

MAGNETIC SUSCEPTIBILITY AS A MEASURE OF TOTAL
IRON PLUS MANGANESE IN SOME FERROMAGNESIAN
SILICATE MINERALS

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ABSTRACT

Specific magnetic susceptibilities of biotites, amphiboles and pyroxenes, are directly related to total Fe (as FeO) + MnO content. For common varieties of these minerals, in which MnO is low, magnetic susceptibility effectively indicates total iron content. Measurements on biotites and amphiboles made with a calibrated Frantz isodynamic separator are sufficiently accurate to make specific susceptibility useful in petrological studies.

INTRODUCTION

The magnetic susceptibilities of some ferromagnesian silicate minerals have been measured in recent years by a number of workers with a magnetic balance—an instrument not readily available in most petrological laboratories. However, the method devised by McAndrew (1957) for the simple measurement of specific susceptibility with the Frantz isodynamic separator has brought such measurements within the scope of the many laboratories equipped with this instrument. The present study, therefore, was directed towards the measurement of the susceptibilities of some biotites and amphiboles with the Frantz separator. In addition, correlations between specific susceptibility and total iron plus manganese content are presented for these biotites and amphiboles, and for previously published data on amphiboles, clinopyroxenes and orthopyroxenes. Such correlations permit estimation of iron-manganese content, for which optical methods may be unreliable, e.g. in biotites and amphiboles.

PREVIOUS MEASUREMENTS

Olivines

Nagata, Yukutake and Uyeda (1957) measured with a magnetic balance the magnetic susceptibility of six olivines, five of which varied in composition from Fa_{64} to $\text{Fa}_{\text{cr. } 35}$, the other being a knebelite. They also showed how the magnetic susceptibility may be calculated from the concentrations and magnetic moments of the paramagnetic ions. The compositions of some of the olivines were estimated from refractive indices. Apart from the knebelite, the only olivine for which a published analysis is available is a common magnesian olivine containing 10.26 per

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cent FeO and 0.09 per cent MnO (Ross, Foster and Myers 1954, p. 707). Its specific susceptibility range calculated by the writer from these figures is 16.9 to 18.7 ($\times 10^{-6}$ e.m.u./gm.), which is in excellent agreement with the measured value (18×10^{-6}) given by Nagata, Yukutake and Uyeda (1957, p. 52).

Clinopyroxenes

Chevallier and Mathieu (1958) measured with a magnetic balance the specific susceptibility of thirteen clinopyroxenes from the Skaergaard intrusion, east Greenland, obtaining good agreement between measured values and susceptibilities calculated by adding the contributions of the magnetic moments of the main paramagnetic ions present.

Orthopyroxenes

Akimoto, Hôrai and Boku (1958) measured with a magnetic balance the specific susceptibility of eight orthopyroxenes varying in composition from Of₀₅ to Of₈₈ mol. per cent, and showed that the molecular susceptibility at room temperature increased with increasing ferrosilite content. The discrepancies between the measured susceptibilities and those calculated by the writer from the analyses given by Akimoto *et al.*, are larger than for the clinopyroxenes of Chevallier and Mathieu (1958) and for the biotites and amphiboles investigated in the present study.

Biotites and amphiboles

Syono (1960) measured with a magnetic balance the specific susceptibility of five analyzed biotites and six amphiboles. For the biotites and three of the amphiboles, the measured susceptibility is much higher than the calculated susceptibility. These discrepancies are attributed by Syono (1960, p. 91) to the presence of combined water, but no similar discrepancies were found in the present study, as shown later.

Cordierites

Syono (1960) showed that the specific susceptibility, measured with a magnetic balance, of four cordierites increased with increasing iron content. Fair agreement between measured and calculated susceptibilities was obtained.

Garnets

Syono (1960) measured the specific susceptibility of four analyzed garnets with a magnetic balance, finding good agreement between measured and calculated values. Frost (1960) measured the specific susceptibility of 23 garnets with a calibrated Frantz isodynamic separator and deduced the susceptibilities of the theoretical garnet end-members.

