The Magnetic Properties of Varieties of Magnetite

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XXII. *The Magnetic Properties of Varieties of Magnetite.*

By ERNEST WILSON and E. F. HERROUN.

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1. *Introductory.*

MAGNETITE is so widely distributed throughout the earth's crust, and is so interesting in many ways, that no apology is needed for describing experiments which throw further light upon the part played by this wonderful substance in influencing the magnetic properties of the rocks of which it is a constituent, or with which it comes in contact. Much work has already been done:—Abt* examined the retentivity of short and long bars and compared it with that of glass hard steel. Weiss† has made probably the most exhaustive experiments on magnetite crystals. He showed that the substance has a curve of magnetisation resembling that of iron, and that the susceptibility along the different crystallographic axes was different, although tending towards the same limiting value as the force increased. E. Holm‡ has shown that in the case of Swedish magnetite the susceptibility varies with the magnetising force. The transformation temperature of magnetite has been examined by Barton and Williams,§ Curie|| and Allan¶.

The primary object of the present communication is to examine the magnetic properties of the various forms in which magnetite is found, ranging from the crystal itself to such substances as magnetite-calcite. Specimens from different parts of the world have been chosen, and the authors have been fortunate in that they have had placed at their disposal the collection of magnetite of the Geological Survey and Museum, numbering about 30 varieties. Prof. H. Louis has supplied certain specimens which he himself has collected, and in addition there are others. The chosen specimens represent widely different characteristics. Variations in magnetic properties as exhibited by crystallised, compact or massive specimens and detached particles, and also the effects of heating have been studied.

* "Wied. Ann." Vol. LII., pp. 749-757, 1894.

† "L'Ecl. electr." Vol. VII., p. 487, 1896. Vol. VIII., p. 56, 105, 1896. "Jour de Phys." 3rd Series, Vol. V., p. 435, 1896.

‡ "Jern-Kontorets Annaler," New Series, 1903, p. 363.

§ B. A. Report, Edinburgh, 1892. "The Electrician," Vol. XXIX., p. 432, 1892.

|| "An de Chim. et de Phys." Vol. V., Series 7, p. 289, 1895.

¶ Physical Society "Journal," Vol XIX., May, 1904.

2. *Instrumentation.*

The type of instrument which has been used for the work described in the present communication, involving as it does the ring method with ballistic galvanometer, was chosen for the following reasons. When the susceptibility is of the order 0.15 or over, the uncertainty of the correction for "end effect" with short specimens becomes serious if the magnetometer is employed. It was not possible to obtain specimens in all cases of greater length than about 4 cm., and an area of cross-section of about 1 sq. cm. was about the practical minimum. An instrument which has formed the subject of a communication to the Royal Society* in connection with recent work carried out for the Geological Survey and Museum begins to have limitations when used to measure susceptibilities of the order 0.15 or over. The instrument actually used is capable of measuring both susceptibilities of a high order and also those so small that the magnetometer can be brought in with accuracy as a check. It has thus been possible to obtain experimental evidence of the accuracy obtainable.

3. *The Ring Magnet.*

The electromagnet which has been used in the experiments for the measurement of susceptibility consists of a ring built up of stampings of stalloy, having an air-gap 2 cm. wide with its sides parallel to a diameter. The specimen is 4 cm. long and has a square section 1 cm. across each side, and is inserted in rectangular holes cut in the pole-pieces of the electromagnet, thus bridging across the air space. Each of the stampings of stalloy has a thickness of 0.32 cm. and they are nine in number. The internal diameter is 7.62 cm. (3 in.) and the external diameter 12.7 cm. (5 in.) The three central stampings, with two additional thin ones to make up the required thickness, are provided with the square recesses above mentioned, and are permanently fixed to the lower three stampings. The upper three stampings are fixed together and can be lifted so as to allow of the insertion of the test piece and then dropped into position, thus closing in the test piece which is then surrounded by the metal to a depth of 1 cm. at each end. Surrounding the ring is a coil of insulated copper wire which is wound on a circular former sufficiently wide near the air-

* "Phil. Trans." R. S., A. Vol. 219 (Appendix), 1919.

gap, to allow of the tilting of the three upper stampings, and also provided with a gap sufficiently wide to allow of the insertion of the specimen. Counting from innermost to outermost the turns of wire, which is wound in three layers, are 146, 140, 126, making a total of 412. The copper wire has a diameter of 0.813 mm., insulated with a double layer of cotton, and the resistance of the winding is 2.25 ohms.

Calculations have been made to find the relation between the current in amperes (C) in the winding and the magnetising force H , produced in the gap. The total line integral of the magnetising force due to the current C is connected with the magnetic induction when no specimen is in the gap by the following equation:—

$$\frac{4\pi nC}{10} = \frac{l_1 I}{A} + l_2 f\left(\frac{\nu I}{A_2}\right),*$$

where n is the number of turns on the ring=412,

l_1 is the length of the air-space=2 cm.,

A is the area of the air-space,

l_2 is the mean length of the lines of magnetic force in the ring=33.9 cm.

