Study on the Stability of VRM with Low-Temperature Treatment and Some Magnetic Characteristics of Granite*

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Abstract

A comparison between a microscopic observation and magnetic examinations such as thermomagnetic curve, low-temperature characteristics and microscopic coercivity spectrum indicates that the magnetic stability of granites is primarily controlled by the grain size: stable granites abundantly possess extremely fine magnetite grains (grain size $< 5\mu$), whereas the unstable sample contains mostly coarse magnetite grain (grain size $\geq 50\mu$).

Magnetic characteristics of VRM of magnetite grain which is produced at relatively high temperatures are examined. VRM produced at higher temperature generally becomes magnetically harder. The increase rate of the magnetic hardness which is expressed as a recovery ratio in low-temperature demagnetization is maximum at about 200°C. However, the extrapolation of the experimental results to a geological condition indicates the recovery ratio (or the magnetic hardness) of VRM produced in a geological condition will be only several times that of IRM produced at room temperature. Therefore, the VRM of granites which must have been produced over a long period of time at relatively high temperatures may still be effectively erased by low-temperature demagnetization.

1. Introduction

Recently, the possibility of the paleomagnetic use of granitic rocks has been discussed by several workers (Currie, Grommé and Verhoogen, 1963; Ito, 1965). It would be advantageous if the remanent magnetization of these rocks could be used for paleomagnetic purpose, since (i) granite is particularly suitable for K-A and Rb-Sr radiometric dating and (ii) granite occurs ubiquitously in almost all geological periods. However, it appears that granites generally have rather unstable NRM; only rarely, samples from some localities possess extremely stable and intense NRM.

In the first part of the present paper, the magnetic characteristics of two types of granites — one having very unstable and the other extremely stable NRM — are compared in an effort to understand what is the principal factor in controlling the stability of their NRM. Apparently, both are closely similar in chemical composition and the microscopic structure of their ferromagnetic constituents.

From their study on granitic rocks of the Sierra Nevada, Currie, Grommé and Verhoogen concluded that it is essential to remove the viscous component of NRM if any reliable paleomagnetic data are looked for from granites. In a recent paper by Ozima, Ozima and Nagata

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(1964), it was proposed that low-temperature treatment effectively erases most of the IRM component of remanent magnetization from rocks — such as most granite — containing titanomagnetite as their major ferromagnetic constituent. However, the low-temperature treatment is particularly effective when the titanomagnetite has little Ti-content. Since the titanomagnetite in granite has little Ti, the low-temperature treatment should be appreciably effective for these rocks. As pointed out by Grommé, however, because of the deep-seated plutonic origin of granites, the viscous component must have been produced over a very long period of time (of the order of one million years) at relatively high temperatures. Hence, it will be essential to investigate how effective the low-temperature treatment is in removing viscous magnetization which was produced during a long time in a magnetic field H at relatively high temperatures. In the latter part of this paper experimental results on the stability of viscous remanent magnetization against low-temperature treatment are described in relation to the time duration of the applied field and also the temperatures at which the remanent magnetization is acquired.

2. Stability of NRM's of some typical granites

It is well known that the major ferromagnetic minerals of granite is usually magnetite with a low titanium content. Some granites, of course, contain pyrrhotite or hematite as a major ferromagnetic constituent, but the author will confine the discussion only to those rocks whose major ferromagnetic constituent is magnetite. As the low-temperature cleaning — at temperatures attained using liquid nitrogen — is more effective for low-titanium magnetite, it would be considered that granite is ideal to test the validity of the low-temperature demagnetization method.

Eighteen granites from various localities were examined. Of these, two samples have an extreme contrast to each other in their properties of remanent magnetization, namely, one showing very stable NRM (Koshiki-jima granite of Japan) and the other (Yosemite granite of Yosemite Valley, California) very unstable NRM. In table I, some magnetic properties of these two granites (K-granite and Y-granite) are compared. In Y-granite, the intensity of NRM is very weak (less than 10^{-6} emu/g) and varies from point to point within a hand specimen by a factor of 10 or more. Furthermore, the NRM is so unstable that the

