Introductory Notes on Shock Remanent Magnetization and Shock Demagnetization of Igneous Rocks

By TAKESI NAGATA[1])

Summary – Effects of mechanical shocks of about 0.5 msec in duration on the remanent magnetization of igneous rocks are experimentally studied. The remanent magnetization acquired by applying a shock (S) in the presence of a magnetic field (H), which is symbolically expressed as $J_R(\mathrm{H_+\ S\ H_0})$, is very large compared with the ordinary isothermal remanent magnetization (IRM) acquired in the same magnetic field. $J_R(\mathrm{H_+\ S\ H_0})$ is proportional to the piezo-remanent magnetization, $J_R(\mathrm{H_+\ P_+\ P_0\ H_0})$.

The effect of applying S in advance of an acquisition of IRM is represented symbolically by $J_R(\mathrm{S\ H_+\ H_0})$. $J_R(\mathrm{S\ H_+\ H_0})$ can become much larger than the ordinary IRM, and is proportional to the advanced effect of pressure on IRM, $J_R(\mathrm{P_+\ P_0\ H_+\ H_0})$.

The effect of shock S applied on IRM in non-magnetic space is represented by the shock-demagnetization effect, $J_R(\mathrm{H_+\ H_0\ S})$, which also is proportional to $J_R(\mathrm{H_+\ H_0\ P_+\ P_0})$.

Because, the duration of a shock is very short, a single shock effect cannot achieve the final steady state. The effect of n-time repeated shocks is represented by $J_0 + \Delta J^*(n)$, where J_0 means the immediate effect and $\Delta J^*(n)$ represents the resultant effect of repeating, which is of mathematical expression proportional to $[1 - \exp\{-\alpha(n-1)\}]$.

Zusammenfassung – Die Effekte des mechanischen Stosses mit der Dauer von etwa 0.5 ms auf der remanenten Magnetisierung wurden experimentell nachgesucht. Das erworbene Remanenz der Magnetisierung nach dem Stoss (S) unter dem magnetischen Feld (H), das hier symbolisch als $J_R(\mathrm{H_+\ SH_0})$ bezeichnet wird, ist sehr stark im Vergleich mit der normalen isothermischen remanenten Magnetisierung (IRM) unter demselben magnetischen Feld. $J_R(\mathrm{H_+\ S\ H_0})$ ist im Verhältnis zur piezo-remanenten Magnetisierung, $J_R(\mathrm{H_+\ P_+\ P_0\ H_0})$.

Der Effekt vom Stoss vor der Erwerbung von IRM wird symbolisch als $J_R(\mathrm{S\ H_+\ H_0})$ bezeichnet. $J_R(\mathrm{S\ H_+\ H_0})$ kann viel stärker als die normale IRM werden, im verhältnis zum Effekt des vorausgegebenen Drucks auf IRM, $J_R(\mathrm{P_+\ P_0\ H_+\ H_0})$.

Der Effekt des Stosses auf IRM im Raum ohne magnetisches Feld wird mit dem Stossentmagnetisierungseffekt dargestellt, $J_R(\mathrm{H_+\ H_0\ S})$, der auch proportional zu $J_R(\mathrm{H_+\ H_0\ P_+\ P_0})$ ist.

Da die Dauer einzelnen Stosses sehr kurz ist, kann der Effekt des einmaligen Stosses den endgültigen stabilen Zustand nicht erreichen. Der Effekt nach n-maligen wiederholten Stossen wird als $J_0 + \Delta J^*(n)$ bezeichnet, wobei J_0 den unverzüglichen Effekt bedeutet, und $\Delta J^*(n)$ beschreibt den resultanten Effekt der Stosswiederholung, dessen mathematische Darstellung proportional zu $[1 - \exp\{-\alpha(n-1)\}]$ ist.

1. Introduction

In his well circulated book 'The Earth', HAROLD JEFFREYS has raised a question in regard to the reliability of remanent magnetization of natural rocks, by saying 'When

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I last did a magnetic experiment (about 1909) we were warned against careless handling of permanent magnets, and the magnetism was liable to change without much carelessness. In studying the magnetism of rocks the specimen has to be broken off with a geological hammer and then carried to the laboratory. It is supposed that in the process its magnetism does not change to any important extent, and though I have often asked how this comes to be the case I have never received any answer.'

The author believes that this simple and naive question has already been answered at the very beginning of researches of rock magnetism and palaeomagnetism. The observed fact on those old days was that the direction and intensity of the natural remanent magnetization (NRM) of new volcanic lavas are scarcely changed by strongly hitting a rock mass of the lava with a geological hammer until it is broken into two or more pieces. In the author's first presentation of a paper discussing the direction and intensity of NRM's of lavas from Volcano Mihara [3][2]), the late HANTARO NAGAOKA and the late MOTONORI MATUYAMA raised the same question as JEFFREYS' directly to the author, because MATUYAMA, who had been extensively working on palaeomagnetism using NRM's of basalts, had always used basalt samples which were naturally broken *in situ* and therefore can be taken off without using a hammer. It is, of course, because he was afraid of a possible effect of hammering on NRM's of rock samples. On those days, the fact that ferromagnetics can have more intense isothermal remanent magnetization (IRM) by more bashing them in the presence of a magnetic field had been widely known, but it was not yet established that NRM's of natural igneous rocks which are due to the thermoremanent magnetization (TRM) mechanism are so intense and stable that repeated hammerings of igneous rock masses to cut off rock specimens from their mother masses can hardly change the direction and intensity of the NRM's. My reply that the effect of hammering is negligibly small for NRM's of igneous rocks insofar as they are due to TRM mechanism, was accepted by the two senior physicists at that time.

It seems true, however, that no quantitative answer has ever been properly given to JEFFREYS' question how a possible effect of the procedure to break off a rock specimen by hammering comes out on the rock magnetization. It does not seem that the author's old experimental result to show negligibly small changes in the direction and intensity of NRM's of igneous rocks as a function of the number of repeated hammerings can satisfy JEFFREYS. In other words, the effects of hammerings of rock samples on their magnetization have to be physically understood in a more quantitative way. In this connexion, SHAPIRO and IVANOV [9] has briefly reported their experimental results on an amplification of the intensity of isothermal remanent magnetization of magnetite by giving repeated mechanical shocks in the presence of a magnetic field (i.e. Dynamic remanence) and also on the demagnetization of magnetite and some igneous rocks by repeated mechanical shocks in non-magnetic space (i.e. Shock demagnetization effect). Empirically, they represented their experimental results in the following expressions.

[2]) Numbers in brackets refer to References, page 177.

(i) The acquisition of the dynamic remanent magnetization in presence of a magnetic field is represented by

$$J_R(E) = J_0(1 - A_e^{-\sigma\sqrt{E}}) \tag{1}$$

where E denotes the kinetic energy of a given mechanical shock.

(ii) When the mechanical shock of E in kinetic energy is repeatedly given n-times on a rock sample in a same magnetic field, the resultant intensity of isothermal remanent magnetization, $J_R(n)$, is roughly approximated by

$$J_R(n) = J_0(1 - B_e^{-kn}). \tag{2}$$

(iii) The direction of axis of mechanical shock is approximately independent of the direction of a magnetic field in the process of acquiring $J_R(E)$ or $J_R(n)$.

(iv) For the shock demagnetization, the residual intensity of remanent magnetization after n-time shockings in a non-magnetic space is roughly approximated by

$$J(n) = J_{r0}\, e^{-\beta n}, \tag{3}$$

where J_{r0} denotes the initial intensity of remanent magnetization.

These experimental results are very suggestive in expressing the effects of mechanical shocks on the magnetizations of rocks. It seems however that more quantitative experimental studies on the problem and theoretical understandings of the experimental results are still highly necessary, especially in connexion with the piezomagnetic phenomena of natural rocks which have recently been clarified (NAGATA and CARLETON [6], [7]; NAGATA [4], [5]). This paper is an introductory remark on the effects of mechanical shocks on the remanent magnetization of igneous rocks with and without the presence of a magnetic field.

