Anisotropy of magnetic susceptibility of rocks induced by experimental deformation

Jinqi Hao ([1]), **Zhijuan Gu** ([2]) **and Jianguo Zhou** ([1])
([1]) *Institute of Geophysics, State Seismological Bureau, Beijing, P.R. China*
([2]) *Institute of Geology, State Seismological Bureau, Beijing, P.R. China*

Abstract
In the present paper, the influence of the rheological process on the Anisotropy of Magnetic Susceptibility (AMS) of rocks is studied experimentally. The cylindrical samples of quartz-magnetite rock undergo a process under the confining stress of 300 MPa, temperature of 500-800°C and strain rate of 5×10^{-5}-1×10^{-4}/s. The residual deformation after the above process ranges 9-42%, depending on the experimental condition. It is found that the magnetic susceptibilities and the shapes of magnetic grains in these samples are almost isotropic before deformation. After being deformed, these samples show certain amounts of anisotropy of magnetic susceptibility and the axes of maximum principal susceptibilities deviate from the original ones more or less. Furthermore, the grains become oblate-ellipsoidal and a certain preferred orientation occurs. The grain shape anisotropy seems to be the main reason for AMS formation. It appears that there is a limitation of the piezomagnetic theory in explaining some tectonomagnetic phenomena. The results obtained in this study imply that ductile deformation at high temperature and pressure in depth during a long time-process may result in another kind of response in rock magnetism, which could be a new mechanism of tectonomagnetic variation.

Key words *anisotropy – rheology – ductile deformation – high-temperature, high-stress experiment – seismomagnetism*

1. Introduction

Several good examples of geomagnetic precursors before earthquakes have been reported and pre-, co-and post-earthquake variation in local geomagnetic field can be taken as diagnostic of the stress field change (Sasai and Ishikawa, 1980; Johnston and Mueller, 1987; Sumitomo and Noritomi, 1986). However, there are arguments against such a viewpoint because the data observed in the past decades showed the complexity of seismomagnetism. No corresponding geomagnetic precursors appear for some of the large earthquakes, while certain large variations in the local geomagnetic field are related to some aseismic tectonic activities with small stress changes. The local geomagnetic change does not correspond to the stress change alone and can hardly be explained only by the piezomagnetic theory. Further searching for the mechanism is required.

Recent study on deep structure reveals that the lithosphere may be divided vertically into two layers. The upper layer is characterized by a brittle response of rocks to stress. In the lower layer high-temperature creep takes place which may be transient creep or steady-state creep (Vetter and Meissner, 1979). Many earthquakes occur at the transition depths between brittle and creep dominated behaviour in the

Mailing address: Dr. Jinqi Hao, Institute of Geophysics, State Seismological Bureau, Beijing 100081, P.R. China; e-mail: fengrui@cdsndmc.css.gov

lithosphere. Therefore, rheology has been noticed more and more in earthquake prediction study. The precursor theories based on elasticity are too limited to understand a variety of phenomena related to earthquakes. The magnetic characters of rocks accompanying the rheological seismogenic process may also be meaningful in earthquake prediction.

Anisotropy of Magnetic Susceptibility (AMS) of rocks induced by progressive ductile deformation in geological period has been used as a tool in fabric analysis to solve the wide variety of geological problems (e.g., Hrouda, 1982). It is reported (e.g., Rathore, 1979) that for some naturally deformed rocks the directions of principal susceptibility axes coincide with those of the principal strain axes to a certain extent and there exists a relationship between the principal magnitude of susceptibility and that of the strain as well. So AMS is considered a strain indicator. The crustal rheological process relating to earthquake generation has a much shorter time-duration than the geological one. The question we want to answer now is can the magnetic anisotropy be induced by seismogenic process?

The ductile deformation on the samples is achieved in the experiment. We do not only measure the modification of magnetic and relevant properties of rocks, but also compare the AMS of naturally ductile-deformed rocks with that of the experimentally deformed ones. The primary producer of the experimentally induced AMS and the laboratory condition of developing AMS are also investigated. Furthermore, the possibility of AMS formation in the crust during seismogenic period is estimated.