A_2 is the area of cross-section of the ring.

ν is the ratio of the induction in the ring to the induction in the air-space.

f is the function defining the magnetising force in terms of the induction in the case of stalloy.

Assuming that the effective area of the air-space is equal to the area of cross-section of the ring, and that the leakage coefficient $\nu=1$, indicating that there is no leakage of the lines of magnetic force, the above equation becomes

$$\frac{4\pi nC}{10} = l_1 \cdot B_1 + l_2 f(B_2),$$

where B_1 and B_2 are the magnetic inductions in the air-space, and ring respectively. In Table I. the function f which defines the magnetising force H_2 in terms of the magnetic induction B_2 is given in the first two columns.† From the assumptions made it follows that $B_1=B_2=H_1$ the magnetic force in the air-space. From the values of H_2 and the mean length, l_2 , the line integral of the magnetising force in the stalloy has been calculated. For the air-space the values of $l_1 H_1=l_1 B_2$ have

* "Phil. Trans." R.S. 1886, p. 331.

† Roy. Soc. "Proc." A. Vol. LXXX., p. 548, 1908.

been found, and by addition the total line integral, which is equal to $\frac{4\pi nC}{10}$ has been obtained. In this manner the relation between the current C and the magnetic force H , has been

TABLE I.—*Stalloy Magnet Ring.*

Curve of induction for stalloy.		$l_2 H_2$ $l_2 = 33.9$ cm. stalloy.	No specimen in air-gap.		Amperes C	Ratio of force in gap to amperes H_1/C	Ratio $\frac{l_2 H_2}{l_1 H_1 + l_2 H_2}$ per cent.
H_2	B_2		$\frac{l_1 H_1}{l_1 = 2}$ cm	$l_1 H_1 + l_2 H_2$			
			Air.				
0.000474	0.1267	0.0161	0.253	0.269	0.00052	244	5.99
0.000739	0.1918	0.0251	0.384	0.409	0.00079	243	6.14
0.00267	0.674	0.0905	1.35	1.44	0.00278	235	6.28
0.00357	0.937	0.121	1.87	1.99	0.00385	243	6.08
0.00695	1.870	0.236	3.74	3.98	0.00769	243	5.93
0.01286	3.60	0.436	7.20	7.64	0.0148	243	5.71
0.0251	8.25	0.851	16.5	17.35	0.0335	246	4.91
0.0358	13.02	1.214	26.0	27.21	0.0526	247	4.46
0.080	38.0	2.710	76.0	78.71	0.152	250	3.44
0.157	94.1	5.32	188	193.3	0.374	252	2.76
0.245	171.0	8.31	342	350.3	0.677	253	2.37
0.312	269.0	10.6	538	548.6	1.06	254	1.93
0.420	629.0	14.2	1,260	1,274	2.46	256	1.11
0.506	1,063	17.2	2,130	2,147	4.15	256	0.80
0.677	2,245	23.0	4,490	4,513	8.72	257	0.51
1.354	6,050	45.9	12,100	12,146	23.5	257	0.38
2.130	8,200	72.2	16,400	16,472	31.8	258	0.44
3.26	9,810	110.5	19,600	19,710	38.1	258	0.56
5.71	11,500	194	23,000	23,190	44.8	257	0.836
16.20	13,480	549	27,000	27,550	53.2	253	1.99

$\frac{4\pi nC}{10} = l_1 B_1 + l_2 f(B_2)$. Assumes area of air-space and stalloy are equal and that there is no leakage.

$l_1 = 2$ cm. $l_2 = 11.43\pi - 2 = 35.9 - 2 = 33.9$ cm. $n = 412$ No. 21 S.W.G. copper wire

calculated, and their ratio should be a constant if the line integral in the stalloy were vanishingly small. The figures show that the ratio is a maximum when the magnetising force is such that the permeability in the stalloy is a maximum, and that it does not seriously deviate from a constant value.

4. Experimental Details.

In the earlier stages of the investigation a galvanometer of the needle type was employed, but owing to the disturbances set up by the ring magnet (even when remote from the galvanometer) and to other local causes, an instrument of the moving-coil type was substituted. This galvanometer had a resistance of 25.7 ohms and a periodic time of 5.95 seconds,

and its sensibility was such that a steady deflection of one scale division at a distance of one metre was produced by a current of 3.77×10^{-8} ampere.

An exploring coil consisting of 120 turns of fine silk-covered copper wire was wound on a square former of thin card, which allowed of the specimen being inserted with considerable closeness of fit. The coil was connected to the galvanometer, and an adjustable resistance was included in the circuit to limit the deflections. Deflections were obtained on reversal of the magnetising current C , firstly with the exploring coil supported on a wooden core having the same dimensions as the actual specimens, and secondly when the wooden core was replaced by the test piece itself. The ratio of the deflections, allowing for the alteration in the resistance when necessary, and correcting for the air space occupied by the card former, has been taken to be the permeability; and hence the susceptibility has been obtained.