2. *Experimental procedures*

A mechanical shock is given by a metallic sphere which falls down from height (h) on a horizontal surface of a non-magnetic metallic anvil, as shown in Fig. 1. An applied mechanical shock is measured by means of a quartz crystal which is fixed to the bottom of Anvil A_2. Cushions C_1 and C_2 are appropriately chosen so that the wave form of mechanical shock given by the impacting ball (B) on the sample (S) becomes as simple as possible. The waveform of mechanical shock given on samples throughout the present work is such as illustrated in Fig. 2. The waveform consists of a main pulse peak and a considerably smaller secondery peak, where the half-value width of the main peak amounts to from 0.4 to 0.5 msec. When a ball of m in mass falls from h to zero in height, its momentum M is given by

$$M = m\sqrt{2\,h\,g}, \tag{4}$$

where g denotes the gravity acceleration. If we assume that an impact of the momen-

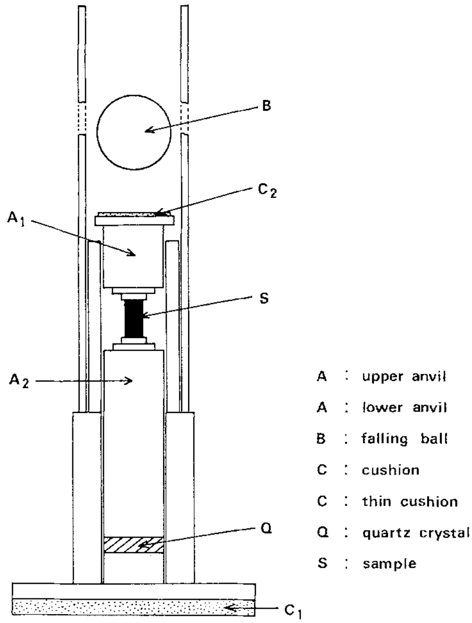

Figure 1
A schematic view of a bashometer which gives a mechanical shock on a rock sample

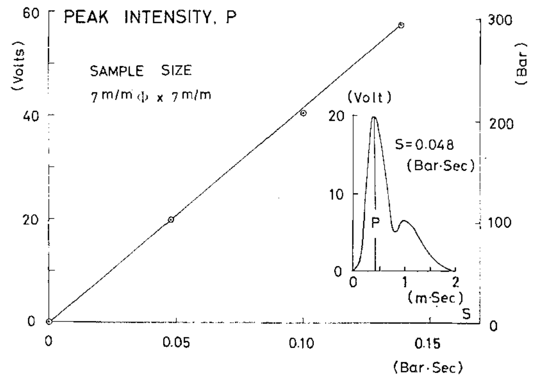

Figure 2
Wave form of a mechanical shock and the relationship between the shock momentum (S) and the peak intensity of pressure (P)

tum can be transferred to a mechanical shock $P(t)$ as a function of time (t) on an appropriate condition, then we get

$$M = \int_t P(t)\,dt = S, \tag{5}$$

where S may be defined as the shock momentum. In Fig. 2, an example of the calibration of the relationship between the peak intensity (P) and the shock momentum (S) is illustrated. In general, S is proportional to P with fluctuating errors of about 5%. This result would indicate that the waveform of shock is kept approximately invariant throughout the present series of experiments. In the present paper, therefore, the magnitude of shock is expressed by the integrated shock momentum S in unit of (bar.sec).

The simple apparatus to give a mechanical shock on a rock sample, which is named a 'bashometer', is set into two systems of Helmholtz coils, which can control the magnetic field surrounding the sample from zero (± 200 gammas) to several tens of Oersteds. Shock momentum S in the bashometer can be changed by changing the initial height (h) and mass (m) of the falling ball. The magnetization of samples was measured by a spinner magnetometer in each case. In every sequence of magnetic and mechanical experiments, a practically perfect AF-demagnetized rock sample is considered to be on its initial virgin condition.

3. *Classification of effects of mechanical shocks*

In the experimental procedure to give an effect of mechanical shock upon an acquisition or a reduction of the remanent magnetization of a rock sample, there are three steps of operations, i.e. an application of a magnetic field on a sample (H_+), a removal of the field (H_0) and an application of mechanical shock (S). Hence, there should be three combinations of the order of the three operations, namely, ($\mathrm{S\ H_+\ H_0}$), ($\mathrm{H_+\ S\ H_0}$) and ($\mathrm{H_+\ H_0\ S}$). The three operational processes correspond to those of the effects of static pressure (P) on the remanent magnetization expressed by ($\mathrm{P_+\ P_0\ H_+\ H_0}$), ($\mathrm{H_+\ P_+\ P_0\ H_0}$) and ($\mathrm{H_+\ H_0\ P_+\ P_0}$) respectively (NAGATA and KINOSHITA [8]: NAGATA and CARLETON [6], [7]). In the present case regarding the shock effects, however, there is no experimental operation corresponding to ($\mathrm{P_+\ H_+\ P_0\ H_0}$), ($\mathrm{H_+\ P_+\ H_0\ P_0}$) and ($\mathrm{P_+\ H_+\ H_0\ P_0}$), which have been dealt with in the case of static pressure effects, because S cannot be separated into two independent operations, P_+ and P_0. This, the effect of mechanical shocks on the remanent magnetization must be examined for the three cases, ($\mathrm{S\ H_+\ H_0}$), ($\mathrm{H_+\ S\ H_0}$) and ($\mathrm{H_+\ H_0\ S}$), and the physical basis of mechanism of each case must be consistent with one another.

Another point which is particularly significant in case of the mechanical shock effect may be the integrated effect of repeated mechanical shocks of a same magnitude. In the case of the piezo-magnetic effect caused by a static pressure, an application of a static pressure practically results in the final steady state in each of various kinds of the remanent magnetization such as, for example, $J_R(\mathrm{H_+\ P_+\ P_0\ H_0})$, $J_R(\mathrm{P_+\ P_0\ H_+\ H_0})$, $J_R(\mathrm{H_+\ H_0\ P_+\ P_0})$ and others. A single mechanical shock which has a very short time duration (a milli-second or less) seems to be unable to attain the final resultant effect on the remanent magnetization, as already been demonstrated by SHAPIRO and IVANOV [9], in empirical formulae (2) and (3). Hence, the resultant remanent magnetization after n-time repeating of mechanical shock operations must be a function of n also. Thus, for example, the remanent magnetization acquired as the result of a simple operation ($H_+ \; S \; H_0$) is considerably different from that caused by repeated operations of S in the presence of a magnetic field H, expressed as ($H_+ \; S_1 \; S_2 \ldots S_n \; H_0$) with $S_1 = S_2 = \cdots = S_n = S$, and from repeated operations of ($H_+ \; S \; H_0$) processes, expressed as ($H_+ \; S_1 \; H_0, H_+ \; S_2 \; H_0, \ldots, H_+ \; S_n \; H_0$).

In the present preliminary study, therefore, the effects of comparatively simple operations ($H_+ \; S \; H_0$), ($S \; H_+ \; H_0$) and ($H_+ \; H_0 \; S$) will be examined as the first problem, and then the effects of n-time repeating of mechanical shocks in respective combinations of H and S will be dealt with as the second problem.

4. *Shock remanent magnetization,* $J_R(H_+ \; S \; H_0)$

The remanent magnetization caused by an experimental operation ($H_+ \; S \; H_0$) will be noted by $J_R(H_+ \; S \; H_0)$ and will be named the *shock remanent magnetization* (SRM). SRM thus defined may correspond to the piezo-remanent magnetization (PRM), which is expressed by $J_R(H_+ \; P_+ \; P_0 \; H_0)$ in notation (Kinoshita and Nagata [8]). Fig. 3 shows an example of observed values of SRM of a typical basaltic rock as a function of magnetic fields (H), where PRM, $J_R(H_+ \; P_+ \; P_0 \; H_0)$, and IRM (isothermal remanent magnetization at room temperature $J_R(H_+ \; H_0)$), of the same sample also are shown.

As shown in the figure, the intensity of SRM is approximately proportional to an applied magnetic field H, when the magnitude of applied shock momentum is kept constant, while the direction of SRM is parallel to that of an applied magnetic field H.

