Magnetic Susceptibility of Some Rock Forming Silicate Minerals Such as Amphiboles, Biotites, Cordierites and Garnets*

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Abstract

Some silicate minerals such as amphiboles, biotites, cordierites and garnets were examined magnetically. Magnetic susceptibility at the room temperature of garnets is in good agreement with the theoretical value estimated by using the effective Bohr magneton number derived empirically from salts bearing above magnetic ions, while in the case of amphiboles, biotites and cordierites, which contain water in their crystal structure, magnetic susceptibility at the room temperature shows fairly larger value than expected.

1. Introduction

Magnetic properties of ferromagnetic minerals contained in rocks have been examined fairly comprehensively, but only few of the silicate minerals such as olivines (Nagata, Yukutake and Uyeda: 1957), orthopyroxenes (Akimoto, Hôrai and Boku: 1958), and monoclinic pyroxenes (Chevallier et Mathieu: 1958 and 1959) have been examined quantitatively. These silicate minerals are paramagnetic, and measured magnetic susceptibility at the room temperature of them agrees well with the calculated value determined from the content of magnetic ions, using the accepted value of effective Bohr magneton number derived from salts bearing above ions.

In the present study, some silicate minerals such as amphiboles, biotites, cordierites and garnets, which are very common in igneous and metamorphic rocks, were examined magnetically.

2. Specimens

Specimens used here were the most pure natural minerals available in Japan offered by the courtesies of Dr. A. Miyashiro and Messrs. S. Aramaki and S. Banno, of Geological Department, Tokyo University, after their mineralogical examinations. The chemical composition of these specimens is given in Table I.

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Table I Chemical analyses of amphiboles, biotites, cordierites and garnets

a) Amphibole

	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
SiO ₂	52.41	43.20	44.07	54.09	56.61	45
Al ₂ O ₃	0.61	12.44	12.37	0.22	0.24	4
TiO ₂	0.45	1.65	1.70	3.54	1.04	0
Fe ₂ O ₃	14.37	3.21	0.18	0.66	1.10	10
FeO	14.82	10.10	10.23	4.69	3.90	26
MnO	1.46	0.21	0.18	0.26	0.29	0
MgO	5.07	13.27	14.20	21.29	22.27	0
CaO	1.33	11.36	12.42	12.14	12.33	2
Na ₂ O	4.94	2.72	1.00	0.21	0.06	7
K ₂ O	2.10	0.40	0.30	0.16	0.18	3
H ₂ O ⁺	2.02	1.38	2.85	0.12	0.10	1
H ₂ O ⁻	0.10	0.07	0.03	2.78	2.45	0
P ₂ O ₅		0.07	n.d.			
F ₂	0.30	n.d.	n.d.			
O for F ₂	0.13					
Total	99.85	100.08	99.53	100.16	100.57	98

Mineralogical description

No. 1 Riebeckite from quartz-syenite, (AM 440702-10), Loc. 500 M. W. of Bungan, Kōganzan, Heiko-yu, Heiko-gun, Kōgen-dō, Korea. (Analyst; Inoue) Ref. 1

No. 2 Hornblende from biotite-amphibolite, (AM 470808-3), Kamata, Hurudono-mura, Higasi-sirakawa-gun, Hukushima-ken, Japan. (Analyst; Haramura) Ref. 2

No. 3 Hornblende from epidote-hornblende-plagioclase-schist, (AM 470621-16), Kamiyama, Tabito-mura, Iwaki-gun, Hukushima-ken, Japan. (Analyst; Miyashiro), Ref. 2

No. 4 Actinolite, Loc. Chester, Vermont, USA. Ref. 3

No. 5 Actinolite, No. 8, Loc. Zöptan, in Mähren, Ref. 3

No. 6 Arfvedsonite, Nunarsuatsiak, Tunugdliarfik, Greenland.

