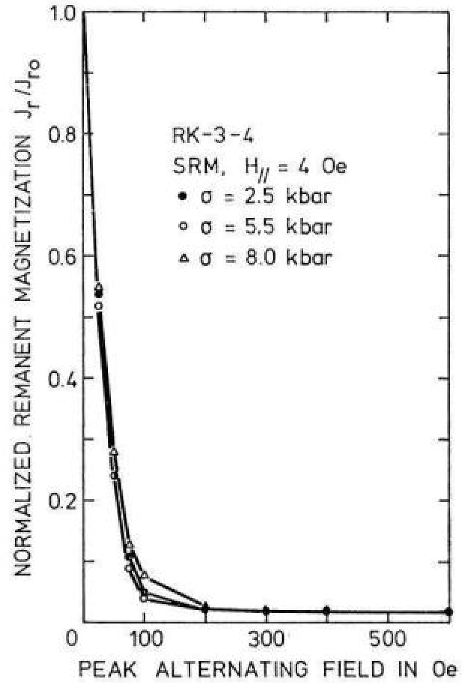

Fig. 6. Ac-demagnetization of shock remanent magnetization (normalized) acquired at different peak stress intensities

The produced SRM is not very stable against ac-demagnetization (Fig. 6). Peak ac-fields of about 100 Oe erase more than 90% of the SRM produced with stress intensities up to 10 kbar. There is only a slight indication that SRM produced at higher stresses has a greater stability. Shock demagnetization however shows clearly that with increasing stress intensity remanent magnetizations with higher coercive forces can be demagnetized (Section 6).

6. *Shock Demagnetization of IRM, TRM and NRM*

The demagnetizing effect of stress waves was studied for high field IRM (~ saturation remanent magnetization), low field TRM and NRM of the Rauher Kulm basalt (Figs. 7—11). The rock samples were impacted in non-magnetic space and the residual remanent magnetization was measured after each impact. Generally a final steady state of magnetization was obtained after 4 or 5 impacts. The values found for the coefficient α are in most cases slightly higher than in magnetizing experiments, but the scattering of the results does not allow to give a quantitative relationship.

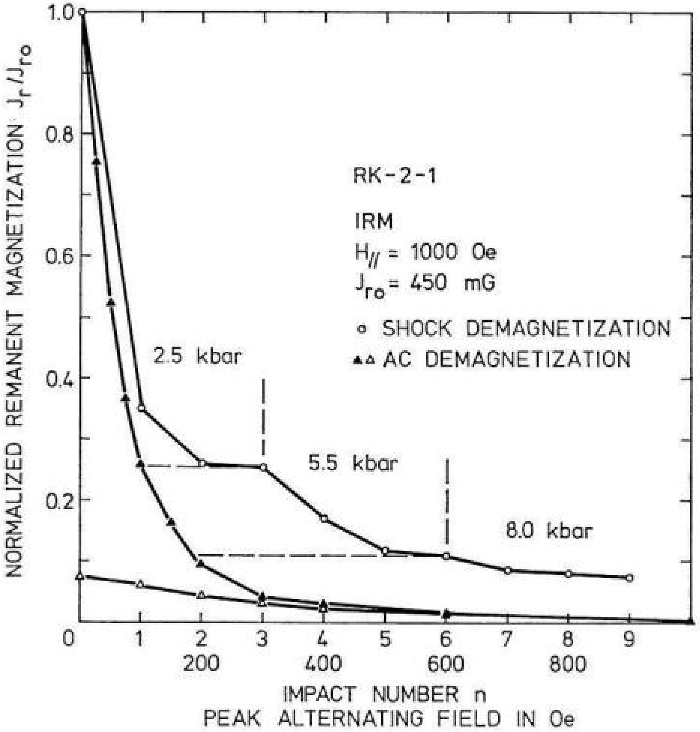

Fig. 7. Shock demagnetization (open circles) and ac-demagnetization (full triangles) of strong field isothermal remanent magnetization. Ac-demagnetization of the residual IRM (open triangles) after shock demagnetization with peak stress intensities of 8 kbar

The demagnetization by stress waves was carried out for remanent magnetizations parallel and perpendicular to the propagating direction of the stress waves, but no systematic difference could be found.