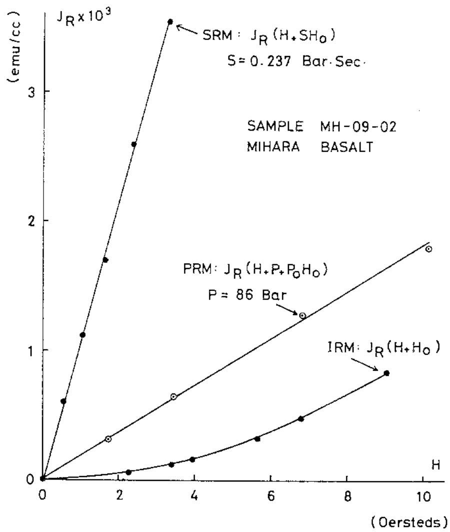

Figure 3
Example of the shock remanent magnetization, $J_R^{\|}(H_+ \; S \; H_0)$, as dependent on magnetic field H in comparison with the piezo-remanent magnetization (PRM), $J_R^{\|}(H_+ \; P_+ \; P_0 \; H_0)$, and the isothermal remanent magnetization (IRM), $J_R(H_+ \; H_0)$

These characteristics of SRM are the same as those of PRM, but the relationship between the intensity of remanence versus the magnetic field intensity in cases of SRM and PRM is fundamentally different from that in IRM, in which $J_R(\mathrm{H}_+ \mathrm{H}_0) = b\,H^2$ with b = constant for small magnetic fields. When H becomes very large, however, the intensity of SRM gradually approaches that of IRM. Hence, when the magnetic fields are considerably smaller than a certain critical value $H_c(S)$ which depends on the magnitude S, the intensity of SRM is expressed as

$$J_R(\mathrm{H}_+ \mathrm{S}\,\mathrm{H}_0) = C\,H\,, \qquad H < H_c(S)\,. \tag{6}$$

SRM and PRM shown in Fig. 3 represent the remanent magnetizations on a condition that the axis of an applied shock or static pressure is parallel to the direction of an applied magnetic field. Denoting SRM's in cases of $S \parallel H$ and $S \perp H$ by $J_R^{\parallel}(\mathrm{H}_+ \mathrm{S}\,\mathrm{H}_0)$ and $J_R^{\perp}(\mathrm{H}_+ \mathrm{S}\,\mathrm{H}_0)$ respectively, experimental results on SRM are summarized by

$$\left.\begin{array}{l} J_R^{\parallel}(\mathrm{H}_+ \mathrm{S}\,\mathrm{H}_0) = C^{\parallel}\,H \\ J_R^{\perp}(\mathrm{H}_+ \mathrm{S}\,\mathrm{H}_0) = C^{\perp}\,H \end{array}\right\} \quad \text{for} \quad H < H_c(S)\,. \tag{6'}$$

Examples of the observed dependences of $J_R^{\parallel}(\mathrm{H}_+ \mathrm{S}\,\mathrm{H}_0)$ and $J_R^{\perp}(\mathrm{H}_+ \mathrm{S}\,\mathrm{H}_0)$ on shock momentum (S) are shown in Fig. 4, where a magnetic field is kept constant. Just as in cases of $J_R^{\parallel}(\mathrm{H}_+ \mathrm{P}_+ \mathrm{P}_0\,\mathrm{H}_0)$ and $J_R^{\perp}(\mathrm{H}_+ \mathrm{P}_+ \mathrm{P}_0\,\mathrm{H}_0)$, both $J_R^{\parallel}(\mathrm{H}_+ \mathrm{S}\,\mathrm{H}_0)$ and $J_R^{\perp}(\mathrm{H}_+ \mathrm{S}\,\mathrm{H}_0)$ are approximately proportional to S for S-values larger than a certain critical value $S_c(H)$, which is dependent on H. When S tends to zero in the presence of a magnetic field. SRM approaches a finite value of IRM, $J_R(\mathrm{H}_+ \mathrm{H}_0)$, in a given magnetic field, but not zero. Thus, the SRM vs. S relationship is empirically expressed as

$$\left.\begin{array}{l} J_R^{\parallel}(\mathrm{H}_+ \mathrm{S}\,\mathrm{H}_0) = D^{\parallel}\,S \\ J_R^{\perp}(\mathrm{H}_+ \mathrm{S}\,\mathrm{H}_0) = D^{\perp}\,S \end{array}\right\} \quad S \gg S_c(H)\,. \tag{7}$$

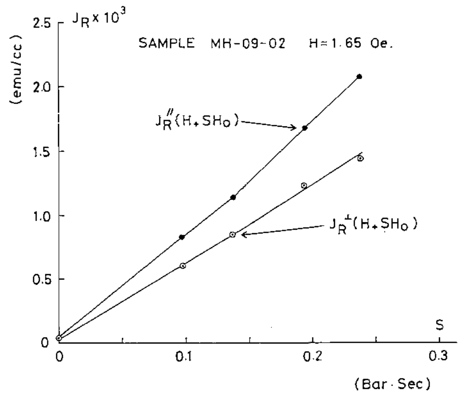

Figure 4

Comparison of the transverse shock remanent magnetization $J_R{}^{\perp}(\mathrm{H}_+ \mathrm{S}\,\mathrm{H}_0)$ as dependent on shock momentum S with the longitudinal shock remanent magnetization, $J_R{}^{\parallel}(\mathrm{H}_+ \mathrm{S}\,\mathrm{H}_0)$

As shown in Fig. 4, $D^{\perp} < D^{\|}$ and empirically

$$D^{\perp} \simeq \tfrac{3}{4} D^{\|}. \tag{8}$$

Combining the empirical expressions represented by (6)′ and (7), one may get

$$\left.\begin{aligned} J_R^{\|}(\mathrm{H}_+\ \mathrm{S}\ \mathrm{H}_0) &= K^{\|}\ H\cdot S \\ J_R^{\|}(\mathrm{H}_+\ \mathrm{S}\ \mathrm{H}_0) &= K^{\perp}\ H\cdot S \end{aligned}\right\} \quad \text{for} \quad H < H_c(S) \quad \text{and} \quad S > S_c(H). \tag{9}$$

In other expressions, (6)′, (7) and (8) lead to

$$\left.\begin{aligned} C^{\|} &= K^{\|}\ S, \qquad & C^{\perp} &= K^{\perp}\ S \\ D^{\|} &= K^{\|}\ H, \qquad & D^{\perp} &= K^{\perp}\ H \end{aligned}\right\} \tag{9′}$$

and consequently $K^{\perp} \simeq \frac{3}{4} K^{\|}$ for small values of H and large values of S.

Since the ordinary IRM, $J_R(\mathrm{H}_+\ \mathrm{H}_0)$, is represented by $J_R(\mathrm{H}_+\ \mathrm{H}_0) = b\ H^2$ for small values of H,

$$\left.\begin{aligned} J_R^{\|}(\mathrm{H}_+\ \mathrm{S}\ \mathrm{H}_0)/J_R(\mathrm{H}_+\ \mathrm{H}_0) &= \frac{K^{\|}}{b}\left(\frac{S}{H}\right), \\ J_R^{\perp}(\mathrm{H}_+\ \mathrm{S}\ \mathrm{H}_0)/J_R(\mathrm{H}_+\ \mathrm{H}_0) &= \frac{K^{\perp}}{b}\left(\frac{S}{H}\right), \end{aligned}\right\} \tag{10}$$

for small values of H and large values of S. Thus, the effect of S on SRM in comparison with IRM acquired in the same magnetic field becomes much larger in accordance with a decrease of an applied magnetic field.

Fig. 5 shows the $J_R(\mathrm{H}_+\ \mathrm{S}\ \mathrm{H}_0)$ vs. S relationship of an Apollo 12 crystalline rock (Sample No. 12053-47) for three different magnetic fields. For the lunar igneous rock