The values of No. 6 are representative ones according to Dr. A. Miyashiro.

b) Biotite

	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
SiO ₂	29.21	32.43	34.97		31.45	33.80
Al ₂ O ₃	13.48	18.64	19.04		15.01	20.28
TiO ₂	0.70	1.10	2.61		1.04	3.28
Fe ₂ O ₃	20.22	4.53	1.28	) 4	12.45	0.75
FeO	16.03	19.92	18.06		21.02	21.04
MnO	2.00	2.33	0.47		2.01	0.51
MgO	1.37	6.86	9.71		4.19	6.84
CaO	0.10	0.41	0.17		0.32	0.04
Na ₂ O	1.99	0.52	0.36		tr.	0.13
K ₂ O	8.29	9.20	10.17		9.21	8.56
H ₂ O ⁺	4.27	3.66	3.31		3.48	4.41
H ₂ O ⁻	2.26	0.45	0.22		0.30	0.38
P ₂ O ₅	none	none	0.15		0.00	
F ₂	n.d.	0.16			0.14	
O for F ₂		0.07			0.06	
Total	99.92	100.14	100.52		100.56	100.02

Mineralogical description

- No. 1 Biotite from cancrinite-syenite-pegmatite, (AM440617-14 (11)), Loc. Fukushima-shin-zan, Sei-men, Heikō-gun, Kōgen-dō, Korea. (Analyst; Inoue) Ref. 1
- No. 2 Biotite from nepheline-syenite, (AM431205-13 (7)). Loc. Shachō-zan, Kennai-men, Heikō-gun, Kōgen-dō, Korea. (Analyst; Inoue) Ref. 1
- No. 3 Biotite, (AM470623-7), Between Isizumi and Kaiya, Tabito-mura, Iwakigun, Hukusima-ken, Japan. (Analyst; Haramura) Ref. 2
- No. 4 Biotite, Specimen of Geological Institute, Tokyo University.
- No. 5 Biotite from nepheline-syenite, (AM440619-13 (12)), Loc. Fukushima-shin-zan, Sei-men, Heikō-gun, Kōgen-dō, Korea. (Analyst; Inoue) Ref. 1
- No. 6 Biotite from garnet-biotite-oligoclase-quartz-gneiss, (AM540812-6A), Nisitakatō, Takatō-mati, Kami-ina-gun, Nagano-ken, Japan. (Analyst; Haramura) Ref. 2

Content of $\text{Fe}_2\text{O}_3 + \text{FeO}$ of No. 4 was determined from the refractive index by Dr. A. Miyashiro.

c) Cordierite

	No. 1	No. 2	No. 3	No. 4
SiO_2	44.64	47.63	47.09	47.67
Al_2O_3	29.96	33.34	34.86	31.12
TiO_2	n.d.	0.03	0.03	2.05
Fe_2O_3	2.72	0.07	0.11	1.18
FeO	11.02	4.91	2.59	11.53
MnO	1.86	0.12	0.05	0.41
MgO	3.08	9.70	11.92	6.14
CaO	0.02	0.04	0.04	tr.
Na_2O	2.05	0.61	0.78	0.12
K_2O	0.75	tr.	tr.	0.03
H_2O^+	) 3.85	2.74	2.21	0.05
H_2O^-		1.01	0.65	0.05
Total	99.95	100.00	100.33	100.35

Mineralogical description

- No. 1 Iron-rich cordierite from pegmatite, Sugama, Oomoritamura, Isikawa-gun, Hukusima-ken, Japan. (analyzed by an analyst of the Geological Survey of Japan) Ref. 4
- No. 2 Cordierite from pegmatite, Near New Haven, Conn., USA. Ref. 5
- No. 3 Cordierite from metamorphic deposit, Laramie Range, Albany County, Wyoming, USA. Ref. 5
- No. 4 Cordierite from a xenolith in volcanic rock of Asama Volcano, Japan. Ref. 4, 6 and 7

d) Garnet

	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7
SiO ₂	39.68			36.82	38.53	38.74	
Al ₂ O ₃	22.05			22.10	22.12	22.09	
TiO ₂	0.98			0.08	0.09	0.07	
Fe ₂ O ₃	4.10			1.54	1.66	2.97	
FeO	11.33			14.96	25.35	23.23	
MnO	1.57			15.08	0.98	0.47	
MgO	13.63			2.73	8.12	11.20	
CaO	6.75			5.93	3.21	1.10	
Na ₂ O	0.19			0.12	0.18	0.23	
K ₂ O	0.04			0.09	0.04	0.11	
H ₂ O ⁺	) 0.28			0.82	0.38	0.05	
H ₂ O ⁻				0.00	0.06	0.02	
P ₂ O ₅				0.01			
Cr ₂ O ₃						0.70	
Total	100.60			100.28	100.72	100.35	