2. Method

In the present study, rock samples undergo a process of increasing temperature, pressure and strain and thus the plastic deformation of samples eventually occurs. Because of the good measurement of the AMS, shape anisotropy and crystallographic anisotropy of magnetite in the samples before and after deformation, the effect of rheology on the magnetic and other natures of rocks can be investigated in depth.

2.1. *Samples*

The samples were taken in parallel from a large block of quartz-magnetite rock collected in Shandong, China. The main minerals consist of fine magnetite (50-70%), quartz (25-45%) and feldspar (5%). Each sample was a cylinder of 10 mm in diameter and 20 mm in length cut into two small cylinders of 10 mm in length, so that the difference in demagnetizing factor can be neglected when the susceptibility is detected at different directions.

2.2. *Production of ductile deformation*

To induce ductile deformation, the temperature of 500-800°C, confining stress of 300 MPa and axial stress of up to 1250 MPa with strain rate of 5×10^{-5}-1×10^{-4}/s were applied to the rock sample by a triaxial experimental apparatus (Shi and Liu, 1988). The difference of time-scale between the laboratory simulation and the seismogenic process is made up by appropriate increment of temperature in the experiment.

2.3. *The measurement of AMS and petrological fabric*

The magnetic susceptibility and its anisotropy of the samples were measured by a MINISEP magnetometer and then the orientation and magnitude of susceptibility ellipsoid computed.

The distribution of crystallographic axes and the grain shape anisotropy of relevant minerals were detected by *X*-ray preferred orientation goniometer and microscope, respectively.

3. Results

3.1. *Ductile deformation*

Under the above experiment, the residual axial deformations of these samples occurred, ranging 9-42% depending on different combinations of experimental parameters (table I, fig. 1). Figure 2a,b gives the recording curves

Table I. The experimental parameters and results of some rock samples

	LC1	LC2	LC3	LC7	LC8	LC9	LC10	LC11
Confining stress (MPa)	300	300	300	300	300	300	300	300
Temperature (°C)	500	700	800	800	800	700	700	700
Strain rate ($\times 10^{-4}$/s)	1	0.5	0.5	0.5	1	1	1	1
Differential stress (MPa)	1250	1060	–	440	330	560	630	825
Axial strain (%)	29.1	31.6	39.0	42.1	41.9	9.0	32.2	38.5
Before deformation								
Degree of AMS	1.0002	1.0002	1.0006	1.0009	1.0009	1.0008	1.0011	1.0010
Dip* (°)	86.5	85.9	87.6	87.6	87.3	84.5	86.5	86.8
After deformation								
Degree of AMS	1.0089	1.011	1.015	1.011	1.019	1.0074	1.025	1.012
Dip* (°)	71.3	82.7	84.5	84.0	84.7	75.9	77.7	80.7

Dip* = the dip of maximum principal susceptibility.