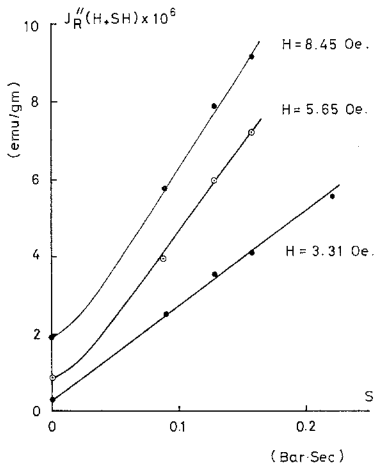

Figure 5
Longitudinal shock-remanent magnetization of lunar crystalline rock

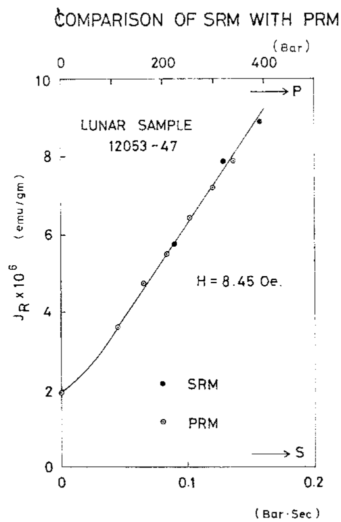

Figure 6
Comparison of the shock remanent magnetization with the piezo-remanent magnetization for a lunar crystalline rock

also, empirical expressions of (6)′, (7) and (9) can satisfactorily stand. In Fig. 6, SRM is compared with PRM of the same sample. As seen in the figure, the dependence of SRM on S is practically the same as that of PRM on P for a same applied magnetic field, if we assume an appropriate proportionality between S and P. In the case of the figure, the proportionality constant is approximately expressed by $S:P \simeq 1$ bar sec: 2500 bar. One may hence consider that the mechanism of acquisition of SRM is close to that of PRM. It seems very likely, in the acquisition processes of SRM, that the effect of an early half process from $P(t)=0$ at the commencement of the shock to $P(t)=$maximum and that of a later half process from $P(t)=$maximum to $P(t)=0$ at the end of shock, in the expression (5), play the similar roles to P_+ and P_- respectively in the acquisition process of PRM. If we assume a rough approximation of S in such a way as

$$S = \int_t P(+)\,dt \simeq P \cdot \overline{\Delta t}, \tag{11}$$

then $\overline{\Delta t}$ is estimated to be 0.4 msec for the case shown in Fig. 6. This estimated value of $\overline{\Delta t}$ is in an approximate agreement with the directly observed value of the half value width of the main pulse of mechanical shock (Fig. 2).

Such an estimate of $\overline{\Delta t}$ could be made for the case of Fig. 3, where both curves of $J_R(H_+ \ S \ H_0)$ vs. H and $J_R(H_+ \ P_+ \ P_0 \ H_0)$ vs. H are practically linear. In this case also, the proportionality between S and P is approximated by $S:P \simeq 1$ bar. sec:2500 bar, and consequently $\overline{\Delta t} \simeq 0.4$ msec. Actual numerical values of SRM parameters such as $K^{\parallel}$, $K^{\perp}$ and $\overline{\Delta t}$ are given in Table I for typical terrestrial basalts and a lunar crystalline rock.

Table I

Parameters of shock remanent magnetization of igneous rocks

Sample	$K^{\parallel}$ (emu/cc /Oe.bar.sec)	$K^{\perp}$ (emu/cc /Oe.bar.sec)	$\overline{\Delta t}$ (sec)
MH-09-02 (Mihara Basalt)	4.9×10^{-3}	3.6×10^{-3}	0.4×10^{-3}
MH-09-01 (Mihara Basalt)	4.4×10^{-3}	--	0.3×10^{-3}
KM-4102-1 (Kita-Matsuura Basalt)	3.9×10^{-3}	–	–
NASA No. 12053-47 (Apollo 12 Lunar Rock)	7.5×10^{-6} (emu/cc /Oe.bar.sec)	–	0.4×10^{-3}

5. *Advanced shock effect on IRM:* $J_R(S \ H_+ \ H_0)$

The intensity of isothermal remanent magnetization acquired by a rock sample which was previously subjected to a mechanical shock (S) in non-magnetic space can be symbolically expressed as $J_R(\mathrm{S\,H_+\,H_0})$. Experimental results have shown that $J_R(\mathrm{S\,H_+\,H_0}) \gg J_R(\mathrm{H_+\,H_0})$ if S is considerably large.

This effect caused by a mechanical shock in advance of giving IRM in a magnetic field H may be called *the advanced shock effect on IRM*. An important observed fact in regard to the advanced shock effect is that the effect is practically cancelled by AF-demagnetizing the acquired $J_R(\mathrm{S\,H_+\,H_0})$ to zero. A completely AF-demagnetized sample has no effect of a previous shock for the second IRM acquisition procedure. This observed fact may indicate that the advance shock effect is not due to any irreversible structural effect in magnetic mineral crystals in rocks, but very likely due to a non-linear superposition of effects of a mechanical shock and an applied magnetic field in the processes of irreversible magnetization of the magnetic minerals.

Fig. 7 illustrates a summary of observed dependences of $J_R^{\|}(\mathrm{S\,H_+\,H_0})$ on S obtained in three different magnetic fields. As shown in the figure, it seems that the normalized values of $J_R^{\|}(\mathrm{S\,H_+\,H_0})$, i.e. $J_R^{\|}(\mathrm{S\,H_+\,H_0})/J_R(\mathrm{H_+\,H_0})$, are expressed by a single function of parameter S/H. $J_R^{\|}(\mathrm{S\,H_+\,H_0})/J_R(\mathrm{H_+\,H_0})$ tends to unity when S approaches zero, while it increases almost proportionally to S/H when S/H increases above a certain value. Thus, we can get empirical expressions as

$$J_R^{\|}(\mathrm{S\,H_+\,H_0})/J_R(\mathrm{H_+\,H_0}) = F(S/H) \tag{12}$$

with $F(0)=1$ and $F(S/H) \simeq N \cdot (S/H)$, for large values of S/H, where N denotes a numerical constant. $F(S/H)$ may be called the magnification ratio caused by an advanced shock effect on IRM. The advanced shock effect on IRM also becomes larger when H is smaller for a constant value of S. All these characteristics of $J_R(\mathrm{S\,H_+\,H_0})$ are basically same as those of $J_R(\mathrm{P_+\,P_0\,H_+\,H_0})$ (Nagata and Carleton [7]).

6. *Shock demagnetization:* $J_R(\mathrm{H_+\,H_0\,S})$

When a rock sample having IRM, $J_R(\mathrm{H_+\,H_0})$, is impacted by a mechanical shock S in non-magnetic space, the residual remanent magnetization, $J_R(\mathrm{H_+\,H_0\,S})$, is demagnetized from the initial value. The demagnetization rate is larger for a larger value of S. Fig. 8 represents an example of the observed relationship between $J_R^{\|}(\mathrm{H_+\,H_0\,S})/J_R(\mathrm{H_+\,H_0})$ and S. Such a demagnetization effect on the remanent magnetization caused by a mechanical shock applied in non-magnetic space may be called the *shock demagnetization effect*. In Fig. 8, is also shown the pressure demagnetization effect as dependent on P in term of $J_R^{\|}(\mathrm{H_+\,H_0\,P_+\,P_0})/J_R(\mathrm{H_+\,H_0})$ for IRM of the same sample acquired in the same magnetic field. It can be observed in the figure that the general tendency of the $J_R^{\|}(\mathrm{H_+\,H_0\,S})/J_R(\mathrm{H_+\,H_0})$ vs. S curve is approximately the same as that of the $J_R^{\|}(\mathrm{H_+\,H_0\,P_+\,P_0})/J_R(\mathrm{H_+\,H_0})$ vs. P curve, if an appropriate proportionality between S and P is assumed. In the case of Fig. 8, the proportionality is roughly represented by $S:P \simeq 1$ bar. sec:2000 bar, so that $\overline{\Delta t} \simeq 0.5$ msec. By taking into consideration the approximate proportionality between $J_R(\mathrm{H_+\,H_0\,S})$ and $J_R(\mathrm{H_+\,H_0\,P_+\,P_0})$, one may derive empirical expressions from the experimental

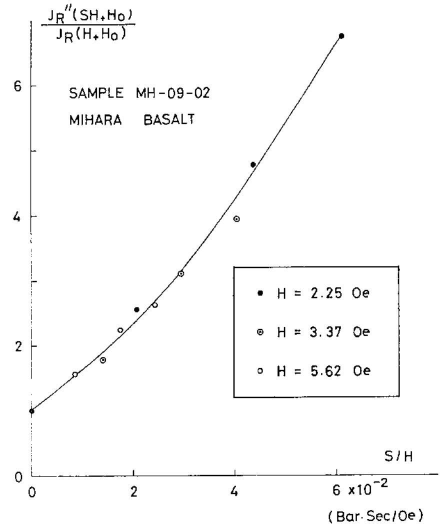

Figure 7
Example of the advanced shock effect on isothermal remanent magnetization