Mineralogical description

No. 1 Garnet from eclogite, Gongen-yama, Sekikawa-mura, Uma-gun, Ehime-ken, Japan. Ref. 8

No. 2 Almandine, Ennis, Montana, USA.

No. 3 Garnet porphyroblast in metagabbro, Gore Mt. (Barton mine), Adirondack, N. Y., USA.

No. 4 Garnet in garnet-quartz-nodule in biotite-schist, (SB57110601), (Segregation nodule?), Tonaru, Bessi, Ehime-ken, (Analyst; Haramura)

No. 5 Garnet from garnet-amphibolite (A-9), Prince Harold Coast, Antarctica, (Analyst; Katsura)

No. 6 Garnet from banded gneiss, (A-20), Prince Harold Coast, Antarctica, (Analyst; Katsura)

No. 7 Specimen of the Geological Institute, Tokyo University.

There is no analysis of No. 2, 3 and 7 of garnets

Most samples were originally separated out by an isodynamic separator. However, it was hardly possible even by the isodynamic separator to separate very small inclusions of ferromagnetic minerals.

3. Experiments

Three kinds of magnetic measurements were made by means of a sensitive quartz spring magnetic balance (Akimoto: 1954) for all specimens; namely (a) measurements of magnetization curve at the room temperature and (b) at low temperatures and (c) measurements of variation of magnetic susceptibility with temperature.

(a) Measurements of magnetic susceptibility at the room temperature

Magnetization curve of these specimens can generally be expressed by $\sigma = \sigma_0 + \chi H$, where σ , σ_0 , χ and H denote respectively the measured magnetization, intensity of ferromagnetic component due to the ferromagnetic impurities, paramagnetic susceptibility and applied field. Therefore, paramagnetic susceptibility, χ , of the specimens was determined from the slope of the straight line part of magnetization curve. Several

Fig. 1 Magnetization curve at the room temperature

Fig. 2 Magnetization curve at 90° K.

examples of the magnetization curve are shown in Fig. 1.

Values of specific susceptibility at the room temperature of these specimens are tabulated in Table II together with those of σ_0 , χ_1 and χ_2 , there, χ_1 and χ_2 are theoretically calculated values by assuming Langevin's free gas model of magnetic ions, being expressed by

$$\chi = \frac{N\mu_B^2}{3kT} (xp_{Bx}^2 + yp_{By}^2 + zp_{Bz}^2),$$

where N , μ_B and k are Avogadro number, Bohr magneton and Boltzmann's constant respectively; x , y , z , and p_{Bx} , p_{By} , p_{Bz} , are the number of the gram-ions of Fe^{2+} , Fe^{3+} , Mn^{2+} , contained in unit gram of specimens and its effective Bohr magneton number respectively. After Stoner (Stoner: 1934), the values of effective Bohr magneton number are taken as follows; $p_{Bx}=5.25$ to 5.53 and $p_{By}=p_{Bz}=5.88$. χ_1 and χ_2 corresponds to $p_{Bx}=5.25$ and 5.53 respectively.

(b) Measurements at low temperatures

Measurements at low temperatures were carried out by immersing specimens to be measured into oxygen liquid in the dewer. Some σ - H curves are shown in Fig. 2.

For the purpose of examining deviation of the magnetization curve from Curie's law to Curie-Weiss' law, the paramagnetic Curie temperature θ_p given by $\chi(T-\theta_p)=C$ was obtained from the observed values of χ at the room temperature and at low temperature, being also tabulated in Table II.