CALCULATION OF SPECIFIC SUSCEPTIBILITY

As a check on measurements it is desirable to calculate approximate susceptibilities from the chemical analyses. It has long been known that the magnetic susceptibility of paramagnetic compounds is determined by the magnetic moments and concentrations of the constituent paramagnetic ions. In the ferromagnesian silicates, which are paramagnetic, the main paramagnetic ion is usually Fe^{2+} , but commonly there are smaller amounts of Fe^{3+} and Mn^{2+} , and Ti^{3+} , Cr^{3+} and Ni^{2+} may also be present. Chevallier and Mathieu (1958) considered Fe^{2+} , Fe^{3+} and Mn^{2+} to be the effective paramagnetic ions in clinopyroxene, and derived expressions by which the specific susceptibility at 20° C. may be calculated from the concentrations and magnetic moments of these ions. The expressions, which may also be applied to other ferromagnesian minerals, are:

$$\chi_1 = 423.6 \times 10^{-6} [27.6x + 34.6(y + z)]$$

$$\chi_2 = 423.6 \times 10^{-6} [30.6x + 34.6(y + z)]$$

where χ_1 and χ_2 are the calculated specific susceptibilities (e.m.u./gm.), and x , y , z are the ionic concentrations (gm.ions/gm.) of Fe^{2+} , Fe^{3+} , and Mn^{2+} , respectively. Chevallier and Mathieu (1958) used the magnetic moments shown in Table 1, as did Syono (1960), and the writer has followed this usage to facilitate comparisons. The values χ_1 and χ_2 correspond to the ends of the range taken for the magnetic moment of Fe^{2+} (Table 1), so that ideally, the measured susceptibility (designated χ_m in this paper) should fall between χ_1 and χ_2 . However, the calculated susceptibility is best regarded only as an approximate guide.

RELATIVE EFFECTS OF THE PARAMAGNETIC IONS

Table 1, in conjunction with chemical composition, shows that the magnetic susceptibility of ferromagnesian silicates is due mainly to iron

TABLE 1. MAGNETIC MOMENTS USED FOR PARAMAGNETIC IONS,
TO WHICH REFERENCE IS MADE
(after Stoner 1934, p. 312)

Ion	Magnetic Moment
Ti ³⁺	ca. 1.7*
Cr ³⁺	3.86
Mn ²⁺	5.88
Fe ³⁺	5.88
Fe ²⁺	5.25-5.53
Ni ²⁺	3.23-3.43

* Deduced from the value of 1.74 given for V⁴⁺.

and manganese. Fe^{3+} and Mn^{2+} have slightly higher magnetic moments than Fe^{2+} and must therefore be granted the same degree of importance as Fe^{2+} , both for the calculation of susceptibilities and for plotting susceptibility against composition. However, if FeO is high, small amounts of Fe_2O_3 and MnO have only small effects on the susceptibility compared with the effect of the FeO. In this paper, both Fe^{3+} and Mn^{2+} have been taken into consideration, even where present in small concentrations, principally because these ions are invariably bracketed with Fe^{2+} in calculations involving the degree of substitution of Fe for Mg in common ferromagnesian minerals. In some garnets Mn is so high that its effect overshadows that of Fe; e.g., Frost (1960) deduced that the susceptibility of pure spessartite is higher than that of pure almandine.

Except for some uncommon varieties, ferromagnesian minerals generally contain only small amounts of titanium, although common biotites may contain as much as 5 per cent TiO_2 by weight. Though Ti^{4+} is diamagnetic, Ti^{3+} , containing one unpaired electron, is paramagnetic, with a magnetic moment of about 1.7 (Table 1). The colours of titaniferous pyroxenes, amphiboles and biotites indicate that small amounts of Ti^{3+} are present, but Ti^{3+} is probably subordinate to Ti^{4+} , since the reverse situation can be expected only when almost all the iron is present as Fe^{2+} (Goldschmidt 1954, p. 412). This probability, together with the small magnetic moment of Ti^{3+} , indicates that the effect of titanium is negligible compared with that of iron and manganese. This has been confirmed in practice by measurement of a titanian amphibole (kaersutite) containing 5.64 per cent TiO_2 , the measured susceptibility being in good agreement with the susceptibility calculated on the basis of iron and manganese only (Table 5, No. 2).

Chromium is generally a very minor or trace constituent of common ferromagnesian minerals, excepting pyroxenes from certain ultramafic rock types. Thus Ross, Foster and Myers (1954) reported up to 2.43 per cent Cr_2O_3 in chromian diopside and up to 0.94 per cent Cr_2O_3 in enstatite. The relatively high magnetic moment of Cr^{3+} (Table 1), together with the low concentrations of Fe and Mn in these minerals would make it necessary to take the effect of Cr into consideration.