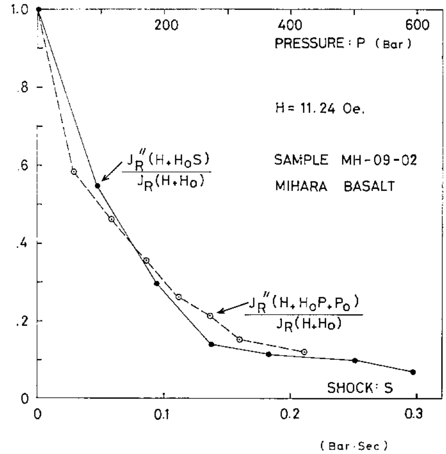

Figure 8
Comparison of the shock demagnetization effect in term of $J_R^{||}(\mathrm{H_+\ H_0\ S})/J_R(\mathrm{H_+\ H_0})$ with the pressure demagnetization effect represented by $J_R^{||}(\mathrm{H_+\ H_0\ P_+\ P_0})/J_R(\mathrm{H_+\ H_0})$

results such as Fig. 6 and the general behaviour of $J_R(\mathrm{H_+\ H_0\ P_+\ P_0})$ (NAGATA and CARLETON [7]) that

$$J_R(\mathrm{H_+\ H_0\ S})/J_R(\mathrm{H_+\ H_0}) = G(S/H) \tag{13}$$

where

$$\left.\begin{aligned} &\frac{dG(S/H)}{d(S/H)} = -M < 0 \quad \text{for small values of } (S/H), \\ &\text{and} \\ &\lim_{(S/H)\to\infty} G(S/H) = 0. \end{aligned}\right\} \tag{14}$$

Although experimental examinations about possible discrepancies between $J_R^{||}(\mathrm{H_+\ H_0 S})$ and $J_R^{\perp}(\mathrm{H_+\ H_0\ S})$ and between $J_R^{||}(\mathrm{S\ H_+\ H_0})$ and $J_R^{\perp}(\mathrm{S\ H_+\ H_0})$ have not yet been carried out, the observed proportionality between S and P in regard to all of the three types of shock-effected remanent magnetizations, $J_R(\mathrm{H_+\ S\ H_0})$, $J_R(\mathrm{S\ H_+\ H_0})$ and $J_R(\mathrm{H_+\ H_0\ S})$, may imply that the transverse effect $(S \perp H)$ is a little less (by about $\frac{1}{4}$) than the longitudinal effect $(S \parallel H)$ in cases of $J_R(\mathrm{H_+\ H_0\ S})$ and $J_R(\mathrm{S\ H_+\ H_0})$ also just as in cases of $J_R(\mathrm{H_+\ S\ H_0})$ and $J_R(\mathrm{H_+\ H_0\ P_+\ P_0})$ and $J_R(\mathrm{P_+\ P_0\ H_+\ H_0})$.

7. *Integrated effect of repeated mechanical shocks*

As described in Sections 1 and 3 in the present paper, a single mechanical shock (S) is unable to attain the final resultant effect on the remanent magnetization, but instead repeated applications of the same shock on a sample result in an approach to the final state of magnetization. For example, Fig. 9 shows an increase of the shock remanent magnetization by n-time repeatings of the SRM operation, the resultant remanent magnetization being symbolically noted by $J_R^{\|}(H_+\ S_1\ H_0, \ldots\ H_+\ S_n\ H_0)$, where $S_1 = \cdots = S_n$. Fig. 10 shows an example of an effect of repeated shock demagnetization of SRM, where the resultant remanent magnetization is expressed as $J_R^{\|}(H_+\ S\ H_0,\ S_1 \ldots S_n)$ with $S = S_1 = \cdots = S_n$. The curve of $J_R^{\|}(H_+\ H_0\ S_1 \ldots S_n)$ vs. n also is very close to the curve of $J_R^{\|}(H_+\ S\ H_0,\ S_1 \ldots S_n)$ vs. n.

A number of experimental results on n-time repeatings of shock operations in cases of the acquisition of SRM and the shock demagnetization have led to a general conclusion that the effect of repeated shocks on any shock-effected remanent magnetization consists of the effect of the first shock and the integrated effect of succeeding

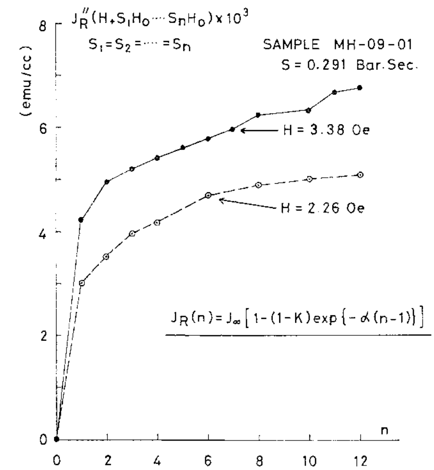

Figure 9
Examples of effect of repeated shocks on the acquisition of shock remanent magnetization

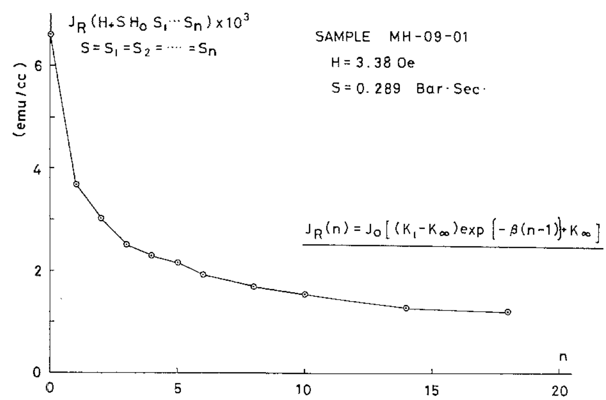

Figure 10
Example of effect of repeated shocks in the shock demagnetization

shocks. In the case of acquisition of SRM, for example,

$$J_R(\mathrm{H}_+\ \mathrm{S}_1\ \mathrm{H}_0, \ldots \mathrm{H}_+\ \mathrm{S}_n\ \mathrm{H}_0) = J_R(\mathrm{H}_+\ \mathrm{S}_1\ \mathrm{H}_0) + J_R^*(n), \tag{15}$$

where $J_R^*(n \to \infty) \equiv J_R^*(\infty)$.

Then, $J_R^*(\infty)$ is empirically represented by

$$J_R^*(n) = J_R^*(\infty)\,[1 - \exp\{-\alpha(n-1)\}] \tag{16}$$

with α = constant.

If we put

$$J_R(\mathrm{H}_+\ \mathrm{S}_1\ \mathrm{H}_0) + J_R^*(\infty) = J_R(\infty), \quad J_R(\mathrm{H}_+\ \mathrm{S}_1\ \mathrm{H}_0) = K\,J_R(\infty), \quad (K < 1) \tag{17}$$

then (15), (16) and (17) lead to

$$J_R(\mathrm{H}_+\ \mathrm{S}_1\ \mathrm{H}_0 \ldots \mathrm{H}_+\ \mathrm{S}_n\ \mathrm{H}_0) = J_R(\infty)\,[1 - (1-K)\exp\{-\alpha(n-1)\}]. \tag{18}$$

In (15), $J_R(\mathrm{H}_+\ \mathrm{S}_1\ \mathrm{H}_0)$ represents the first shock effect while $J_R^*(n)$ the integrated effect of succeeding shocks.

Similarly, the effect of n-time repeated shock demagnetizations is expressed as

$$J_R(\mathrm{H}_+\ \mathrm{H}_0\ \mathrm{S}_1 \ldots \mathrm{S}_n) = J_R(\mathrm{H}_+\ \mathrm{H}_0) - \Delta J_R(1) - \Delta J_R^*(n), \tag{19}$$

where $\Delta J_R(1)$ represents the first shock effect and is identical to

$$\Delta J_R(1) = J_R(\mathrm{H}_+\ \mathrm{H}_0) - J_R(\mathrm{H}_+\ \mathrm{H}_0\ \mathrm{S}_1) = (1 - K_1)\,J_R(\mathrm{H}_+\ \mathrm{H}_0), \tag{20}$$

with

$$J_R(\mathrm{H}_+\ \mathrm{H}_0\ \mathrm{S}_1) = K_1\,J_R(\mathrm{H}_+\ \mathrm{H}_0) \qquad K_1 < 1, \tag{21}$$

and $\Delta J_R^*(n)$ represents the integrated effect of succeeding shocks, being expressed by

$$\Delta J_R^*(n) = J_R(\mathrm{H}_+\ \mathrm{H}_0\ \mathrm{S}_1) - J_R(\mathrm{H}_+\ \mathrm{H}_0\ \mathrm{S}_1 \ldots \mathrm{S}_n). \tag{22}$$