To obtain an idea about the coercive forces of the remanent magnetizations that can be erased by a certain peak stress amplitude the demagnetization by shock can be compared to the ac-demagnetization experiments. Ac-demagnetization of a residual remanent magnetization after impacting can give similar information. By applying ac-demagnetization to such a residual remanent magnetization, the remanence generally decreases only slightly until a certain peak value of the alternating field is reached, where it then decreases approximately as in ac-demagnetization of the original remanent magnetization of the same type. Because the residual remanent magnetization is not constant at low ac-fields (of the order of 100 Oe, Figs. 7 and 8), we must assume that magnetic grains with low coercive forces have not been completely demagnetized by the applied stress waves.

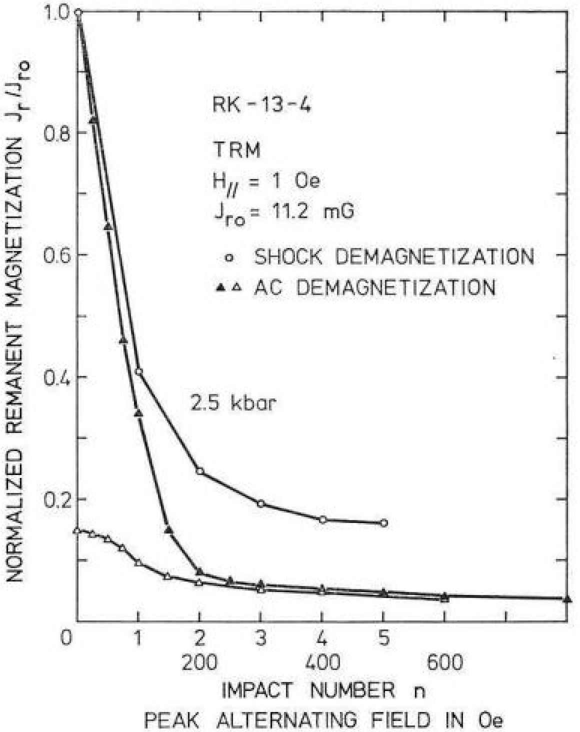

Fig. 8. Shock demagnetization (open circles) and ac-demagnetization (full triangles) of low field thermoremanent magnetization. Subsequent ac-demagnetization of the residual TRM after shock demagnetization with peak stress intensities of 2.5 kbar

On the other hand the ac-demagnetization curves of the residual remanent magnetization always lie below the ac-demagnetization curve of the original remanent magnetization. Therefore also grains with high coercive forces must have been affected by the stress waves.

The influence of the peak stress intensity was studied in two different ways. In one series of experiments the samples having the original remanent magnetization were impacted several times with the same velocity, beginning with a low velocity, until a certain final steady state was achieved. Then the sample having the residual remanent magnetization was impacted several times with a higher velocity, and so on (Fig. 7). In another series of experiments the demagnetization was made by impacting samples having always the original remanent magnetization with different velocities. Both experimental procedures gave similar results.

Fig. 7 shows shock demagnetization and ac-demagnetization of IRM produced at room temperature in a magnetic field of 1000 Oe. For com-