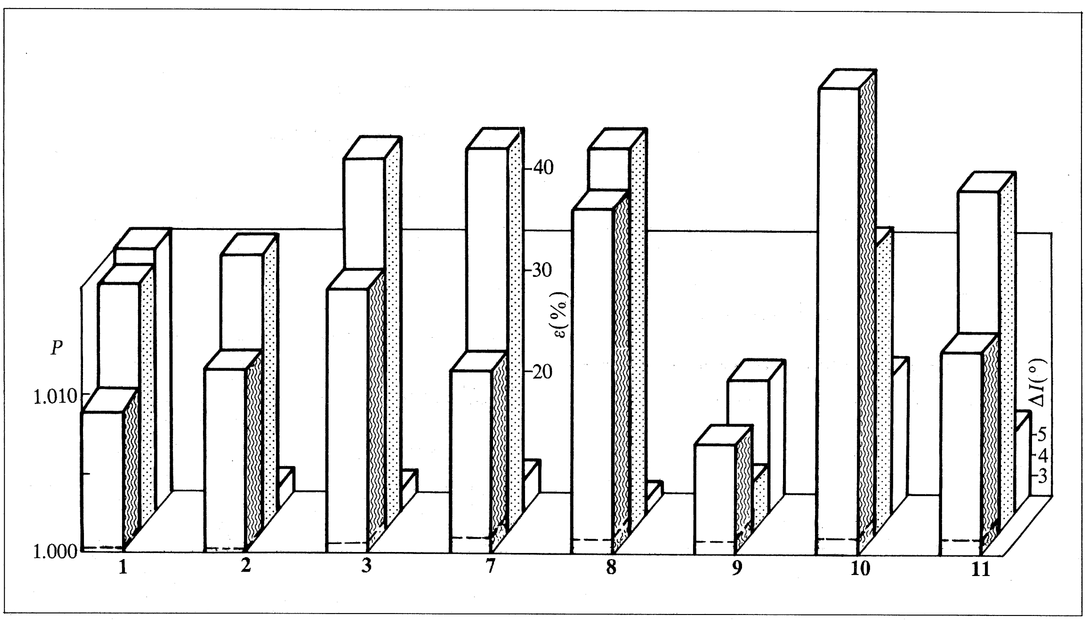


Fig. 1. Degree of anisotropy P for before deformation (dashed line) and after deformation (solid line), the dip deviation of maximum principal susceptibility (ΔI) and axial strain ε during deformation, for a part of the samples (numbered 1-11).