Small amounts of nickel occur in some magnesian olivines, the largest quantity of NiO reported by Ross, Foster and Myers (1954) being 0.50 per cent. However, Ni^{2+} has such a low magnetic moment (Table 1) and NiO is so subordinate to FeO, that the effect of the nickel should be insignificant. Thus, the analyzed magnesian olivine of Nagata, Yukutake and Uyeda (1957), referred to earlier, shows good agreement between the measured susceptibility and that calculated on the basis of iron and manganese only, despite its NiO content of 0.41 per cent.

NEW MEASUREMENTS ON BIOTITES AND AMPHIBOLES

The specific magnetic susceptibilities of some Australian biotites and amphiboles have been measured at room temperature with a Frantz isodynamic separator using the method and calibration of McAndrew (1957). The critical currents—the currents at which equal flow down each channel of the chute takes place at a particular transverse slope—were obtained by graphing weight against current. Weighing is preferable to visual estimation and enables the use of smaller samples; about 0.5 gm. was found to be satisfactory. The measurements were made at a corrected transverse slope of 20° , the currents required being less than 0.90 amp.

Compressed air was used for cleaning the chute and hopper between runs on different samples, since the correction to the transverse slope reading may change when the chute is removed.

Ferromagnetic impurities were removed as thoroughly as possible from the samples to be measured, by a hand magnet and by a pass through the Frantz separator at low current. The samples were sized fractions of $-52+100$ mesh (B.S.S.), except for biotite No. 11 and amphibole No. 2, of which the $-52+200$ fractions were used. The $-52+100$ fraction was favoured because the instrument was calibrated with material of this size range (McAndrew 1957, p. 64).

Biotites

The eleven biotites measured are from Precambrian metamorphic rocks of the Broken Hill district, New South Wales, which have been studied in recent years by the Mineragraphic Investigations section of the C.S.I.R.O., Melbourne. Five of these were separated by the late Dr. A. B. Edwards and analyzed in 1954. The other six were separated by the writer during a study of the banded albite-rich rocks of the district (Vernon 1961). The large range in iron content shown by these biotites makes them especially suitable for the present study.

The chemical composition and optical properties of the biotites are shown in Table 2, and the structural formulae calculated on the basis of 12 (O, OH, F) atoms are shown in Table 3. The analyzed concentrates were at least 99.5 per cent pure, quartz being the most common impurity, although chlorite is present in No. 6 and garnet in No. 11. Biotite No. 11 contains 1.93 per cent CaO, which cannot be ascribed to impurities of apatite, since P_2O_5 is only 0.01 per cent, or of garnet, since grain-counts of the concentrate revealed only 0.4 per cent by weight of a garnet containing about 3 per cent CaO. The calcium therefore appears to be accommodated in the X group of the biotite structure (Table 3).

The measured specific susceptibilities are given in Table 4, together

TABLE 2. CHEMICAL COMPOSITION OF ELEVEN BIOTITES FROM THE BROKEN HILL DISTRICT, N.S.W.