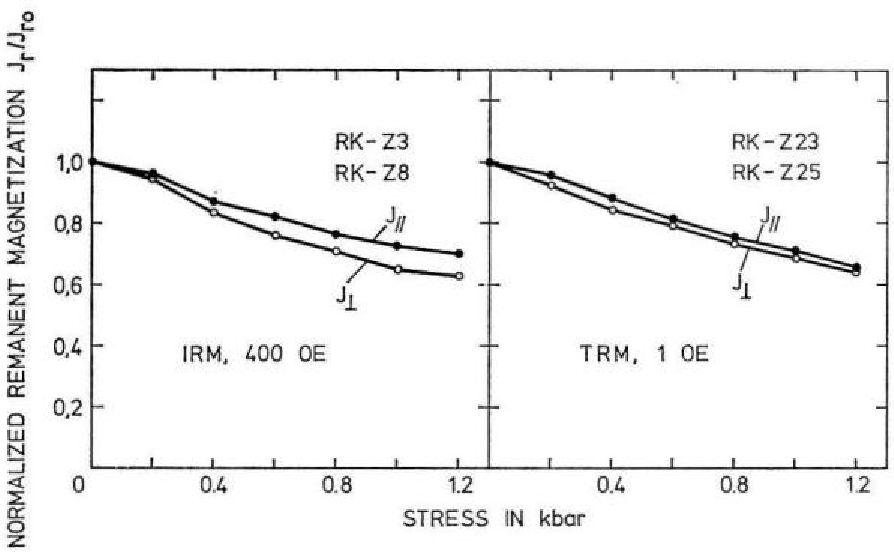

Fig. 9. Demagnetization of strong field isothermal remanent magnetization and low field thermoremanent magnetization by static uniaxial stress (after Zinsser, 1970). The residual remanence $J_r(H^0 P^+ P^0 H^0)$ is plotted as function, of the applied stress

parison the demagnetization by static uniaxial compressive stress of an IRM produced at 400 Oe in the same rock is shown (Zinsser, 1970). The difference of the magnetizing fields in both cases is not significant as in the used stress range both shock and static stress demagnetization hardly affect magnetizations of grains with coercive forces higher than 200 to 300 Oe. From Fig. 7 it can be seen that peak stresses of 2.5 kbar correspond to a demagnetizing ac-field of about 100 Oe, 5.5 kbar to about 200 Oe and 8.0 kbar to about 250 Oe. An extrapolation of the demagnetization rates obtained by static experiments to the stresses used in the dynamic experiments leads approximately to the same values (Figs. 7 and 9).

Results of shock demagnetization and ac-demagnetization of a TRM produced in a field of 1 Oe are shown in Fig. 8. Demagnetization of TRM by static uniaxial compression is shown in Fig. 9 (Zinsser, 1970). The RK-basalt has a low Curie-temperature of about 220 °C. TRM can therefore be produced several times without major alterations of the samples due to heating, provided the heating time does not exceed a few minutes (Creer, Petersen and Petherbridge, 1970). TRM produced several times in the same sample has the same value and the coercivity spectra are also identical. We can therefore assume that no important changes have occured in the homogeneous titano-magnetites by the heating operations. — The shock demagnetization of strong field IRM and weak field TRM is very similar.

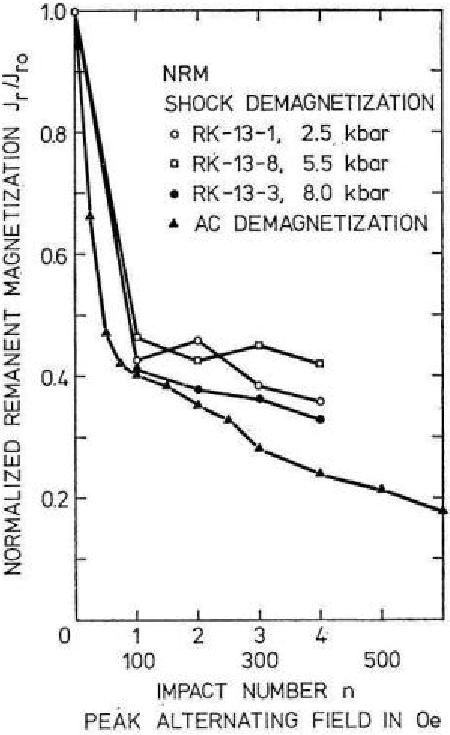

Fig. 10. Shock demagnetization and ac-demagnetization of NRM. $J_{r0,\,13-1}=2.05$ mG, $J_{r0,\,13-3}=2.70$ mG, $J_{r0,\,13-8}=2.36$ mG

This corresponds to the similarity of the ac-demagnetization of strong field IRM and weak field TRM. As in the case of IRM, the extrapolation of static demagnetization experiments leads to the demagnetization values obtained by shock demagnetization of TRM (Figs. 8 and 9).