Table I

	Yosemite granite	Koshiki-jima granite
major ferromagnetic component	almost pure magnetite	almost pure magnetite
Curie point	570°C	570°C
average grain size	50–100 μ	several microns
coercivity	20 α	200 α
NRM	10^{-6} emu/g	$(0.5 \sim 1.3) \times 10^{-8}$ emu/g
NRM/TRM	0.01	0.5
effect of the low temperature treatment on NRM	?	$k=15 \rightarrow k=30$

direction of remanent magnetization changes appreciably within a few tens of minutes in time. The recovery ratio, that is, the ratio of the intensity of remanent magnetization after the low-temperature treatment to that of original remanent magnetization, of NRM also varies from 0.6 to 1.0 from point to point within a hand specimen. The effect of the low-temperature treatment does not improve the grouping of the direction of NRM. On the other hand, NRM of K-granite is fairly strong and stable (about $(1\sim0.5)\times 10^{-4}$ emu/g): the intensity of NRM decreases to 80% after demagnetization in an a-c field of 200 Oe. In this case, the low-temperature treatment appreciably reduces the scatter of the direction of NRM.

Each sample was so cut to be a long rectangular block and a saturation ARM was produced in a weak d-c magnetic field (10 Oe). ARM thus produced was demagnetized by an a-c field, progressively, increased by 10 Oe. From the change in the intensity of ARM, one can obtain a distribution histogram of microscopic coercivity (Ozima, 1963). Fig. 1-a and 1-b show the microscopic coercivity distribution of the K- and Y-granites, respectively. The mean value of coercivity is 200 and 20 Oe for K- and Y-granite samples, respectively. In order to understand the difference in the magnetic properties of these granites, polished sections also were examined. In the Y-granite, large grain of magnetite (0.05–1 mm) are

Fig. 1 Shows microscopic coercivity distribution histogram of Koshiki-jima granite sample (1-a) and Yosemite granite sample (1-b). $\bar{h}_c$ indicates the a-c field at which the saturation ARM is reduced to a half of the original intensity.

abundant whereas grains smaller than 0.005 mm are very rare. In contrast, the K-granite, which also contains numerous large crystals of magnetite (about 0.05 mm in maximum), possesses abundant grains of size less than 0.005 mm.

As far as the intrinsic magnetic properties, such as the Curie point or the thermomagnetic curve, are concerned, no significant difference is found between those two samples, thereby reflecting the almost identical composition of their ferromagnetic minerals. It is rather surprising, then, to find that the behaviours of their remanent magnetizations are so different from each other. The high stability and intensity of NRM and the high recovery

Fig. 2-a

Fig. 2-b

Fig. 2 Shows the relationship between the recovery ratio and the intensity of the artificial TRM and IRM for Koshiki-jima granite sample (2-a) and Yosemite granite sample (2-b).

ratio seem to indicate that NRM of the K-granite is of a typical TRM type. On the other hand, the extreme instability, the low intensity of NRM and the low recovery ratio indicate that NRM of Y-granite sample is not related to primary TRM, but rather to some viscous component (possessing characteristics of IRM) which has been acquired in the geomagnetic field. In addition, artificial TRMs produced in the K-granite and Y-granite also show significant differences at low-temperature. Fig. 2-a shows the relationship between the recovery ratio of the artificial TRM and IRM and the intensity of these remanent magnetizations for the K-granite. The recovery ratio for TRM decreases with increasing intensity, which is a typical characteristic of TRM. In contrast, as shown in Fig. 2-b, stronger TRM is associated with a larger recovery ratio in the Y-granite. This is the typical characteristic of IRM. Summarizing, it may be said that NRM and the artificial TRM of K-granite is, so to speak, “typical TRM” while NRM and the artificial TRM of the Y-granite is more like IRM. As herein used, “typical TRM” refers to remanent magnetization resulting from the rotation of single domain magnetic moments, whereas IRM refers to the remanent magnetization which is produced essentially by domain wall movements.

Except the conspicuous difference of grain size, no other remarkable difference of assemblages of opaque minerals can be found between the two samples. It seems likely that the presence of magnetite of a very fine grain size in K-granite is responsible for the large differences in the coercivity and the recovery ratio (Nagata, Kobayashi and Fuller, 1964). Thus only large difference in the coercivity may well explain why the remanent magnetization of K-granite is so intense and stable in comparison with the other. In brief, it seems that the grain size of magnetite primarily controls the coercivity and the acquisition of remanent magnetization of granite.