(c) Variation of susceptibility with temperature

In order to ascertain whether Curie's law is valid or not, variation of magnetic

Table II Magnetic susceptibility of amphiboles, biotites, cordierites and garnets, comparing with the theoretically calculated values and paramagnetic Curie temperature (unit; emu/gr).

Specimen	calculated value		observed value			θ_p ° K
			at room temp.		at 90° K	
	$10^5\chi_1$	$10^5\chi_2$	$10^5\chi$	σ_0	$10^5\chi$	
Amphibole-1	5.34	5.61	7.5	0.013	3.3	32
2	2.27	2.45	2.2	0.010	1.3	
3	1.73	1.91	3.3	0.001	1.2	15
4	0.94	1.02	1.3	0.000	0.3	—
5	0.90	0.96	1.3	0.000	0.3	—
6	6.1	6.6	8.0	0.000	4.2	43
Biotite-1	6.74	7.00	7.8	0.000	4.9	52
2	4.46	4.82	6.1	0.002	3.0	40
3	3.27	3.59	4.6	0.000	2.0	30
4		0.6	0.4	0.000	—	—
5	6.12	6.49	7.6	0.047	4.2	46
6	3.66	4.03	5.3	0.008	2.2	30
Cordierite-1	2.67	2.87	3.3	0.010	1.5	33
2	0.84	0.92	1.0	0.002	0.3	—
3	0.45	0.50	0.6	0.000	—	—
4	2.17	2.38	2.1	0.001	0.68	5
Garnet-1	2.91	3.11	3.1	0.001	1.15	15
2			5.9	0.003	2.2	16
3			3.6	0.003	—	—
4	5.83	6.10	5.7	0.033	2.3	25
5	4.63	5.08	4.8	0.015	1.9	21
6	4.42	4.83	4.2	0.020	1.6	19
7			4.3	0.015	—	—

susceptibility with temperature was examined; namely χ - T measurement for the range from liquid oxygen point to about 500°C. Because all the specimens except garnets examined here become unstable above about 500°C, making decomposition and changing into magnetite etc., no measurement above 500°C was carried out.

Examples of results of measurements are given in Fig. 3, where it is shown that χ is inversely proportional to T , but generally the χ^{-1} - T curve does not cross 0°K point.

Fig. 3 variation of magnetic susceptibility with temperature

4. Discussions

Summarizing above results, χ at the room temperature $\sim \chi_1$ and χ_2 diagram and $\Theta_p \sim \chi_1$ and χ_2 diagram are given in Fig. 4 and 5.

In Fig. 4, it is seen that the observed values of χ at the room temperature are not in good agreement with the estimated values of χ_1 and χ_2 , except for case of garnets. The measured values of magnetic susceptibility of amphiboles, biotites and cordierites are larger than calculated values χ_1 and χ_2 by 20% $\sim$ 30% generally. It seems that this discrepancy exceeds possible range of experimental errors, which can be estimated to be less than 10% at the largest.

Comparing chemical composition of these minerals, magnetic susceptibility of which cannot be exactly given by the Langevin's law, with those of the minerals for which

magnetic susceptibility is well represented by the Langevin's law such as garnets, olivines and pyroxenes, it may be found that the former group minerals contain OH radicals or H_2O molecules in their crystal structure, but in the latter there is no water component. In Fig. 5 also, it is shown that paramagnetic Curie temperature of the former group of minerals are fairly larger than that of the latter.

This fact may suggest that some very weak interaction or something like weak magnetic coupling among magnetic ions through OH radicals or H_2O molecules in these minerals containing water may affect their magnetic susceptibility. Further careful study will be necessary in order to examine existence of such a weak interaction through OH radicals or H_2O molecules.

Fig. 4 Relation between measured magnetic susceptibility, χ , at the room temperature and theoretically calculated values, χ_1 and χ_2

Fig. 5 Relation between paramagnetic Curie temperature, θ_p , and theoretically calculated magnetic susceptibility, χ_1 and χ_2

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