Shock demagnetization and ac-demagnetization of the natural remanent magnetization of the RK-basalt are shown in Fig. 10 (intensity) and Fig. 11 (direction). The NRM consists of both an unstable, viscous component and a stable TRM component (Soffel, 1968). In the demagnetization curves showing the decrease of intensity scattering is rather high. This is mainly due to a viscous magnetization of about 0.2 to 0.3 mG acquired by the samples in the Earth's field in a few minutes which is about 10% of the NRM intensity. Thus a relationship between the demagnetization effect and the peak stress used can not be obtained from these demagnetization curves. The comparison of the changes of the direction of the NRM with ac-demagnetization and shock demagnetization however shows clearly that with increasing peak stress the final stable direction is approached

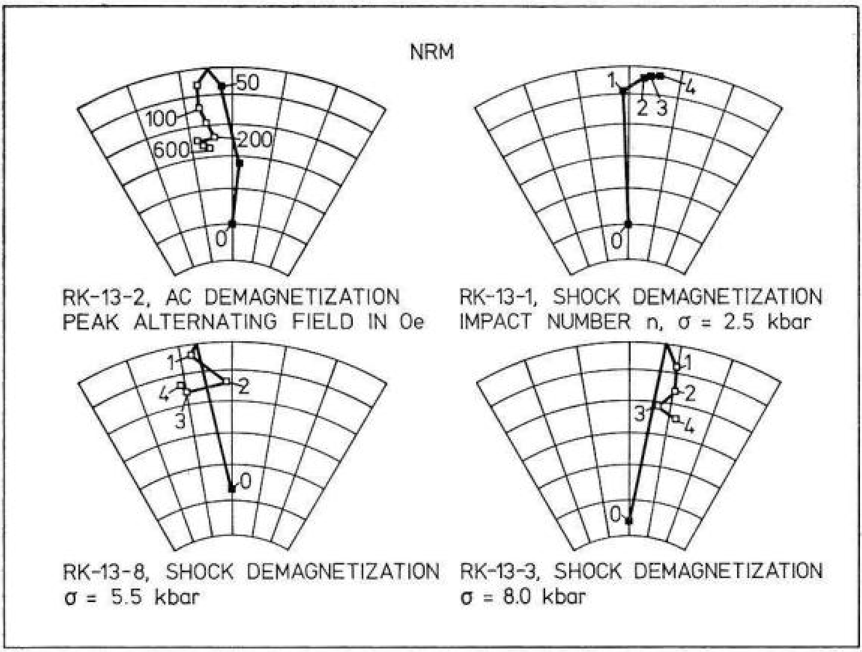

Fig. 11. Shock demagnetization and ac-demagnetization of NRM showing changes of the direction. The grid intervall is 10 degrees. A common zero original declination was chosen as the samples were not orientated. Full squares: upper hemisphere, open squares: lower hemisphere

asymptotically. From Fig. 11 it follows that 2.5 kbar correspond to a peak ac-field of about 50—75 Oe, 5.5 kbar to about 75—125 Oe and 8 kbar to about 150—200 Oe (see also Fig. 7).

7. *Conclusion*

In the preceeding sections the main features of the magnetizing and demagnetizing effect of stress waves with peak stress intensities between 2.5 and 10 kbar have been described for a basaltic rock from the Rauher Kulm. The characteristics of shock magnetization and shock demagnetization in the high stress range are similar to those in the low stress range and also to those of experiments with static uniaxial compressive stress. It is thus probable that existing theories for static experiments can be applied to dynamic experiments, taking into account the short duration of the stress impulse and the effect of repeated shocks. Nagata (1971) applied the theory of Nagata and Carleton (1969), which was established for static experiments, to his dynamic experiments in the low stress range. In this theory it is assumed that the changes of remanent magnetization are due to irreversible movements of 90° domain walls. The results in the high stress range agree in general with this theory but as the RK-basalt shows both single-domain and multi-domain behaviour, it is probable that in the stress range from 2.5 to 10 kbar both irreversible displacements of 90° domain walls and irreversible rotations of spontaneous magnetization contribute to changes of the remanent magnetization (Dunlop, Ozima and Kinoshita, 1969; Nagata, 1970; Stacey and Johnston, 1972). Theories for single-domain particles must also be considered. — In the future more detailed investigations of the stability of SRM and the relation to the coercivity spectrum are desirable, using materials with selected spectra of coercive forces and remanent magnetizations within a defined coercive force intervall. The effect of the duration of the stress impulse and a possible relation with the viscous remanence properties of the material also deserve more detailed investigations. The advanced shock effect (Nagata, 1971) which is described by $J_r(SH^+H^e)$ has not been investigated in this study. It will be dealt with in a further study in connection with measurements of the magnetic after-effect on the RK-basalt.