Putting

$$\lim_{n\to\infty} J_R(\mathrm{H}_+\ \mathrm{H}_0\ \mathrm{S}_1 \ldots \mathrm{S}_n) = J_R(\infty) = K_\infty\,J_R(\mathrm{H}_+\ \mathrm{H}_0), \quad (K_\infty < 1), \tag{23}$$

$\Delta J_R^*(n)$ is empirically expressed by

$$\Delta J_R^*(n) = J_R(\mathrm{H}_+\ \mathrm{H}_0)\,(K_1 - K_\infty)\,[1 - \exp\{-\beta(n-1)\}]. \tag{24}$$

Hence, (19) is transformed to

$$\left.\begin{aligned} J_R(\mathrm{H}_+\ \mathrm{H}_0\ \mathrm{S}_1 \ldots \mathrm{S}_n) &= J_R(\infty) + \{J_R(\mathrm{H}_+\ \mathrm{H}_0\ \mathrm{S}_1) - J_R(\infty)\}\exp\{-\beta(n-1)\} \\ &= J_R(\mathrm{H}_+\ \mathrm{H}_0)\,[K_\infty + (K_1 - K_\infty)\exp\{-\beta(n-1)\}]. \end{aligned}\right\} \tag{25}$$

The empirical formulae (18) and (25) well stand for the experimental results of repeated shocks in SRM and the shock demagnetization respectively. The observed relationship between $J_R(\mathrm{H}_+\ \mathrm{S}_1, \ldots\ \mathrm{S}_n\ \mathrm{H}_0)$ and n is practically identical to that between $J_R(\mathrm{H}_+\ \mathrm{S}_1\ \mathrm{H}_0, \ldots\ \mathrm{H}_+\ \mathrm{S}_n\ \mathrm{H}_0)$ and n, while the $J_R(\mathrm{H}'_+\ \mathrm{S}\ \mathrm{H}'_0\ \mathrm{S}_1\ \ldots\ \mathrm{S}_n)$ vs. n curve is practically the same as $J_R(\mathrm{H}_+\ \mathrm{H}_0\ \mathrm{S}_1\ \ldots\ \mathrm{S}_n)$ vs. n curve provided $J_R(\mathrm{H}'_+\ \mathrm{S}\ \mathrm{H}'_0) = J_R(\mathrm{H}_+\ \mathrm{H}_0)$. Numerical values of parameter K, K_1 and K_∞ for several typical igneous rocks are summarized in Table II.

The effect of repeated shocks on the remanent magnetization phenomenologically resembles the magnetic aftereffect accompanying a sudden change in the magnetic field (e.g. CHIKAZUMI [1]), in which a change in magnetization I caused by a sudden change in an applied magnetic field at time $t=0$ consists of I_0, which represents the immediate change in magnetization, and $\Delta I(t)$ which represents the gradual change with time (t) in magnetization, namely, the component of magnetic aftereffect. The

Table II
Parameters of repeated shock effect on remanent magnetization of igneous rocks

Sample	Remark	Acquisition of of SRM		Shock Demagnetization of SRM		
		K	α	K_1	K_∞	β
MH-09-01 (Mihara Basalt)	$H=3.38$ Oe. $S=0.289$ bar.sec	0.60	0.24	0.55	0.18	0.20
MH-09-01 (Mihara Basalt)	$H=2.26$ Oe. $S=0.289$ bar.sec	0.57	0.24	–	–	–
MH-09-02 (Mihara Basalt)	$H=11.24$ Oe.* $S=0.087$ bar.sec	–	–	0.28	0.07	0.79
MH-09-02 (Mihara Basalt)	$H=1.65$ Oe. $S=0.237$ bar.sec	0.76	0.22	0.58	0.22	0.12
NASA No. 12053-47 (Apollo 12 Lunar Rock)	$H=5.65$ Oe. $S=0.136$ bar.sec	0.72	0.44	–	–	–

*) Remark: Shock Demagnetization of IRM.

first shock effect and the integrated effect of succeeding shocks in the shock magnetization phenomena may correspond respectively to the immediately changing component (I_0) and the aftereffect one (ΔI) in the magnetic aftereffect phenomenon.

The first shock effect may immediately take place corresponding to the maximum peak pressure of the shock in the acquisition of SRM or the shock demagnetization. Because of a very short duration of the pressure peak, however, the magnetization phenomenon of the material concerned cannot attain the final thermodynamically steady state corresponding to the given peak value of the pressure. Succeeding $(n-1)$ time repeated shocks in the same magnetic field condition may give rise to a probability for the material to gradually approach the final steady state. Let us consider the remanent magnetization J_R composed of N aligned magnetic elements having j as individual magnetic moment: namel $Nj=J_R^*(n)$ for (16) and $Nj=\Delta J_R^*(n)$ for (24). Then, the most probable rate of increase in magnetization by repeated shocks may be approximated by

$$\frac{d(Nj)}{d(n-1)}=\alpha j(N_\infty-N), \tag{26}$$

where $N_\infty j$ represents $J_R^*(\infty)$ in (15) while it represents $\Delta J_R^*(\infty)=(K_1-K_\infty)\,J_R(\mathrm{H}_+\ \mathrm{H}_0)$ in (24). The solution of (24) for the initial condition that $J_R^*(n)=0$ for $n=1$ is given by

$$J_R^*(n) = J_R^*(\infty)\,[1-\exp\{-\alpha(n-1)\}]\,,$$

which is idential to (16). Replacing α by β, the solution of (26) for the initial condition, $\Delta J_R^*(n=1)=0$, is expressed by

$$\Delta J_R^*(n) = (K_1-K_\infty)\,J_R(\mathrm{H}_+\ \mathrm{H}_0)\,[1-\exp\{-\beta(n-1)\}]$$

which is identical to (24).

8. Theoretical interpretations of $J_R(\mathrm{H}_+\ \mathrm{S}\ \mathrm{H}_0)$, $J_R(\mathrm{S}\ \mathrm{H}_+\ \mathrm{H}_0)$ *and* $J_R(\mathrm{H}_+\ \mathrm{H}_0\ \mathrm{S})$

As already discussed in the preceding sections, characteristics of $J_R(\mathrm{H}_+\ \mathrm{S}\ \mathrm{H}_0)$, $J_R(\mathrm{S}\ \mathrm{H}_+\ \mathrm{H}_0)$ and $J_R(\mathrm{H}_+\ \mathrm{H}_0\ \mathrm{S})$ are fundamentally similar to those of $J_R(\mathrm{H}_+\ \mathrm{P}_+\ \mathrm{P}_0\ \mathrm{H}_0)$, $J_R(\mathrm{P}_+\ \mathrm{P}_0\ \mathrm{H}_+\ \mathrm{H}_0)$, and $J_R(\mathrm{H}_+\ \mathrm{H}_0\ \mathrm{P}_+\ \mathrm{P}_0)$ respectively. Because of the presence of the repeated shock effect in the case of shock-effected remanent magnetization, it may be more adequate to consider that

$$\left.\begin{aligned} &J_R(\mathrm{H}_+\ \mathrm{S}\ \mathrm{H}_0) \simeq K\,J_R(\mathrm{H}_+\ \mathrm{P}_+\ \mathrm{P}_0\ \mathrm{H}_0)\,,\\ &J_R(\mathrm{S}\ \mathrm{H}_+\ \mathrm{H}_0) \simeq K\,J_R(\mathrm{P}_+\ \mathrm{P}_0\ \mathrm{H}_+\ \mathrm{H}_0)\,,\\ &J_R(\mathrm{H}_+\ \mathrm{H}_0) - J_R(\mathrm{H}_+\ \mathrm{H}_0\ \mathrm{S}) \simeq \left(\frac{1-K_1}{1-K_\infty}\right)\\ &\qquad\qquad\times\{J_R(\mathrm{H}_+\ \mathrm{H}_0) - J_R(\mathrm{H}_+\ \mathrm{H}_0\ \mathrm{P}_+\ \mathrm{P}_0)\}\,,\end{aligned}\right\} \tag{27}$$