	1	2	3	4	5	6	7	8	9	10	11
SiO ₂	39.51	39.94	38.76	38.28	35.89	35.84	39.00	38.26	35.53	35.16	33.21
Al ₂ O ₃	19.66	18.10	19.07	19.69	17.72	15.47	21.80	16.73	15.79	17.50	17.26
FeO	1.66	3.86	3.74	4.21	6.05	3.45	1.60	3.59	7.77	1.86	3.59
MgO	5.71	4.80	9.46	12.10	11.25	15.25	15.94	19.00	16.57	23.95	26.60
MnO	20.74	18.20	17.02	13.64	12.31	12.12	6.08	7.00	7.52	5.07	3.24
CaO	0.09	0.07	0.07	0.12	0.73	0.36	0.18	0.39	0.49	0.43	1.93
Na ₂ O	0.90	0.18	0.66	0.34	0.50	0.26	0.24	0.42	0.30	0.14	0.10
K ₂ O	8.20	9.46	8.36	9.48	8.26	8.74	7.20	7.62	8.74	8.66	7.20
H ₂ O	1.37	2.38	1.92	1.37	3.97	2.38	4.04	3.37	2.10	2.43	3.21
H ₂ O ⁺	0.20	0.12	0.05	0.05	0.45	0.07	0.22	0.19	0.10	0.00	0.10
CO ₂	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TO ₂	0.73	1.39	0.91	0.56	1.59	4.80	3.06	2.70	4.80	3.27	2.86
PO ₂	0.03	0.08	0.02	0.04	tr.	0.96	0.37	0.19	0.16	0.70	0.01
MnQ	tr.	0.08	tr.	tr.	tr.	0.12	0.12	0.19	0.18	0.37	0.39
Li ₂ O	2.24	2.00	0.00	1.02	0.00	—	—	—	0.00	—	0.00
F	101.04	100.67	100.84	100.90	100.62	99.82	99.74	99.83	100.05	99.54	99.74
Total	0.94	0.84	0.34	0.43	0.75	—	—	—	—	—	—
Less 0 for F	100.10	99.83	100.50	100.47	99.87	—	—	—	—	—	—
Corrected Total	1.596	1.603	1.610	1.620	1.631	1.638	1.650	1.659	1.659	1.665	1.671
$\frac{Y}{X}$	Very pale fawn (almost colourless)	Very pale fawn (almost colourless)	Pale greenish fawn	Pale greenish fawn	Straw	Greyish straw	Straw	Straw	Straw	Straw	Straw
Y=Z	Light orange brown	Light fox brown	Olive green	Olive green	Dark brown	Dark greyish brown	Rich red-brown	Very deep brown (opaque)	Very deep brown (almost opaque)	Very deep brown (almost opaque)	Very deep red-brown (almost opaque)

- From biotite seam in albite-rich rock, adit of Big Hill Mine, Thackaringa area, Analyst, P. J. Sinnott.
- From albite-rock, Pyrite Hill, east limb of Shurring Vale Syncline, Analyst, P. J. Sinnott.
- From biotite seam in albite-rich rock, northern part of main body of albite-rich rock, Thackaringa area, Analyst, P. J. Sinnott.
- From biotite seam, same locality as 3. Analyst, P. J. Sinnott.
- From biotite mass about 1 mile north-west of Big Hill, Thackaringa area, Analyst, P. J. Sinnott.
- From biotite-magnetite-garnet schist, about 3,200 ft. north-east of entrance gate to Aerodrome, Broken Hill, Analyst, G. C. Carlos.
- From biotite-magnetite-garnet schist, about 5 miles north-west of Broken Hill, Analyst, G. C. Carlos.
- From Anglen Gneiss (Almeida), Pyrite Hill, east limb of Stirling Vale Syncline, Analyst, P. J. Sinnott.
- From quartz-olite schist, Broken Hill, north side of Ansett A.N.A. hangar, Broken Hill Aerodrome, Analyst, G. C. Carlos.
- From hanging wall Gneiss, D.D.H. 834, 494 ft.—496 ft., Cosgrove section, north of De Bayat Fault, North Broken Hill Mine, Analyst, G. C. Carlos.
- From quartz-olite schist, Broken Hill, north side of Ansett A.N.A. hangar, Broken Hill Aerodrome, Analyst, P. J. Sinnott.
- From quartz-olite schist, Broken Hill, north side of Ansett A.N.A. hangar, Broken Hill Aerodrome, Analyst, P. J. Sinnott.
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- From quartz-olite schist, Broken Hill, north side of Ansett A.N.A. hangar, Broken Hill Aerodrome, Analyst, P. J. Sinnott.