The assumption above made as to the ratio of the deflections is justified on the following considerations. Firstly, an exploration of the magnetic field in the gap showed that it was substantially constant over the whole area. It was in fact about 5 per cent. weaker in the region near the edge of the air space than at the centre. On reversing a current of 1.02 ampere in the magnetising coil the value of H , the magnetic force in the air space was found to be 248 C.G.S. units. Thus the ratio of this force to the current is 244, and Table I. indicates a ratio of about 254. It does not appear necessary to give other illustrative cases, and it is sufficient to notice that a fair agreement can be obtained. As a further test the susceptibilities of certain specimens were obtained by the magnetometer, and when placed in the ring magnet substantial agreement was found. For example, a piece of Manchurian magnetite, obtained by permission from specimen 9,500 in the collection of the Geological Survey and Museum, when tested in the magnetometer with a force of 53 C.G.S. units, had a susceptibility of 0.118. When tested in the ring magnet, the susceptibility was found to vary from 0.11 to 0.12 when the magnetic force had about the same value.

This method of inserting the test piece in a magnetic circuit as above described and testing it for susceptibility, obviously depends to some extent for its accuracy upon the closeness of fit with the pole-pieces, and the authors do not wish to claim for the method a greater accuracy in the result than

TABLE II.

H _{max} .	Traver- sella Piedmont, No. 712.	New York.	Hoy Tor, Devon.	Peartyn, Corn- wall, 242A.	Peartyn, Corn- wall, 242c.	Ar- kansas, U.S.A., No. 1.	Ar- kansas, U.S.A., No. 2.	Alten- fjord, Norway.	Lake Champlain New York.	South Man- churia, No. 9,500.	Mag- netite- calcite, Aran.	Man- gane- se Steel.
1.25	1.68	...	...	...	...	...	...	...	...	...	...	...
3.75	2.06	0.566	...	...	...	...	...	...	...	...	...	...
10.5	2.47	0.892	0.52	0.235	0.1515	0.139	0.138	0.133	0.119	0.085	0.104	0.226
17.0	3.07	1.251	0.668	0.246	0.155	0.179	0.163	0.147	0.147	0.105	0.108	0.272
27.2	3.09	1.44	0.741	0.265	0.162	0.186	0.169	0.171	0.151	0.105	0.117	0.272
56.0	2.74	1.37	0.892	0.279	0.183	0.207	0.179	0.169	0.147	0.107	0.118	0.311
84.0	2.44	1.25	0.805	0.341	0.204	...	0.195	0.217	0.151	0.122	0.1275	0.387
112.0	2.09	1.108	0.738	0.382	0.222	0.236	0.205	0.248	0.148	0.117	0.119	0.428
175.0	1.51	0.89	...	...	...	...	...	...	...	...	...	...
203.0	1.37	0.816	0.55	0.487	0.27	0.313	0.277	0.27	0.131	0.124	0.118	0.527
257.0	1.14	0.702	0.469	0.492	0.293	0.352	0.33	0.259	0.127	0.116	0.109	0.535
388.0	0.89	...	0.354	0.437	0.30	...	0.327	0.218	0.113	0.106	0.099	0.433
525.0	0.60	0.43	0.287	0.371	0.273	0.305	0.292	0.188	0.093	0.097	0.085	0.376
756.0	0.45	...	...	0.208	...	0.268	...	...	...	0.09	...	0.310

TABLE III.

No.	Description	Sp. gr. of speci-men.	$H_{\max}$	De- flection on re- versal θ .	De- flection on break θ_r .	$\theta/2 - \theta_1$ 0/2 per cent.	Mag- netising force at max. succep- tibility.	Max. succep- tibility.	Coer- cive force for $H_{\max.} = 525$.	$B_{\max.}$ for $H = 525$.	Ergs per cycle per cb. cm. for $H_{\max.} = 525$.	Intensity of magnetisation retained after being in a field of 18,000 C.G.S. units.	
												After 3 hours.	After 6 days.
712	Traversella (crystal)	5.06	567	260	114	12.3	22.5	3.12	12.2	4,495	23,200	2.81	1.84
...	New York...	4.86	569	325	135	16.7	31.5	1.46	16.8	3,270	14,000	7.45	6.75
...	Hey Tor, Devon...	4.30	525	235	99	15.4	49.0	0.90	23.8	2,528	15,300	7.6	2.3
242A	Penryn, Cornwall...	4.56	525	260	80	38.5	236.0	0.49	110.0	2,680	81,600	60.6	57.8
242C	Penryn, Cornwall...	4.59	525	227	76	32.8	368.0	0.31	95.0	2,300	58,000	48.2	48.0
1	Arkansas ...	4.68	525	247	74	39.8	298.0	0.363	150.0	2,580	89,600	69.7	66.3
2	Arkansas ...	4.74	525	238	72	39.5	315.0	0.348	150.0	2,450	81,800	68.7	65.2
...	Altenfjord, Norway	4.02	525	239	94	21.0	175.0	0.272	65.0	1,760	13,900	27.8	24.7
...	Lake Champlain, New York	4.14	525	221	102	7.3	43.8	0.172	15.2	1,112	720	3.08	2.34
9,500	S. Manchuria	3.40	525	349	160	8.2	140.0	0.127	31.0	1,132	1,660	6.12	5.35
W30	Magnetite-calcite, Aran	3.40	525	288	141	2.1	85.0	0.129	12.1	1,080	151	1.89	1.14
...	Manganese steel	7.68	788	221	70	36.4	228.0	0.54	108.0	3,012	68,800	62.0	49.7