where P represents the maximum peak pressure in the mechanical shock S. Since $K<1$, the roughly estimated value of $\overline{\Delta t}$ from the direct comparison of $J_R(\mathrm{H}_+\ \mathrm{S}\ \mathrm{H}_0)$ with $J_R(\mathrm{H}_+\ \mathrm{P}_+\ \mathrm{P}_0\ \mathrm{H}_0)$ may represent the lower limit of $\overline{\Delta t}$. Since $(K_1/K_\infty)>1$ on the other hand, the $\overline{\Delta t}$ value estimated from the direct comparison of $J_R(\mathrm{H}_+\ \mathrm{H}_0\ \mathrm{S})$ with $J_R(\mathrm{H}_+\ \mathrm{H}_0\ \mathrm{P}_+\ \mathrm{P}_0)$ may give the upper limit of $\overline{\Delta t}$. The physical mechanisms of the static pressure effect on the remanent magnetization of igneous rocks have been theoretically attributed by NAGATA and CARLETON [6, 7] to the results of the irreversible movements of 90° domain walls caused by a combination of applications and removals of a magnetic field and a static pressure. According to their theory, the piezo-remanent magnetization for small values of H is approximately expressed by a linear function of both H and P as

$$\left.\begin{aligned} J_R^{\parallel}(\mathrm{H}_+\ \mathrm{P}_+\ \mathrm{P}_0\ \mathrm{H}_0) &\simeq \frac{16}{5\pi}\,b\,H\,H_c\\ J_R^{\perp}(\mathrm{H}_+\ \mathrm{P}_+\ \mathrm{P}_0\ \mathrm{H}_0) &\simeq \frac{12}{5\pi}\,b\,H\,H_c\end{aligned}\right\}\quad(\text{for } H \ll H_c)\,, \tag{28}$$

where

$$H_c \equiv \frac{3\,\lambda_s}{\sqrt{2}\,J_s}\,P \equiv h_c\,P\,. \tag{29}$$

with λ_s: isotropic magnetostriction coefficient of magnetic material,

J_s: spontaneous magnetization of magnetic material.

A comparison of the empirical formula (9) with (27), (28) and (29) may lead to

$$K^{\parallel} = \frac{16}{5\pi}\, b\, K\, h_c \left(\frac{P}{S}\right), \quad K^{\perp} = \tfrac{3}{4} K^{\parallel}, \tag{30}$$

where the result of calibration of (P/S) shown in Fig. 2 has given

$$\left(\frac{P}{S}\right) \simeq 2.2 \times 10^3 (\text{sec})^{-1}.$$

The theoretical expression for $J_R^{\parallel}(\mathrm{P_+\ P_0\ H_+\ H_0})$ has been given as

$$\left.\begin{aligned} &J_R^{\parallel}(\mathrm{P_+\ P_0\ H_+\ H_0}) = B\,H^2 = J_R(\mathrm{H_+\ H_0}), \quad \text{for} \quad H_c \leqq H, \\ &J_R^{\parallel}(\mathrm{P_+\ P_0\ H_+\ H_0}) = \frac{2b}{\pi}\left[H^2 \sin^{-1}\left(\frac{H}{H_c}\right) + \frac{8}{15} H\, H_c \sqrt{1-\left(\frac{H}{H_c}\right)^2}\right. \\ &\qquad \left. \times \left\{1 + \frac{9}{8}\left(\frac{H}{H_c}\right)^2 - \frac{1}{4}\left(\frac{H}{H_c}\right)^4\right\}\right], \quad \text{for} \quad H_c \geqq H, \end{aligned}\right\} \tag{31}$$

the numerical values of which are plotted in Fig. 11. The theoretical curve can approximately represent the relationship between $J_R^{\parallel}(\mathrm{S\ H_+\ H_0})/J_R(\mathrm{H_+\ H_0})$ and S/H shown in Fig. 7, as far as the proportionality between S and P is accepted. When P becomes so large that the condition of $H_c \gg H$ is satisfied, $J_R^{\parallel}(\mathrm{P_+\ P_0\ H_+\ H_0})/J_R^{\parallel}(\mathrm{H_+\ H_0})$ is approximately expressed as

$$J_R^{\parallel}(\mathrm{P_+\ P_0\ H_+\ H_0})/J_R(\mathrm{H_+\ H_0}) = \frac{16}{15\pi}\left(\frac{H_c}{H}\right) \simeq \frac{16}{15\pi} h_c \left(\frac{P}{H}\right) \quad (H_c \gg H). \tag{32}$$

Then, (27) being taken into account, we may get, for large values of (S/H),

$$J_R^{\parallel}(\mathrm{S\ H_+\ H_0})/J_R(\mathrm{H_+\ H_0}) = \frac{16}{15\pi} h_c\, K \left(\frac{P}{S}\right)\left(\frac{S}{H}\right). \tag{32'}$$

The theoretical expression of $J_R^{\parallel}(\mathrm{H_+\ H_0\ P_+\ P_0})$ has been given as

$$\left.\begin{aligned} &J_R^{\parallel}(\mathrm{H_+\ H_0\ P_+\ P_0}) = J_R(\mathrm{H_+\ H_0})\left(1 - \frac{16}{15\pi}\frac{H_c}{H}\right) \quad \text{for} \quad H_c \leqq H, \\ &J_R^{\parallel}(\mathrm{H_+\ H_0\ P_+\ P_0}) = J_R(\mathrm{H_+\ H_0})\left[\frac{2}{\pi}\sin^{-1}\mu_c - \frac{16}{15\pi}\left(\frac{H_c}{H}\right)\left\{1 - \sqrt{1-\mu_c^2}\right.\right. \\ &\qquad \left.\left. + \frac{8}{\pi}\left(\frac{H_c}{H}\right)\right\}\sqrt{1-\mu_c^2}\left\{\frac{3}{20}\left(\frac{H}{H_c}\right)^2 - \frac{1}{30}\left(\frac{H}{H_c}\right)^4\right\}\right], \quad \text{for} \quad H_c \geqq H, \end{aligned}\right\} \tag{33}$$

where

$$\mu_c \equiv H/H_c.$$

The numerical values of above expressions are plotted also in Fig. 11. Assuming the proportionality between S and P, the theoretical curve of $J_R^{\|}(\mathrm{H}_+\ \mathrm{H}_0\ \mathrm{P}_+\ \mathrm{P}_0)/J_R(\mathrm{H}_+\ \mathrm{H}_0)$ vs. (P/H) in Fig. 11 can reasonably explain the general tendency of the observed curve of $J_R^{\|}(\mathrm{H}_+\ \mathrm{H}_0\ \mathrm{S})/J_R(\mathrm{H}_+\ \mathrm{H}_0)$ vs. S shown in Fig. 8. When S is so small that $(H_c/H)\leqq 1$ in (33), $J_R^{\|}(\mathrm{H}_+\ \mathrm{H}_0\ \mathrm{S})/J_R(\mathrm{H}_+\ \mathrm{H}_0)$ may be approximately expressed by use of (27) as

$$J_R^{\|}(\mathrm{H}_+\ \mathrm{H}_0\ \mathrm{S})/J_R(\mathrm{H}_+\ \mathrm{H}_0) \simeq 1 - \frac{16}{15\pi} h_c \left(\frac{1-K_1}{1-K_\infty}\right)\left(\frac{P}{S}\right)\left(\frac{S}{H}\right). \qquad (33')$$

If we can know the numerical values of K, K_1 and K_∞, therefore, we should be able to estimate the approximate magnitude of $h_c \equiv 3\lambda_s/\sqrt{2}\, J_s$ individually from the ob-