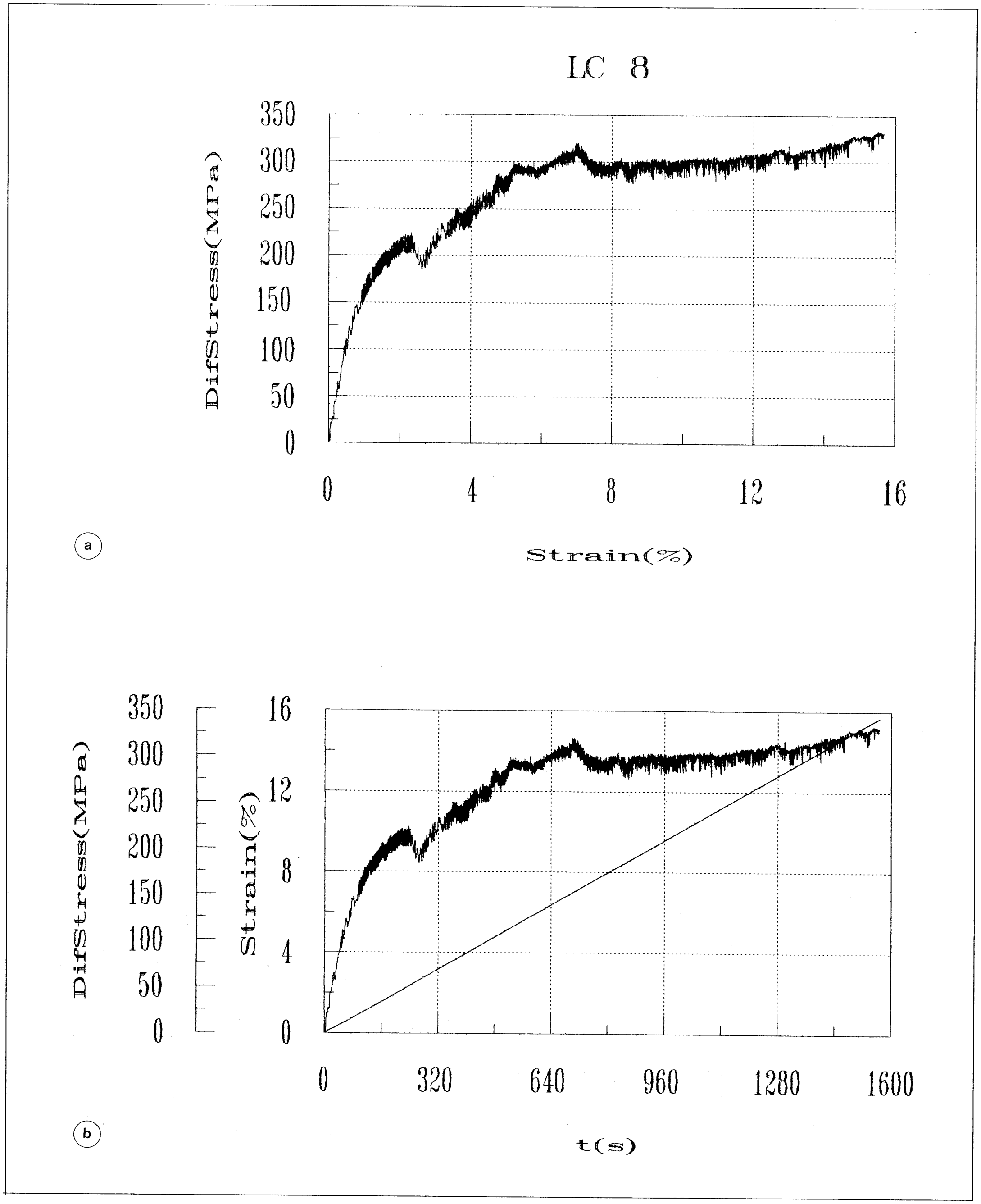


Fig. 2a,b. The experimental curves of sample LC8. a) Axial strain *versus* differential stress; b) variation of differential stress and axial strain with loading time.

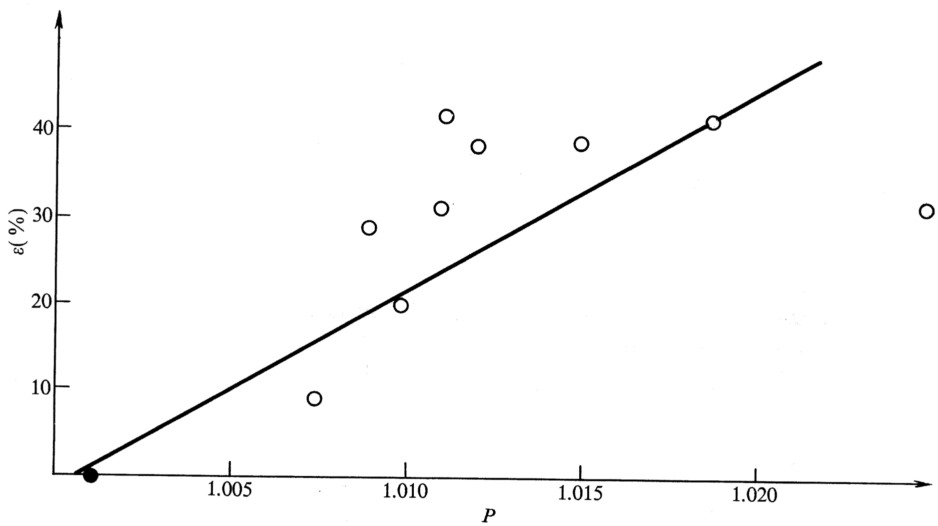


Fig. 3. The plot of axial strain ε *versus* degree of anisotropy P for experimentally deformed (circle) and undeformed (dot) rock samples.

for a sample in which the steady-state creep appears at the differential stress beyond 300 MPa, and the plastic deformation was then developed (table I).

3.2. *AMS*

The parameters of magnetic susceptibility and its anisotropy were measured for natural rock. It was found that these samples have high magnetic susceptibility ranging $(0.17\text{-}0.35)\times 4\pi$ SI and rather low degree of anisotropy (the ratio of $\kappa_{max}/\kappa_{min}$ of principal susceptibility) from 1.0002 to 1.0011. The dip of maximum principal susceptibility ranged 84.5-87.6° (table I).

After deformation at high temperature and stress, the above mentioned parameters were considerably changed. The degree of AMS increased evidently (ranging 1.0074-1.025) and the dip of maximum principal susceptibility decreased by 2.6-15.2° (table I, fig. 1).

Figure 1 clearly shows the effect of deformation on the AMS, in which the AMS before and after deformation are denoted by dashed and solid lines, respectively. Also, it is found that P, the degree of AMS, seems to have a linear relation to ε, the amount of the residual deformation, of the samples (fig. 3). The best fitted relation is

$$P = 1.001 + 0.043\,\varepsilon.$$

3.3. *The preferred crystallographic and grain-shape orientations*

The pole figure of magnetite and quartz in natural rocks did not show a distinguishable preferred orientation. On the contrary, for the experimentally deformed samples, pole figures showed meaningful preferred orientation with a maximum density of 4 (m.r.d.) (fig. 4).