that to which it is entitled. It is difficult with rock specimens to obtain intimate contact at all points between them and the metal, as they are easily broken or chipped. The procedure was first to cut the test piece from the hand specimen—and in this connection we wish to express our thanks to Dr. W. G. Gordon, Head of the Geological Department of King's College, London, for allowing us to make use of his rock-cutting apparatus—and then to grind down the specimen with carborundum powder in water until it just entered the gaps in the pole-pieces. In this manner very fair contact was made and the

FIG. 1.—K-H CURVES FOR MAGNETITE.

tests show that the results are reliable. Specimens, on being taken out and replaced, when either turned over or turned end to end, gave very closely the same result.

The results obtained are tabulated in Tables II. and III., and illustrated by curves in Figs. 1 and 2. Table II. gives the susceptibility (κ) for all the specimens examined, together with the values of the magnetising force H in C.G.S. units. Table III. gives the specific gravity of the bars actually used in the ring magnet. It also gives information as to the retentivity, maximum susceptibility and the force at which it

occurs, coercive force, dissipation of energy due to the reversal of the magnetising force, and finally the variation of the intensity of magnetisation retained after an application of a force of about 18,000 C.G.S. units obtained by placing the specimen between the coned pole pieces of a powerful electro-magnet. The specimens will now be considered in detail, roughly in the order of their maximum susceptibility.

FIG. 2.—K-H CURVES FOR MAGNETITE

Traversella, Piedmont. No. 712, G. S. & M.

The specimen bar was cut (by permission of the Director of the Geological Survey and Museum) at right angles to the principal axis of a large dodecahedral crystal. This material was extremely brittle with almost vitreous fracture exhibiting a bright semi-metallic lustre. Its specific gravity, 5.06 is the highest of any of the various magnetites examined. It also furnishes the highest figure for susceptibility giving a maximum of 3.12 for a force of $H=22.5$. Its coercive force 12.2 is the smallest of any of the specimens of true magnetite and in consequence its retained magnetism is the lowest.

The above value for the susceptibility is considerably below the results obtained by P. Weiss, as exhibited in his curves

of magnetisation. This may possibly be attributed to a difference in the nature of the specimen.

Small fragments after heating in air to about $1,000^{\circ}\text{C}$. appeared to undergo no material alteration in magnetic properties, but the authors have not been able to carry out experiments on a sufficiently large test-bar to decide this point fully.

The values obtained using magnetising forces ranging from 1.25 to 756 C.G.S. units will be found in column 2 of Table II., and the curve showing the variation of K with H in Fig. 1.

New York State. (Exact locality not known.).

This is a very uniform material of specific gravity 4.86, very hard and compact with no indication of any cleavage planes. Its fracture is irregular, bright with numerous glistening points and semi-metallic lustre. It is characterised by a high maximum susceptibility 1.46 and small coercive force, coming in these respects second to the Traversella crystal. As will be seen from the table its permanent magnetisation only amounted to $I=7.45$, notwithstanding that while in the field of the electromagnet, the value of B in this material is very high.

After having been raised to a temperature of about $1,000^{\circ}\text{C}$. and allowed to regain atmospheric temperature, the magnetic susceptibility for a given force ($H=53$) was found to be unchanged; and there was no measurable alteration in its specific gravity.

Hey Tor, Bovey Tracey, Devon.

A specimen belonging to Prof. H. Louis, of Newcastle-on-Tyne, exhibited great irregularity in the distribution of magnetite. The latter consisted of minute crystals mixed with earthy material. Its fracture was dull and earthy with some sparkling points due to the small crystals. The density varied considerably in different parts from 3.89 to 4.30.

Its susceptibility was as high as 0.9 for forces of about 50 units, and its coercive force relatively small (23.8). The magnetite which it contains belongs therefore to the class having high susceptibility and but little retentivity, the maximum value of I being only 7.6 three hours after having been placed in a field of 18,000 units; this fell in four days to only 2.3. Heated to about $1,000^{\circ}\text{C}$. in air and allowed to cool, it showed no tendency to disintegrate and only lost 0.38 per cent.

of its weight, which loss may have been water in its pores, and it showed no change in specific gravity. But although there was very little alteration in appearance or weight its susceptibility for a given force was found to have decreased 11.4 per cent., and its residual magnetism to a somewhat greater extent. This furnishes an example of a magnetite that distinctly diminishes in susceptibility and coercive force after being strongly heated and is an interesting contrast to the next variety.