TABLE 3. STRUCTURAL FORMULAE OF ELEVEN BROKEN HILL BIOTITES*

	1	2	3	4	5	6	7	8	9	10	11	
(Z) {	Si	2.83	2.87	2.84	2.88	2.65	2.78	2.86	2.92	2.78	2.79	2.66
	Al	1.17	1.13	1.16	1.12	1.35	1.22	1.14	1.08	1.22	1.21	1.34
(Y) {	Al	0.49	0.41	0.49	0.62	0.19	0.19	0.74	0.43	0.23	0.43	0.29
	Ti	0.05	0.08	0.06	0.03	0.09	0.28	0.17	0.16	0.28	0.24	0.17
	Fe'''	0.09	0.21	0.21	0.24	0.34	0.20	0.09	0.21	0.46	0.11	0.22
	Fe''	0.34	0.29	0.58	0.76	0.69	0.99	0.98	1.21	1.08	1.59	1.78
	Mg	2.21	1.95	1.86	1.53	1.35	1.40	0.66	0.80	0.88	0.60	0.39
	Mn	—	0.01	—	—	0.01	0.01	0.01	0.01	0.01	0.03	0.03
(X) {	Ca†	0.01	—	—	0.01	0.06	—	—	—	0.02	—	0.16
	Na	0.12	0.03	0.09	0.05	0.07	0.04	0.03	0.06	0.06	0.02	0.02
	K	0.75	0.87	0.78	0.91	0.78	0.86	0.67	0.74	0.87	0.88	0.73
{	OH	0.65	1.14	0.94	0.69	1.95	1.23	1.98	1.72	1.10	1.29	1.71
	F	0.51	0.46	0.19	0.24	0.42	—	—	—	—	—	—
Z	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	
Y	3.18	2.95	3.20	3.18	2.67	3.07	2.65	2.82	2.94	3.00	2.88	
X	0.88	0.90	0.87	0.97	0.91	0.90	0.70	0.80	0.95	0.90	0.91	
(OH, F)	1.16	1.60	1.13	0.93	2.37	1.23	1.98	1.72	1.10	1.29	1.71	

* Ideal formula $XY_3Z_4O_{10}(OH, F)_2$. Nos. 1–11 as for Table 2.

† P_2O_5 and equivalent CaO to make apatite, subtracted from analysis.

with susceptibilities calculated from the concentrations of paramagnetic ions, showing there is general agreement between measured and calculated values.

Amphiboles

The measured and calculated specific susceptibilities of seven amphiboles from various Australian localities are given in Table 5 (Nos. 1–7), together with partial compositions and ionic concentrations of paramagnetic ions. Full compositions are not given, because they are, or shortly will be, incorporated in readily obtainable publications. For six of the amphiboles, χ_m falls either between χ_1 and χ_2 or very close to one of these values. In addition, a tremolite from Mount Fitton, South Australia was found to have a very low susceptibility (1.2×10^{-6} e.m.u./gm.), as expected.

Additional data have been obtained from a paper by Rosenzweig and Watson (1954), who measured the currents at which equal separation occurred on a Frantz separator at a transverse slope of 30° , for eight

TABLE 4. COMPOSITION AND MAGNETIC SUSCEPTIBILITY OF ELEVEN BIOTITES

Specimen Number*	Iron and manganese content (weight per cent)				Concentration of magnetic ions (gm. ions/gm. of biotite)			Calculated specific susceptibility (e.m.u./gm.)		Measured specific susceptibility (e.m.u./gm.)
	FeO	Fe ₂ O ₃	MnO	Total Fe (as FeO) + MnO	10 ⁴ z (for Fe ²⁺)	10 ⁴ y (for Fe ³⁺)	10 ⁴ z (for Mn ²⁺)	10 ⁶ χ ₁	10 ⁶ χ ₂	10 ⁶ χ _m
1	5.71	1.66	trace	7.20	7.93	2.08	—	12.3	13.3	12.0
2	4.81	3.86	0.08	8.36	6.68	4.83	0.11	15.1	15.9	12.0
3	9.46	3.74	trace	12.83	13.14	4.68	—	22.2	23.9	21.7
4	12.10	4.21	trace	15.89	16.81	5.26	—	27.4	29.5	27.4
5	11.25	6.05	0.11	16.81	15.63	7.56	0.15	29.6	31.6	28.5
6	15.25	3.45	0.12	18.48	21.18	4.31	0.17	31.3	34.0	34.0
7	15.94	1.60	0.12	17.50	22.14	2.00	0.17	29.1	31.9	35.6
8	19.00	3.59	0.19	22.42	26.39	4.49	0.27	37.8	41.2	43.2
9	16.57	7.77	0.18	23.74	23.01	9.71	0.25	41.5	44.4	39.1
10	23.95	1.86	0.37	25.99	33.26	2.33	0.52	43.1	47.3	48.0
11	26.60	3.59	0.39	30.22	36.94	4.49	0.55	50.6	55.3	50.7

* Nos. 1-11 as for Table 2.