The microscopic observation of the thin sections of undeformed samples demonstrated that they have almost isometric-granular structure and no preferred orientation (fig. 5). But for experimentally deformed samples, some oblate-ellipsoidal magnetite grains and their preferred orientation were observed. L_{max}/L_{min}, the dimension ratio of magnetite grains, was 1-2 (for 30% of grains), about 2 (40%) and about 3 (30%) and the direction of preferred orienta-

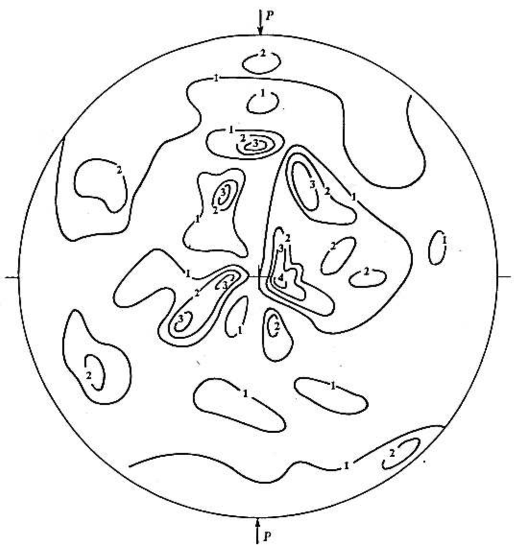


Fig. 4. The pole figure of (400) magnetite obtained by *X*-ray preferred orientation goniometer. The arrows denote the direction of differential stress.

tion of the longest axis of the grains was nearly perpendicular to the axis of differential stress (fig. 6).

4. Discussion

4.1. *AMS caused by experimental deformation*

A plastic deformation of 9-42% was produced in the present experiment. Our study makes it clear that anisotropy of magnetic susceptibility also takes place in the meantime and has a certain relationship with the plastic deformation (fig. 3). It is similar to the AMS induced by natural deformation though the former is smaller than the latter. This difference may be caused by a different time-duration of deformation.

In order to check the dominant experimental-condition of AMS-development, the samples undergo different combinations of temperature, confining stress, axial stress and strain rate in this study.