Acknowledgments. The authors wish to thank Prof. G. Angenheister, director of the Institut für Angewandte Geophysik, University of Munich, for his encouragement and support. They are also grateful to Dr. N. Petersen, Dr. E. Schmidbauer, Dr. A. Schult, Prof. H. Soffel and Dipl.-Phys. H. Zinsser for many helpful discussions. The work has been supported by the Deutsche Forschungsgemeinschaft.

References

Abdullabekov, K. N., Bezuglaya, L. S., Golovkov, V. P., Skovorodkin, Yu. P.: On the possibility of using magnetic methods to study tectonic processes. Tectonophysics *14*, 257–262, 1972

Barsukov, O. M., Skovorodkin, Y. P.: Magnetic observations in the region of the Medeo blast work. Izvestiya, Solid Earth, 310–311, 1969 (English edition)

Creer, K. M., Petersen, N.: Thermochemical magnetization in basalts. Geophys. J. *35*, 501–516, 1969

Creer, K. M., Petersen, N., Petherbridge, J.: Partial self-reversal of remanent magnetization and anisotropy of viscous magnetization in basalts. Geophys. J. *21*, 471–483, 1970

Davis, P. M., Stacey, F. D.: Geomagnetic anomalies caused by a man-made lake. Nature *240*, 348–349, 1972

Domen, H.: A note on remanent magnetism caused by impulsive pressure. Bull. Fac. Educ. Yamaguchi Univ. *10*, 71–76, 1961

Dunlop, D. J., Hanes, J. A., Buchan, K. L.: Indices of multidomain magnetic behaviour in basic igneous rocks: Alternating-field demagnetization, hysteresis and oxide petrology. J. Geophys. Res. *78*, 1387–1393, 1973

Dunlop, D. J., Ozima, M., Kinoshita, H.: Piezomagnetization of single-domain grains: A graphical approach. J. Geomagn. Geoelectr. *21*, 513—518, 1969

Gerlach, W.: Über den Erschütterungseinfluß auf die Magnetisierung und seine Temperaturabhängigkeit. Helv. Phys. Acta *22*, 142—148, 1949

Hargraves, R. B., Perkins, W. E.: Investigations of the effect of shock on natural remanent magnetism. J. Geophys. Res. *74*, 2576—2589, 1969

Hasbrouck, W. P., Allen, J. H.: Quasi-static magnetic field changes associated with the Cannikin nuclear explosion. Bull. Seismol. Soc. Am. *62*, 1479—1487, 1972

Helbig, K.: Optimum configuration for the measurements of the magnetic moment of samples of cubical shape with a flux-gate magnetometer. J. Geomagn. Geoelectr. *17*, 373—380, 1965

Hornemann, U., Pohl, J., Bleil, U.: A compressed air gun accelerator for shock magnetization and demagnetization experiments up to 20 kbar. J. Geophys. *41*, 13—22, 1975

Johnston, M. J. S., Stacey, F. D.: Transient magnetic anomalies accompanying volcanic eruptions in New Zealand. Nature *224*, 1289—1290, 1969

Koenigsberger, J. G.: Über remanenten Magnetismus von Gesteinen. Gerlands Beitr. Geophys. *35*, 204—216, 1932

Koenigsberger, J. G.: Die Abhängigkeit der natürlichen remanenten Magnetisierung bei Eruptivgesteinen von deren Alter und Zusammensetzung. Beitr. angew. Geophys. *5*, 193—246, 1936

Kulterman, R. W., Neilson, F. W., Benedick, W. B.: Pulse Generator based on high shock demagnetization of ferromagnetic material. J. Appl. Phys. *29*, 500—501, 1958

Lowrie, W., Fuller, M.: On the alternating field demagnetization characteristics of multi-domain thermoremanent magnetization in magnetite. J. Geophys. Res. *76*, 6339—6349, 1971