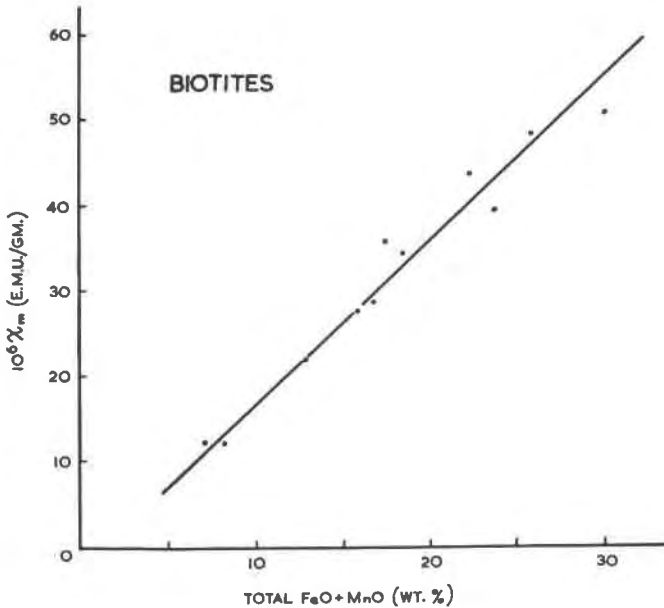


FIG. 1. Relation between χ_m and total Fe (as FeO)+MnO for the biotites of Table 4, which may be expressed: $C=1.15+0.53 \times 10^6 \chi_m$, where C is weight per cent total Fe (as FeO)+MnO. The correlation coefficient (corrected for the small number of cases) is +0.979, and the residual variance is 4.21 per cent.

TABLE 5. COMPOSITION AND MAGNETIC SUSCEPTIBILITY OF FIFTEEN AMPHIBOLES

Specimen Number*	Iron and manganese content (weight per cent)				Concentration of magnetic ions (gm. ions/gm. of amphibole)			Calculated specific susceptibility (e.m.u./gm.)		Measured specific susceptibility (e.m.u./gm.)
	FeO	Fe ₂ O ₃	MnO	Total Fe (as FeO) + MnO	10 ⁴ x (for Fe ²⁺)	10 ⁴ y (for Fe ³⁺)	10 ⁴ z (for Mn ²⁺)	10 ⁶ χ ₁	10 ⁶ χ ₂	10 χ _m
1	6.82	0.30	0.57	7.66	9.47	0.38	0.80	12.8	14.0	13.4
2	10.92	1.75	0.09	12.59	15.17	2.19	0.13	21.1	23.1	22.6
3	10.24	2.35	0.36	12.72	14.22	2.94	0.51	21.7	23.5	24.3
4	14.41	1.47	0.23	15.96	20.01	1.84	0.32	26.6	29.1	29.8
5	14.32	0.92	0.24	15.39	19.89	1.15	0.34	25.4	28.0	31.1
6	16.84	1.89	0.84	19.38	23.39	2.36	1.18	32.5	35.5	35.6
7	19.92	9.10	0.63	28.74	27.67	11.38	0.89	50.3	53.9	53.7
8	8.89	1.11	0.13	10.02	12.35	1.39	0.18	16.7	18.3	17.1
9	9.12	2.33	0.23	11.45	12.67	2.91	0.23	19.5	21.2	18.5
10	10.14	3.90	0.24	13.89	14.08	4.88	0.34	24.1	25.9	22.8
11	11.07	2.87	0.40	14.05	15.38	3.59	0.56	24.1	26.0	25.0
12	10.50	4.42	0.28	14.76	14.58	5.53	0.39	25.7	27.6	23.5
13	12.61	2.87	0.22	15.41	17.51	3.59	0.31	26.2	28.4	25.8
14	12.58	5.04	0.30	17.42	17.47	6.30	0.42	30.3	32.5	29.6
15	14.69	5.33	0.43	19.92	20.40	6.66	0.61	34.5	37.1	33.0

- * 1. Pale brown hornblende (pargasite) from hornblende-pyroxene-granulite, Peak Hill, Broken Hill district, New South Wales (Edwards 1958, p. 7).
 2. Titaniferous amphibole (kaersutite) from alkali olivine-basalt, near Spring Mountain, W. of Glen Innes, northern N.S.W.
 3. Green hornblende from amphibolite, 8000 ft. N.E. of Duchess railway station, northwestern Queensland. Analyst: P. J. Sinnott.
 4. Brown hornblende from hornblende gabbro, 2 miles W. of Beaconsfield, northern Tasmania (Baker 1959, p. 27).
 5. Green hornblende (contaminated with several per cent of blue-green and brown hornblende) from amphibolite, Broken Hill Basin, N.S.W. (Edwards 1958, p. 7).
 6. Cummingtonite from same rock as No. 3. Analyst: P. J. Sinnott.
 7. Deep green hornblende, from area of massive hornblende, W. of Silver Rock Tank, Broken Hill district, N.S.W. (Edwards 1958, p. 7).
 8-15. Amphiboles from Pennsylvania and Delaware investigated by Rosenzweig and Watson (1954). The host-rocks are: metagabbro (8, 9), hornblende gneiss (10), metagabbro (11), hornblende-biotite schist (12), norite (13), pegmatoid schlieren in gneiss (14), hornblende gneiss (15).