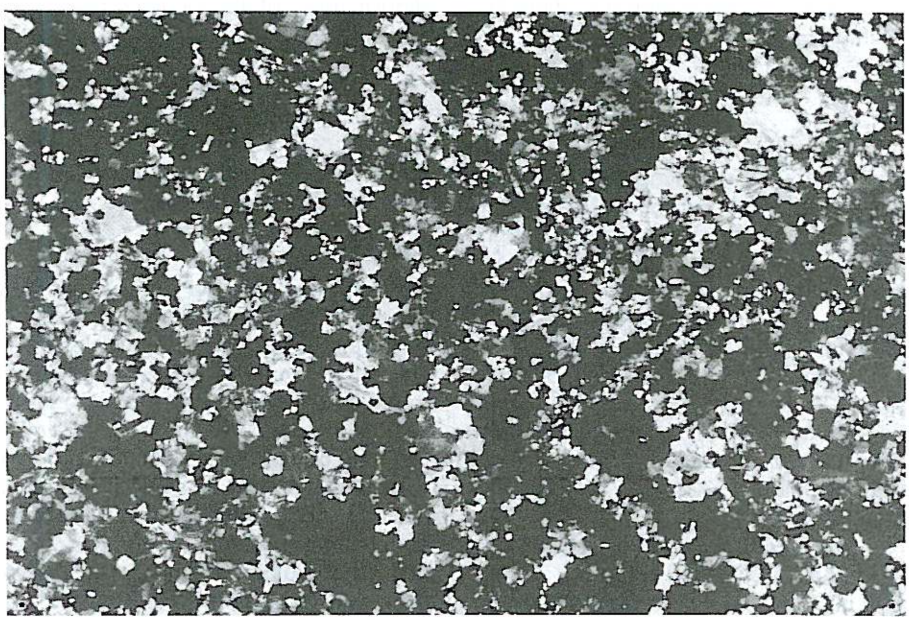
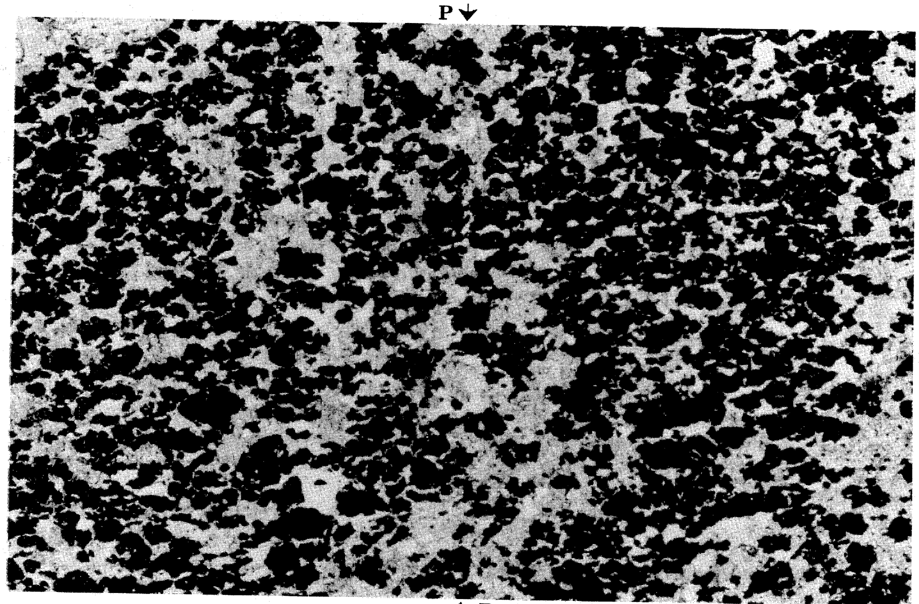


Fig. 5. The thin section of the undeformed sample. It has a nearly isometric-granular structure and no preferred orientation is observed.

P ↓



↑ P

Fig. 6. The thin section of the deformed sample. Oblate-ellipsoidal magnetite-grains (dark areas) and preferred orientation are observed. The arrows denote the direction of differential stress.

For the samples listed in table I, the ductile deformation achieved and AMS formed for all samples at temperature higher than 500°C and other conditions of the confining pressure and strain rate. In fact, some other experiments were performed at a temperature of 200°C, a strain rate of 5×10^{-6}-2×10^{-5}/s and confining stress of 300 MPa, but for most of these samples AMS were not formed and brittle fracture eventually occurred. We would say that the temperature is important but the dominant experimental condition to induce AMS is to reach enough plastic deformation.

4.2. *The primary producer of AMS*

To solve this problem, the preferred crystallographic orientation and the grain-shape anisotropy of magnetite were also measured in this study. The pole figure of magnetite manifested an evident crystallographic anisotropy. But we did not take it as the dominant cause of AMS generation because magnetite is a sort of high-symmetric crystal and its crystallographic anisotropy shows evidently only in strong field. However, the oblate-ellipsoidal magnetite grains and their alignment may produce the AMS because the easy axis of magnetization tends to be along the longest axis of ferromagnetic grains. This kind of effect is even strong for highly magnetic grains such as magnetite (Hrouda, 1982) which is the main magnetic mineral in our samples.

Figure 7 clearly exhibits the relation between the degree of anisotropy of susceptibility (P) with that of strain in the markers of gneiss samples (denoted by circles) and their regression line (Yu and Zheng, 1992). For comparison, the AMS and the dimension ratio of magnetite grains obtained in our experiment are also given in this figure as a dot. This figure indicates that the magnetic anisotropy of both naturally and experimentally deformed rocks has the same reason, *i.e.* the shape alignment of ferromagnetic grains.