3. Stability of viscous remanent magnetization against low-temperature treatment

The partial demagnetization of a sample by the low-temperature treatment is caused by diminishing crystalline anisotropy energy of contained magnetite at low-temperatures (Ozima, Ozima and Nagata, 1964). It has been experimentally confirmed that IRM added to artificial TRM of a magnetite grain assemblage or basalt is almost completely erased when the specimen is cooled to liquid nitrogen temperature and reheated to room temperature in non-magnetic space.

It was also shown by Rimbert (1958) that IRM becomes more stabilized when the duration of the application of the magnetic field for producing IRM (or VRM) becomes longer. As pointed out by Currie, Grommé and Verhoogen, VRM of granite must have been produced by an application of the geomagnetic field during a long time at relatively high temperatures, because large deep-seated granitic intrusions must take a very long time to cool down from the Curie point to atmospheric temperature. Hence, it seems essential to study the relationship between low-temperature demagnetization and both the time duration of the applied field and the temperature at which VRM is acquired.

- (i) The relationship between the stability of VRM and the time duration of the applied field
The time effect on the stability of VRM was examined using a Yosemite granite sample.

Fig. 3 Shows the recovery ratio of VRMs of the Yosemite granite sample which are produced by different time duration of a magnetic field ($H=63$ oe) application.

In Fig. 3, the recovery ratio is plotted against the intensity of VRM produced by different time durations of applying a magnetic field of $H=63$ Oe at room temperature. This result in Fig. 3 seems to support the suggestion by Grommé that the longer is the application of a magnetic field, the more stable becomes the remanent magnetization against low-temperature demagnetization. However, as seen in the figure, an extrapolation of the experimental line of the recovery ratio to 10^6 years shows that the recovery ratio is still small even for 10^6 years in a magnetic field: for VRM which was formed by the application of H (63 Oe) at an atmospheric temperature for 10^6 years, the recovery ratio will only be about 0.3.

Fig. 4 shows the recovery ratio of an assemblage of artificial magnetite grains (grain size $\sim 50 \mu$) in which various initial remanent magnetizations (IRM) were produced by varying the length of time of the application of a magnetic field. In this case, the stability of

Fig. 4 Shows the recovery ratio of VRMs of an artificial magnetite grain assemblage (grain size $\sim 50 \mu$) which are produced by different time duration of the application of magnetic field. The stabilization of the VRM with longer application of a magnetic field is more remarkable with stronger magnetic fields.

remanent magnetization becomes greater with increased duration of application of a magnetic field. This tendency is more marked when a stronger field is applied. Extrapolation of these experimental results indicates that for a magnetite grain assemblage (grain size $\sim 50 \mu$) the recovery ratio of VRM which would be acquired during about 10^6 years in the earth's field (0.5 Oe) is about 0.01. Therefore, a VRM acquired at room temperature over a geologically long time will have to be erased by about 99% by the low-temperature cleaning technique.

(ii) The relationship between the stability and the temperature at which VRM is acquired

VRM was produced in a magnetite grain assemblage (grain size $\sim 100 \mu$) at various temperatures (room temperature $\sim 400^\circ\text{C}$) in a constant magnetic field (10 Oe) and at various duration of application of the magnetic field. Fig. 5 shows the recovery ratio versus the time-duration of the application of the magnetic field H . The ratio becomes larger when IRM and VRM are obtained at high temperatures; that is, IRM and VRM are more stable when produced at higher temperatures. It is interesting to note that the recovery ratio is generally higher with increasing duration of the magnetic field at higher temperature. As shown in the figure, the slope is the steepest at $T=200^\circ\text{C}$, that is, the time effect is the most conspicuous at that temperature. Extrapolation of this laboratory experiment to a geological condition (say, $t=10^6$ years, $T=400^\circ\text{C}$) still indicates that the stability of VRM thus produced in the geomagnetic field is much less than that of TRM (the recovery ratio of TRM produced in the earth's field is about 0.23). Certainly, a low-temperature treatment should also be effective for a more stabilized VRM produced during such a condition.