amphiboles from hornblende gneisses and gabbroic rocks occurring in Pennsylvania and Delaware. The writer has calculated χ_m , χ_1 , and χ_2 (Table 5, Nos. 8-15) from the Frantz settings and analyses of these amphiboles, using the calibration of McAndrew (1957). The discrepancies are larger than for Nos. 1-7, χ_m generally being lower than χ_1 . This consistent discrepancy undoubtedly arises from the writer's use of the calibration of another instrument, along with the fact that the transverse slope as read on the Frantz separator scale is not necessarily the actual slope of the chute (McAndrew 1957, p. 64).

RELATION BETWEEN SPECIFIC SUSCEPTIBILITY AND IRON-
MANGANESE CONTENT

The variation of χ_m with weight per cent total Fe (as FeO) + MnO for the biotites of Table 4, the amphiboles of Table 5, the clinopyroxenes of Chevallier and Mathieu (1958), and the orthopyroxenes of Akimoto, Hôrai and Boku (1958) are shown in Figs. 1, 2, 3, and 4, respectively. Conventionally, composition is shown as the abscissa in determinative charts of this kind. However, since the object of such charts is to permit

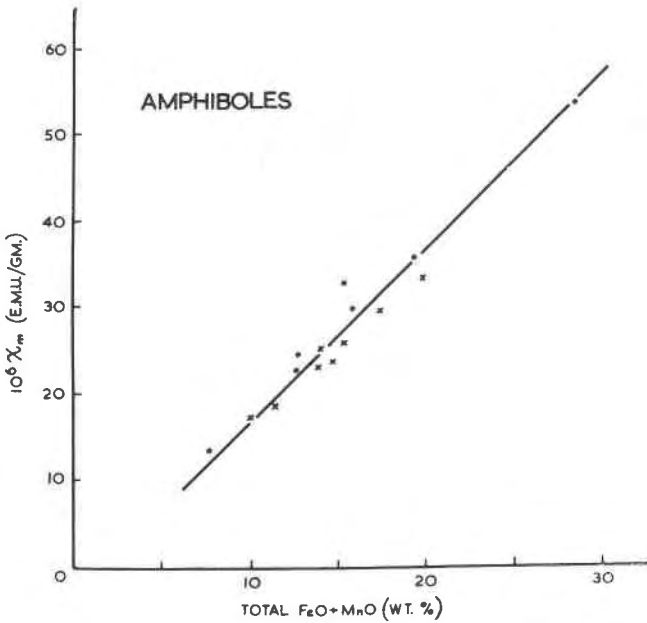


FIG. 2. Relation between χ_m and total Fe (as FeO) + MnO for the amphiboles of Table 5. Dots represent amphiboles 1-7; crosses represent amphiboles 8-15. The linear relationship is: $C = 1.63 + 0.50 \times 10^6 \chi_m$, where C is total Fe (as FeO) + MnO. The residual variance is 5.06 per cent, and r (corrected) is +0.974.

estimation of composition from the physical property, χ_m has been made the independent variable, and the calculated lines of regression are those of composition on χ_m . The biotites, amphiboles and clinopyroxenes show high degrees of positive linear correlation, but the relationship for the orthopyroxenes is more variable. This may be related to the much larger discrepancies between measured and calculated susceptibilities shown by these orthopyroxenes.