Penryn, Cornwall. No. 242 G. S. & M.

The specific gravity of different pieces from the same specimen varied from 4.50 to 4.65. It is a hard, strong material with a dull fracture and contains small inclusions of a red-brown softer substance, but otherwise compact. This softer substance was found to consist mainly of ferric oxide and ferrous carbonate. When tested in its natural state, its maximum susceptibility had the value of 0.31 for a force of 368 C.G.S. units. After heating to about 1,000°C. the susceptibility rose to 0.492 for $H=235$. In order to exclude any possibility of reduction by furnace gases specimens were heated in an electric furnace in air for 10 minutes to a temperature of 1,000°C. and showed the same marked increase in susceptibility, the maximum of which occurred at a smaller force than for the unheated specimens.

As this kind of magnetite was the only one amongst the many varieties examined by the authors which showed a marked increase in susceptibility, it was thought probable that this might be due to the conversion of some of the ferrous carbonate and ferric oxide existing, as above mentioned, as small inclusions throughout its mass, into magnetic oxide on heating to 1,000°C.

This view was rendered the more probable from consideration of the result of an experiment in which a specimen of this magnetite was heated to about 520°C. for 100 hours to ascertain if prolonged heating to just below the temperature at which magnetite loses its magnetic properties would produce any change. It was found that not only did it fail to show any appreciable increase, but when afterwards it was heated for one hour to 650°C., it showed no further change. Finally, heating it to 1,000°C. in the electric furnace produced no increase in its susceptibility, which after all these various

heatings showed no increase, but had actually diminished about 5 per cent.

As a control two small pieces from the same portion of rock were heated rapidly to 1,000°C. and kept at that temperature for five minutes and allowed to cool in air; they both showed a marked increase in susceptibility of over 60 per cent. The density was slightly raised by this heating process from 4.57 to 4.60, and in a previous case from 4.55 before heating to 4.63 after heating. In these two cases the percentage loss in weight was 1.14 per cent. and 1.07 per cent. respectively. The fact that prolonged heating in air to a temperature of 520°C. prevented the increase in susceptibility may probably be due to the oxidation and decomposition of the ferrous carbonate yielding ferric oxide, while when rapidly raised to 1,000°C. it was transformed (in conjunction with some of the ferric oxide mixed with it) into magnetic oxide (Fe_3O_4). Both the loss of weight and increase of density as well as the great increase in susceptibility receive explanation by this theory, with which the changes of colour and appearance also agree.

G. Folgheraiter* examined the effect of heating on various volcanic rocks and found in general an increase in magnetic properties especially in the amount of retained magnetism, and considered this to be due partly to the conversion of non-magnetic into magnetic substances, and partly to the orientation of magnetite crystals. Brunhes and David† have noticed that the flow of hot lava over clay transformed it into a brick-like material that is magnetic.

With a view to testing the effect of heat upon known material a mixture of kaolin with an equal weight of finely powdered native ferrous carbonate (Chalybite) was made into a stiff clay with water, moulded into bars, dried and finally heated gradually to a temperature of about 900°C.

A rectangular bar 4 cm. $\times$ 1 cm. $\times$ 1 cm. after being baked was used in the ring magnet and gave a value for K of 0.0224 in a field of 284 units, and 0.021 for $H=178$. Before heating the value of K was too small to measure by this method, but by the use of the magnetic balance it was found to have a susceptibility of 0.000218. Hence its susceptibility was increased about 100-fold by heating to a bright red heat.

In one experiment with a cut bar of this Penryn magnetite the specimen was heated to 1,000°C. and allowed to cool in a

* "Rend. Acc. dei Lincei," Jan. 4 and Feb. 4, 1895.

† "Comptes Rend." 137, p. 975, 1903.

vertical position standing on a piece of asbestos cardboard. When cold its lower end was found to be, as was to be expected, a *N*-seeking pole, and the intensity of magnetisation it had acquired under the influence of the vertical component of the earth's field was found to be 1.48 C.G.S. units. Experiments conducted on the same bar before heating showed that it required a force of 95 units to impart nearly the same (1.40) intensity of permanent magnetism. Evidently during the cooling process the susceptibility reaches a high value and the magnetism then induced is retained permanently after cooling.

This fact may have an important bearing on the question of the intensity of magnetisation of beds of magnetite in a natural state.

The values for the susceptibility with different magnetising forces for this kind of magnetite are given in columns 5 and 6 of Table II., *A* being the substance after having been heated to 1,000°C. and *C* being obtained from a bar in its natural state, unheated.