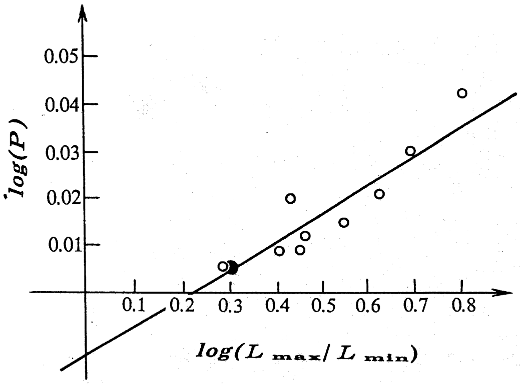


Fig. 7. The relation between the degree of anisotropy of susceptibility (P) and that of strain (L_{max}/L_{min}) for naturally deformed (circle) and experimentally deformed (dot) samples.

We come to the conclusion that the grain shape anisotropy should be the primary cause of anisotropy of susceptibility of experimentally deformed rocks, while the turning of the dip of maximum principal susceptibility during deformation should be attributed to the alignment of magnetic grains.

4.3. *The significance for earthquake prediction*

It is well known that magnetic anisotropy can influence the configuration of a magnetic anomaly over the magnetic anisotropy body. Hence, if AMS is formed accompanying the seismogenic rheological processes, the geomagnetic field would be modified by it in both direction and strength.

The magnetic susceptibility of deformed rocks observed in the present experiment is taken as the effect of rheological property on rock magnetism in the depth. Nevertheless, the extent to which this kind of effect can influence regional field *in situ* remains to be studied. Due to the difference of temperature, pressure, time scale and boundary conditions between laboratory and crust, the creep and magnetic changes resulting from the seismogenic process in the crust should be greater than that obtained in the present experiment. Though our result cannot be used directly to analyze the magnetic effect of an earthquake, it is important, when we investigate the seismomagnetic effect, to separate the seismogenic process into two parts, *i.e.* the instantaneous break of rock body and slow loading. The former should be dealt with by elastic theory and piezomagnetism, while the latter by the effect of rheological character on geomagnetic field as well. In fact, such special variations similar to the latter in geophysical fields, such as gravity, crustal deformation, ground water and so on, is frequently observed before great earthquakes. There probably exists a certain coherent relationship among them. In other words, the geomagnetic variation connecting with the rheological process might be another mechanism of seismomagnetism.

Acknowledgements

This project is sponsored by the Chinese Joint Seismological Science Foundation.

Contribution No. 97B0001, Institute of Geophysics, SSB, China.

REFERENCES

JOHNSTON, M.J.S. and R.J. MUELLER (1987): Seismomagnetic observation during the 8 July 1986 magnitude 5.9 North Palm Spring earthquake, *Science*, **237**, 1201-1203.

HROUDA, F. (1982): Magnetic anisotropy of rocks and its application in geology and geophysics, *Geophys. Surv.*, **5**, 37-82.

RATHORE, J.S. (1979): Magnetic susceptibility anisotropy in the Cambrian slate belt of North Wales and correlation with strain, *Tectonophysics*, **53**, 83-97.

SASAI, Y. and Y. ISHIKAWA (1980): Tectonomagnetic event preceding a *M* 5.0 earthquake in the Izu Peninsula - aseismic slip of a buried fault?, *Bull. Earthq. Res. Inst.*, **55**, 895-911.

SHI, L. and S. LIU (1988): The design of three-axial experimental apparatus of 2 GPa solid confining pressure, in *Proceedings of the High-Temperature and High-Pressure Rock Mechanics Conference China* (Academic Press, Beijing), 122-129 (in Chinese).

SUMITOMO, N. and K. NORITOMI (1986): Synchronous precursors in the electrical earth resistivity and the geomagnetic field in relation to an earthquake near the Yamasaki fault, Southwest Japan, *J. Geomagn. Geoelectr.*, **38**, 971-989.

VETTER, U.R. and R.O. MEISSNER (1979): Rheologic properties of the lithosphere and applications to passive continental margins, *Tectonophysics*, **59**, 367-380.

YU, Q. and M. ZHENG (1992): *Magnetic Fabric of Rocks and its Application in Geosciences* (Geological Press, Beijing), pp. 110 (in Chinese).