The olivines of Nagata, Yukutake and Uyeda (1957) have not been

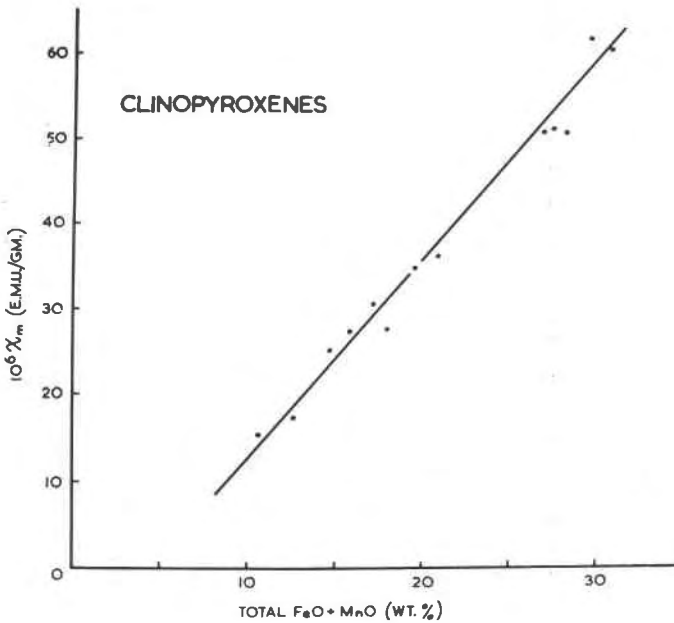


FIG. 3. Relation between χ_m and total Fe (as FeO)+MnO for the clinopyroxenes of Chevallier and Mathieu (1958), which may be expressed: $C = 4.43 + 0.44 \times 10^6 \chi_m$, where C is total Fe (as FeO)+MnO. The residual variance is 2.04 per cent, and r (corrected) is +0.990.

plotted in this way, since more chemical data are required. Nagata, Yukutake and Uyeda (1957) plotted molecular susceptibility at room temperature against mol. per cent Fa. However, their most iron-rich olivine (knebelite) is rich in manganese, which is not taken into account in their chart. Removal of this point would make a better linear fit for the other, more common varieties.

CONCLUSIONS

Specific magnetic susceptibilities given in this and previously published papers give a good measure of total iron plus manganese content for the biotites, amphiboles and clinopyroxenes. For common varieties of these minerals, in which MnO is low, specific susceptibility effectively indicates total iron. The published results for orthopyroxenes and olivines also strongly suggest a direct relationship between susceptibility and iron-manganese content. However, the relationship for the orthopyroxenes is as yet not well defined, and more chemically analyzed samples will need to be measured before the exact relationship for olivines is known.

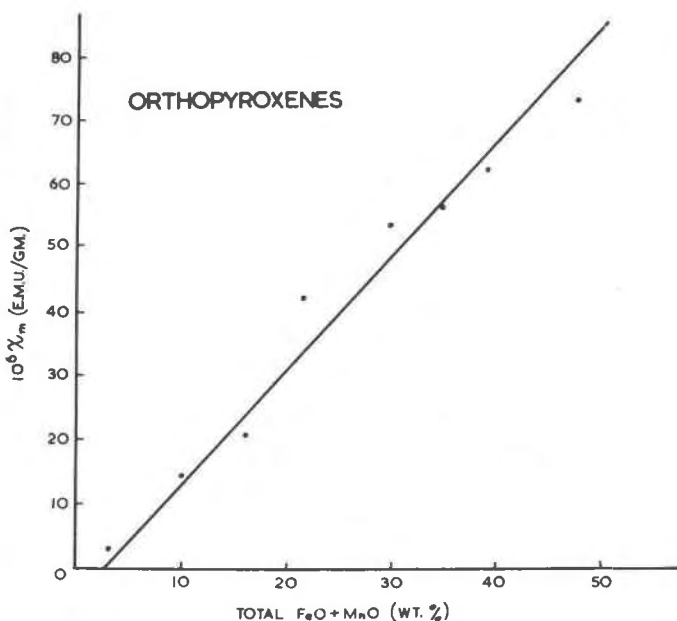


FIG. 4. Relation between χ_m and total Fe (as FeO)+MnO for the orthopyroxenes of Akimoto, Hôrai and Boku (1958), which may be expressed: $C = 2.53 + 0.57 \times 10^6 \chi_m$, where C is total Fe (as FeO)+MnO. The linear regression accounts for only slightly more than half the total variance of C, so the chart has little determinative value, though it does indicate a general increase of χ_m with increasing total Fe (as FeO)+MnO.

Estimation of iron content from magnetic susceptibility is not complicated by the presence of titanium, unlike estimation from refractive indices, e.g. in biotites (Hall 1941).

Measurements made with the Frantz isodynamic separator appear to be satisfactory, showing that specific susceptibility can be added to the properties of ferromagnesian minerals commonly employed in petrological studies.

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