Nagata, T.: Effects of a uniaxial compression on remanent magnetizations of igneous rocks. Pageoph *78*, 100—109, 1970

Nagata, T.: Basic magnetic properties of rocks under the effects of mechanical stresses. Tectonophysics *9*, 167—195, 1970

Nagata, T.: Introductory notes on shock remanent magnetization and shock demagnetization of igneous rocks. Pageoph *89*, 159—177, 1971

Nagata, T., Carleton, B. J.: Notes on piezo-remanent magnetization of igneous rocks (III). J. Geomagn. Geoelectr. *21*, 623—645, 1969

Petersen, N.: Beobachtung einiger mineralogischer und magnetischer Eigenschaften dreier Basaltproben nach unterschiedlicher thermischer Behandlung. J. Geomagn. Geoelectr. *18*, 463—479, 1966

Pohl, J.: Magnetisierung und Entmagnetisierung von Stahl und Magnetit durch Stoßwellen. Unpublished report. Institut für Angewandte Geophysik, Universität München, 1967

Pohl, J.: Magnetisierung der Gesteine und Interpretation der Anomalien des Erdmagnetfeldes im Ries-Krater. Dissertation, Universität München, München 1971

Refai, E.: Magnetfeld und Magnetisierung der Basaltvorkommen im Raum von Kemnath. Z. Geophys. *27*, 175—187, 1960

Rikitake, T.: Geomagnetism and earthquake prediction. Tectonophysics *6*, 59—68, 1968

Schmidbauer, E., Petersen, N.: Some magnetic properties of two basalts under uniaxial compression measured at different temperatures. J. Geomagn. Geoelectr. *20*, 169—180, 1968

Schmucker, U.: Gesteinsmagnetische Untersuchungen und Experimente am Basalt des Steinberges bei Barlissen. Abh. Akad. Wissensch. Göttingen, Math.-Phys. Klasse, Nr. *26*, 100 S., Göttingen 1957

Shapiro, V. A., Ivanov, N. A.: The stability parameters of dynamic magnetization compared with other types of remanent magnetization. Izvestiya, Solid Earth 681—685, 1966 (English edition)

Shapiro, V. A., Ivanov, N. A.: Dynamic remanence and the effect of shocks on the remanence of strongly magnetic rock. Dokl. Akad. Nauk. USSR *173*, 1065—1068, 1967

Short, N. M.: Effects of shock pressures from a nuclear explosion on mechanical and optical properties of granodiorite. J. Geophys. Res. *71*, 1195—1215, 1966

Soffel, H.: Die Bereichsstrukturen der Titanomagnetite in zwei tertiären Basalten und die Beziehung zu makroskopisch gemessenen magnetischen Eigenschaften dieser Gesteine. Habilitationsschrift, Naturwiss. Fak. Univ. München, 1968

Stacey, F. D.: The seismomagnetic effect. Pageoph *58*, 5—22, 1964

Stacey, F. D., Barr, K. G., Robson, G. R.: The volcano-magnetic effect. Pageoph *62*, 96—104, 1965

Stacey, F. D., Johnston, M. J. S.: Theory of the piezomagnetic effect in titanomagnetite-bearing rocks. Pageoph *97*, 146—155, 1972

Talwani, P., Kovach, R. L.: Geomagnetic observations and fault creep in California. Tectonophysics *14*, 245—256, 1972

Zinsser, H.: Induzierte und remanente, insbesonders thermoremanente Magnetisierung von Proben zweier Basaltvorkommen (Rauher Kulm und Parkstein, Oberpfalz) in Abhängigkeit von einaxialer Druckspannung. Diplomarbeit, Institut für Angewandte Geophysik, Universität München, 1970

Dr. J. Pohl
Institut für Angewandte Geophysik
der Universität
D-8000 München 2
Theresienstr. 41
Federal Republic of Germany

Dr. U. Bleil
Institut für Geophysik
der Ruhr-Universität
D-4630 Bochum
Buscheystrasse
Federal Republic of Germany

Dr. U. Hornemann
Arbeitsgruppe für
Ballistische Forschung
D-7858 Weil
Hauptstr. 18
Federal Republic of Germany