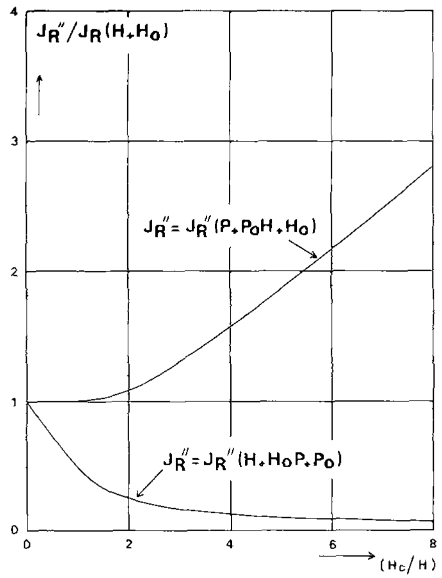

Figure 11
Theoretical curves of the advanced pressure effect on IRM (or the after-effect of pressure on IRM), $J_R^{\|}(\mathrm{P}_+\ \mathrm{P}_0\ \mathrm{H}_+\ \mathrm{H}_0)/J_R(\mathrm{H}_+\ \mathrm{H}_0)$ and the pressure demagnetization, $J_R^{\|}(\mathrm{H}_+\ \mathrm{H}_0\ \mathrm{P}_+\ \mathrm{P}_0)/J_R(\mathrm{H}_+\ \mathrm{H}_0)$ (after NAGATA and CARLETON 1969)

served data of $J_R(\mathrm{H}_+\ \mathrm{S}\ \mathrm{H}_0)$ for small values of H, $J_R^{\|}(\mathrm{S}\ \mathrm{H}_+\ \mathrm{H}_0)/J_R(\mathrm{H}_+\ \mathrm{H}_0)$ for large values of S, and $J_R^{\|}(\mathrm{H}_+\ \mathrm{H}_0\ \mathrm{S})/J_R(\mathrm{H}_+\ \mathrm{H}_0)$ for small values of S. Although the numerical values of K, K_1 and K_∞ have been measured for specific values of H and S (e.g. Table II), they have not yet been generally determined as a function of H and S for individual rock samples. However, it can be argued based on the experimental data that $\frac{1}{2}<K<1$ for $H=2\sim 11$ Oe and $S=0.07\sim 0.29$ bar. sec., which are the ranges of H and S delat with in the present work. Furthermore, since $K_1<0.6$ for the observed data and there must hold the inequality relation $0<K_\infty<K_1<1$, the possible range of $(1=K_1)/1=K_\infty)$ is $0.4<(1=K_1)/(1=K_\infty)<1$. These numerical conditions for the possible ranges of K and $(1=K_1)/(1=K_0)$ may allow us to use (30), (32)′ and (33)′

to evaluate the order of magnitude of h_c, using the observed values of K, K_1 and K_∞ listed in Table II. Based on the above-mentioned background, the magnitude of h_c of Sample MH-09-02 will be evaluated in three different ways.

Since $K^{\parallel} = 4.9 \times 10^{-3}$ emu/cc/Oe bar sec, $b = 1.0 \times 10^{-5}$ emu/cc/Oe^2, and $K = 0.60$ for this sample, (30) leads to $h_c \simeq 0.38$ (Oe/bar) $= 3.8 \times 10^{-7}$ cgs emu/cc. Since $\{J_R^{\parallel}(\mathrm{S\,H_+\,H_0})/J_R(\mathrm{H_+\,H_0})\}/(S/H) = 1.0 \times 10^2$ Oe/bar sec for the largest value of S in Fig. 7, (32)′ leads to $h_c \simeq 0.23$ (Oe/bar) $= 2.3 \times 10^{-7}$ cgs emu/cc. On the other hand, (33) and (33)′ indicate that

$$J_R^{\parallel}(\mathrm{H_+\,H_0\,S})/J_R(\mathrm{H_+\,H_0}) = 1 - \frac{16}{15\,\pi}\left(\frac{1-K_1}{1-K_\infty}\right) \quad \text{for} \quad \left(\frac{P}{S}\right)\left(\frac{S}{H}\right) h_c = 1. \tag{34}$$

Since $K_1 \simeq 0.55$ and $K_\infty \simeq 0.175$ for this sample, $J_R^{\parallel}(\mathrm{H_+\,H_0\,S})/J_R(\mathrm{H\,H_0}) = 1 - (16/15\pi)(1-K_1)/(1-K_\infty) = 0.815$ corresponds to $S = 0.020$ bar sec for $H = 11.24$ Oe in Fig. 8. Hence, (34) leads to $h_c \simeq 0.26$ (Oe/bar) $= 2.6 \times 10^{-7}$ cgs emu/cc. It may thus be summarized that the numerical values of h_c estimated in the three different ways for the basalt sample are roughly in agreement with one another. For reference, the magnitude of $3\lambda_s/\sqrt{2}\,J_s \equiv h_c$ for magnetite is to be about 1.8×10^{-7} cgs emu/cc. It must be taken into consideration here that the three estimated values of h_c for Sample MH-09-02 are evaluated on the assumption that H represents the effective magnetic field (H_{eff}) in the ferromagnetic minerals. Certainly, H_{eff} must be smaller than H, and the former and the latter may be approximately related by

$$H_{\mathrm{eff}} \simeq \frac{H}{1 + N\,\kappa}$$

where N and κ denote respectively the average demagnetizing factor of the ferromagnetic minerals and their average magnetic susceptibility. For spherical magnetite grains, $(1 + N\kappa)$ has been estimated to be $1.5 \sim 2.0$. Hence, the three values of h_c estimated from the shock-effected magnetizations must be divided by $(1 + N\kappa)$ for comparing with the h_c-value directly derived form J_s and λ_s of the ferromagnetic minerals. Then, the h_c values estimated from $J_R(\mathrm{H_+\,S\,H_0})$, $J_R(\mathrm{S\,H_+\,H_0})$ and $J_R(\mathrm{H_+\,H_0\,S})$ phenomena are roughly in agreement with $3\,\lambda_s/\sqrt{2}\,J_s$ for magnetite-like ferromagnetics.

9. *Concluding remarks*

The shock remanent magnetization, $J_R(\mathrm{H_+\,S\,H_0})$, the advanced shock effect on IRM, or the aftereffect of shock on IRM, $J_R(\mathrm{S\,H_+\,H_0})$, and the shock demagnetization effect, $J_R(\mathrm{H_+\,H_0\,S})$, for igneous rocks are experimentally demonstrated in the present work. As summarized by (27) the origins of these effects seem to be essentially same as those of $J_R(\mathrm{H_+\,P_+\,P_0\,H_0})$, $J_R(\mathrm{P_+\,P_0\,H_+\,H_0})$ and $J_R(\mathrm{H_+\,H_0\,P_+\,P_0})$ respectively, which have already been established. In other words, these effects are due to a nonlinear superpositions of the irreversible movements of the 90° domain walls caused by a shock or shocks and those by a magnetic field. As discussed in Section 7, however, it seems that an application of a mechanical shock of very short time duration on a sample cannot achieve the completion of the shock effect, which is represented by the effect of the pressure peak in the shock momentum. When the same shock operations are repeated, the resultant effect approaches the completed final state in an exponential form.

It seems very likely that the relative rate of the first shock effect to the succeeding repeated shock effects in the shock-effected remanent magnetization phenomena may depend on the magnitudes of applied shocks and a magnetic field as well as on the material characteristics. This problem has to be examined in the future work.

Acknowledgement

The author is indebted to Dr. P. J. WASILEWSKI of U.S. Geological Survey and J. R. DUNN of University of Pittsburgh for their very helpful assistance in the course of experimental work.

REFERENCES

[1] S. CHIKAZUMI, *Physics of Magnetism* (John Wiley and Sons, New York, 1964) pp. 303–320.
[2] H. JEFFREYS, *The Earth*, 5th ed. (Cambridge Univ. Press, Cambridge, 1970) pp. 457–459.
[3] T. NAGATA, *On the Natural Remanent Magnetization of the Lava Composing the Central Cone of Volcano Mihara*, Bull. Earthq. Res. Inst. *18* (1940), 281–288.
[4] T. NAGATA, *Effects of Uniaxial Compression on Remanent Magnetization of Igneous Rocks*, Pure Appl. Geophys. *75* (1970a), 100–109.
[5] T. NAGATA, *Basic Magnetic Properties of Rocks under the Effects of Mechanical Stresses*, Tectonophysics *9* (1970b), 167–195.
[6] T. NAGATA and B. J. CARLETON, *Notes on Piezo-Remanent Magnetization of Igneous Rocks*, J. Geomag. Geoele. *20* (1968), 115–127.
[7] T. NAGATA and B. J. CARLETON, *Notes on Piezo-Remanent Magnetization of Igneous Rocks (II) and (III)*, J. Geomag. Geoele. *21* (1969), 427–495, 623–645.
[8] T. NAGATA and H. KINOSHITA, *Studies of Piezo-Magnetization (I) Magnetization of Titanoferous Magnetite under Uniaxial Compression*, J. Geomag. Geoele. *17* (1965), 121–136.
[9] V. A. SHAPIRO and N. A. IVANOV, *Dynamic Remanence and the Effect of Shocks on the Remanence of Strongly Magnetic Rock*, Doklady Akad. Nauk. U.S.S.R. *173* (1967), 1065–1068.