Arkansas (I. & II.).

Two specimens obtained from independent sources (one of the specimens was kindly given to the authors by Dr. Gordon) showed a marked similarity in properties. It consists of a hard compact material with irregular cleavage planes and almost vitreous fracture in some directions while exhibiting a silky lustre in others.

The specimen bar called "Arkansas I." had a specific gravity of 4.68 and "Arkansas II." varied from 4.70 to 4.82, the actual bar experimented with having a specific gravity of 4.74. Both samples showed distinct permanent magnetisation when received and portions of a specimen exhibited a high intensity of magnetisation (*I.*) of the order of 30 C.G.S. units. As will be seen in Table III. the highest sub-permanent magnetisation exhibited by one of the 4-cm. bars amounted to 69.7, but this was after exposure to a field of about 18,000 units. After being magnetised in a field of 806 the intensity of retained magnetism was 44.5 immediately after removal, and fell to 43.1 in 12 hours. It is evident that a magnetisation of even 30 C.G.S. units for *I* can only be caused either by a field strength enormously exceeding the earth's force, or by intense local forces such as lightning flashes, as suggested by Pockels* in connection with the magnetisation exhibited by

* "Annal. Phys. Chem.," 63, pp. 195-201, 1897.

specimens of basalt, or by molecular changes accompanying heating and cooling under pressures with which we are at present unacquainted.

The coercive force exhibited by both specimens is the same, viz., 150 units for $H_{\max} = 525$, and is higher than for any other magnetite the authors have examined.

A specimen heated to $1,000^{\circ}\text{C}$. showed a minute increase in weight after regaining room temperature, but only to the extent of 0.08 per cent. ; no change in the density was detected. The susceptibility, which for the specimen was 0.202 for a field of 52 C.G.S. units before heating, was found after heating to have increased for the same force to 0.286, being an increase of 41.6 per cent. Its residual magnetism was also greater, but its coercive force was very materially reduced, so that the retained magnetism was less than half that exhibited by other portions of the same unheated specimen after being in an intense field. While the after effects of heating in this case are to increase K and diminish coercive force (as with hard steel), in the case of Penryn magnetite "242" both K and coercive force were permanently increased.

The dissipation of energy in ergs per cycle per cubic centimetre reaches the high figure of 89,600 for this material for $H_{\max} = 525$ units, and is the highest recorded in Table III. column 12.

Altenfjord, Norway.

A specimen of magnetite from the above locality was kindly placed at the disposal of the authors by Prof. H. Louis. It was found to be essentially an aggregate of magnetite and felspar having an irregular but crystalline fracture. Its density varied from 4.0 to 4.2 following the variation in proportion of magnetite to felspar.

Its susceptibility for different magnetising forces will be found in column 9 of Table II. Its maximum susceptibility (Table III.) reached the comparatively low value of 0.272 for a force of 175 C.G.S. units.

Heating for 10 minutes to a temperature of about $1,000^{\circ}\text{C}$. had no subsequent effect on its weight or specific gravity; the susceptibility of a specimen after this treatment was found to be slightly increased, its value for a given force rising from 0.227 to 0.239, or about 5.3 per cent. increase. The retained magnetisation, however, was found to be substantially the same before and after heating, so that there was no appreciable change in its retentivity.

Lake Champlain, New York State.

One of the varieties of magnetite from this locality was supplied to the authors by Prof. H. Louis and was found to be an aggregate of magnetite and iron pyrites; it had an irregular glistening fracture in which the pyrites could be easily detected by its lighter colour. Its density was found to vary very considerably, 4.10 to 4.62 being the limits for different parts of the same hand specimen, the denser parts being visibly richer in magnetite.

Its magnetic values are recorded in Tables II. and III., and its curve ($K-H$) in Fig. 2. Its low maximum in susceptibility 0.172 is no doubt due to the variable admixture of pyrites.

The effect of heating this substance to 1,000°C. is to disintegrate it to a greater or less extent, owing to the decomposition of the pyrites. There is a slight loss in weight and decrease in density, the actual figures for the latter in one case being 4.62 before heating and 4.60 after. The susceptibility for the same force was found in a specimen which did not disintegrate to any extent to be diminished about 7.5 per cent., the retained magnetisation being similarly reduced.

South Manchuria. No. 9500 G. S. & M.

A specimen of magnetite from the above locality was obtained by permission of the Geological Survey and Museum from their collection. It is essentially a schist having a slaty cleavage in which the laminated structure is easily detected. Owing to its comparative poorness in magnetite its specific gravity is the lowest yet dealt with, being only 3.40, and remarkably constant in different parts of the same specimen. For the same reason its susceptibility is the lowest the authors have found for any rock which can be described as "Magnetite." Its susceptibility, which is 0.085 for $H=10.5$, passes through a maximum of 0.127 for $H=140$, falling again to 0.09 for $H=756$. As the $K-H$ curve in Fig. 2 shows, its susceptibility is more nearly a constant than any other variety examined. In this connection the Authors have not yet found in any specimen of magnetite so low a value of the susceptibility (0.016) as that given by Allan.* This, however, may be due to the low value of the magnetising force which he employed.