(iii) Theoretical consideration

It was shown by Rimbert (1958) that VRM becomes more stable with increased duration of the application of a magnetic field. Similarly low-temperature experiments reveal that VRM produced during progressively longer time application of the field, is increasingly more resistant against low-temperature demagnetization. This is easily understood when

Fig. 5 Shows the recovery ratios of natural magnetite grain assemblage (grain size $\sim 100 \mu$) versus the time duration of the application of a magnetic field. The experiments were carried out at various temperatures (room temperature, 200°C , 300°C , 400°C).

Neél's theory (1955) is considered. According to this theory, the effect of thermal agitation can be replaced by a fluctuating viscosity field $H_f(t)$ in addition to the applied field H . $H_f(t)$ is then given by $H_f(t) = S_v(Q + \log t)$, where Q is a numerical constant, t the time interval since the beginning of the application of a magnetic field H and S_v is a viscosity field constant, $S_v = S/\chi_{irr}$. Therefore, VRM which is produced by the application of a magnetic field H for a time duration of t would be regarded as IRM produced by the application of an effective magnetic field $H + H_f(t)$. Thus, VRM becomes more intense with an increase of the time duration of a magnetic field application. Since IRM becomes more stable with increase of the intensity (Roquet, 1954), VRM produced during a longer field application should also be more intense and stable than VRM produced in the same magnetic field but with a shorter application of H .

Fig. 6 Shows variation of magnetic viscosity field constant S_v as a function of absolute temperature (after Shimizu, 1960).

As noted before, the stabilization effect of remanent magnetization during longer applications of H is greatest around 200°C. This effect may be related to the characteristic temperature variation of S_v of magnetite (Fig. 6, Shimizu, 1960). As shown in the figure, S_v becomes maximum around 200°C except the temperature range just below the Curie point.

In a previous paper by Ozima and Ozima (1965), it was shown that the part of a remanent magnetization which is demagnetized by the low-temperature treatment is essentially related to the crystalline anisotropy energy. The fact that VRM produced at higher temperatures is more stable against low-temperature demagnetization, then, suggests that the component of VRM acquired at high temperatures is more related to other modes of domain constraint—such as magnetostriction energy.

4. Conclusion

- (i) Although granites usually have weak and unstable NRM, some granites are known to

possess strong and stable NRM. Yet, chemical and crystallographic characteristics of the ferromagnetic minerals of these two types of granite are nearly the same. Experimental study shows that the striking distinction between the remanent magnetizations of the two types of granite is mostly due to differences in the size of their magnetite grains. The stable one abundantly possesses extremely fine magnetite grains (grain size $< 5 \mu$), whereas the unstable sample contains mostly coarse magnetite grains (grain size $\sim 50 \mu - 100 \mu$),

(ii) VRM of magnetite grains (grain size $\sim 50 \mu$) produced with a longer application of a magnetic field becomes more resistant to the low-temperature demagnetization.

(iii) VRM of magnetite grains (grain size $\sim 100 \mu$) produced at higher temperatures is generally more resistant to low-temperature demagnetization. The increase rate of a recovery ratio with longer application of a magnetic field is maximum at about 200°C . This may be explained by the experimental fact (Shimizu, 1960) that the viscosity magnetic field constant S_v of magnetite becomes maximum at about 200°C .

(iv) The extrapolation of the experimental results to a geological condition — application of the geomagnetic field for 10^6 years at temperature of 400°C — indicates the recovery ratio of VRM produced in such a condition will be only several times as large as that of IRM produced at room temperature in the geomagnetic field. In case of magnetite grain assemblage (grain size $\sim 100 \mu$), the recovery ratio of VRM produced at their geologic condition would then be about 0.007, which is still far less than that of TRM produced in the geomagnetic field (0.23). The low-temperature cleaning should therefore be effective to erase such stabilized VRM.

(v) In case of the Y-granite, the change of the direction of NRM amounts to several ten degrees in a few tens of minutes, it is not possible to assign any definitive direction to the NRM and it may not be justified to evaluate the applicability of the low-temperature treatment in the case of these extremely unstable granites.

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