Heating to 1,000°C. in an electric furnace caused a small loss of weight amounting to 0.07 per cent., probably due to

* Loc. cit.

loss of water ; the specific gravity was subsequently found to be unchanged and its magnetic properties were not materially affected. There was a very slight increase in susceptibility, but so small that it falls almost within the limits of experimental error.

Its magnetic values are recorded in column 11 of Table II. and also in Table III.

Magnetite Calcite. (W. 30) Aran, Wales.

A small specimen of the above rock having been supplied to the authors by the Geological Survey and Museum, it has been included in this series, although strictly speaking it can hardly be designated as a Magnetite. It consists of a matrix of calcite in which are disseminated irregularly numerous very small crystals or crystalline grains of magnetite. In spite of the small proportion of magnetite which it contains (a proportion so variable in different parts that an analysis would give only a vague indication) its susceptibility reaches a slightly higher figure than the Manchurian magnetite last mentioned. The small residual and retained magnetisations, the small coercive force—substantially the same as that of the Traversella crystal—all point to the conclusion that what magnetite is present is in the form of the pure crystal.

From the nature of the matrix—calcium carbonate—it is impossible to investigate the effect of very high temperatures on this material.

A 13 per cent. Alloy of Manganese and Iron.

A rectangular specimen of this alloy was cut from a ring which was given to one of the authors some years ago by Sir R. A. Hadfield, F.R.S. It was maintained at a temperature of about 530°C. for 100 hours, with a consequent increase in the susceptibility on return to atmospheric temperature. The results of the experiment with this specimen are interesting as they exhibit a similarity to those of some of the specimens of magnetite. In particular, it is interesting to note the relatively high value of the coercive force and considerable retained magnetisation in this annealed manganese steel, as it is commonly asserted without reference to its condition that manganese steel is almost devoid of these properties.

SUMMARY.

The magnetic properties of certain varieties of magnetite as exhibited by crystallised, compact or massive specimens and detached particles have been examined. In each case the susceptibility has been found to vary with the magnitude of the magnetising force after the manner of iron, the relative variation being much more pronounced in the case of those specimens having the higher susceptibility. The maximum susceptibility in the specimens examined occurs at a force ranging from 13 C.G.S. units in the crystal to 368, its magnitude varying from 3.12 to 0.127 C.G.S. units.

The effect of heating has been greatly to increase susceptibility in some cases and in others a negative effect has been produced. In the case of a specimen of Penryn magnetite, the large increase in the susceptibility was traced to the conversion of ferrous-carbonate and ferric-oxide into magnetite.

As bearing upon the intensity of magnetisation of magnetite in a natural state, it may be mentioned this specimen of Cornish magnetite acquired an intensity of 1.48 C.G.S. units on cooling in the earth's field from 1,000°C., whereas in the cold before heating such an intensity required a field of 95 C.G.S. units to impart the same degree of retained magnetisation.

Very high susceptibility in magnetite is never associated with high coercive force or retained magnetisation, the greatest values for the latter exhibited by specimens having an intermediate value of susceptibility of the order of 0.3 or 0.4. Lower susceptibility may be associated with high coercive force, but naturally the retained magnetisation is not very great, owing to the lower maximum of induced magnetisation.

DISCUSSION.

Prof. LOUIS said that he was not competent to discuss the physical problems involved, but was intensely interested in the practical applications of the work done by the authors of the Paper. He congratulated them on having taken a step towards the solution of the very puzzling questions why magnetite differed so widely from all other minerals in its magnetic properties, and why there were such wide differences in these properties between different specimens of magnetite. The most magnetic magnetite that he had ever met with was in one of the higher peaks of the great mass of magnetite that formed the huge hill of Kirunavaara, where the mineral was so strongly magnetic that on breaking it with a hammer the small chips remained adhering to the face of the mineral by magnetic attraction. The suggestion of the authors that such effects might be due to lightning seemed to fit this case very well. He was not at all surprised at the results obtained from the Penryn mineral: this evidently contained spathic ore, and if this latter were heated even to 500°C. without access of air, the carbonate of iron would be converted into a substance approximating to Fe_3O_4 in composition, and this "artificial magnetite" was strongly magnetic; the presence of Fe_2O_3 was not at all necessary for this action to take place. Carbonate of iron is so easily converted into "artificial magnetite" that this method is quite often used on the large scale for separating spathic ore from such minerals as blende; he (Prof. Louis) had found that in this way it was possible to obtain a certain amount of concentration even in the case of such unpromising material as Cleveland ironstone. He assumed that the Lake Champlain specimen must have been heated with free access of air, so that the pyrites present had been completely oxidised, because pyrites

heated in the absence of an oxidising agent became converted into a sulphide approximating to pyrrhotite in composition, which was fairly magnetic. He hoped that the authors would investigate this particular point and determine under what conditions of heating pyrites gave the most strongly magnetic product. The change began at a comparatively low temperature, and the speaker had met with difficulties in the satisfactory concentration of certain iron ores owing to this effect. The high magnetic susceptibility of the specimens from Traversella was especially interesting, because it was to the ore from this locality—a mixture of magnetite and copper pyrites—that electro-magnetic separation on a commercial scale was first applied. It is quite possible that the high susceptibility was due to these specimens having been cut from an idiomorphic crystal. He sincerely hoped that the authors would continue their extremely interesting researches upon the magnetic properties of minerals.

Prof. A. H. Cox communicated the following: I regret that I am unable to be present at the reading of Prof. Ernest Wilson's Paper, but, although I am not qualified to speak upon the purely physical aspect of Prof. Wilson's researches, I should like to be allowed to congratulate him upon the success of his work upon the measurements of small susceptibilities. The designing of a portable instrument that will measure such small susceptibilities marks an advance which will greatly facilitate work on certain problems, the solution of which appears likely to lead to results of great economic importance. The results so far obtained from the investigation of local magnetic disturbances in certain selected areas, have shed a new light upon the underground structure in one of the most important of our concealed coalfields, and encourage the hope that we have in our hands an additional method of attacking the problem of underground geology. The determinations made by Prof. Wilson gave the necessary clue as to which rocks were responsible for causing the magnetic disturbances in those districts. One of the difficulties encountered during the investigation into the origin of the disturbances was the fact that no susceptibility determinations of such weakly magnetic materials as the rocks involved could be carried out during the course of the outdoor work. Before specimens could be tested magnetically a certain amount of preparation was necessary, and they had all to be sent to Prof. Wilson's laboratory. Now, as the result of his researches, it should be possible to carry out susceptibility determinations at the points where the rocks actually occur, thus effecting a great saving of time, and removing one of the great difficulties in further investigations into the relationship between magnetic disturbance and geological structure. If, as seems probable, such investigations lead to results of national importance, the value of Prof. Wilson's work becomes more than of purely scientific import.

Dr. D. OWEN said that the authors' experiments gave interesting information as to the nature of the differences of magnetic quality usually found between various specimens of lodestone. The experimental method, though not quite free from sources of error, appeared to allow of a degree of accuracy satisfactory for the purpose; it would, however, be of interest to have the figure of accuracy stated. In interpreting Figs. 1 and 2 it should be noted that the values of the magnetising force must not be taken too literally. Since many of the specimens were composed of small crystals of magnetite, it is evident that demagnetising forces of uncertain extent must have been present. The fact that the specimen of Traversella showed a much lower value of susceptibility than that obtained by P. Weiss is not surprising, in view of the fact that even good samples of the mineral contain a large amount of impurity, of the order of some 10 per cent. The somewhat low density (5.06) of the specimen supports this view. The explanation proposed by the authors to account for the rise of susceptibility of some specimens after subjection to a rise of temperature appeared reasonable. The ferrosomagnetic oxide thereby produced is, like magnetite, distinctly ferro-magnetic.

Comparative figures of susceptibility of the artificial and crystalline varieties would be of interest in this connection. In regard to the problem of the high intensity of magnetisation possessed by some specimens of magnetite, have the authors any evidence as to whether a crystal heated above the critical temperature and allowed to cool in a zero magnetic field would show any sign of magnetisation?

Mr. C. R. DARLING said that magnetic separators were used for other minerals than magnetite, and it was of interest in connection with the effect of heating obtained by the authors, that in some of these cases heating rapidly to 1,000°C. improved the ease with which separation was accomplished.

Mr. POWER said he had been engaged on the magnetic separation of tin and wolfram ores, and had experienced trouble on account of the magnetic product containing about 33 per cent. of tin. On separating this the iron content was found to be very low. Heating to a high temperature did not alter the magnetic properties. Various pickling processes were tried, but, although a little of the iron was got out, there was still enough left to render the tin magnetic. With regard to the pyrites in the Champlain magnetite, if pyrites is heated slowly it is not nearly so magnetic on cooling as when heated rapidly.

Prof. FORTESCUE asked what steel was used in the experiment shown on the table.

Mr. F. E. SMITH said the authors in their formula took the air-gap as being the space between the jaws of the magnet poles. What effect had the recesses in the pole-pieces on the results? With regard to the magnetic properties of manganese steel, it was well known that this steel had a permeability of approximately unity in weak fields. Employed on the bridge of a ship, for instance, it would be without effect on the compass. If, however, it was subjected to a strong field it became quite magnetic.

Mr. J. GUILD asked if it would not be possible to make observations of the permeability of the specimens at other than air temperatures. The temperature permeability curves would probably show at a glance the answers to many of the points raised in connection with heat treatment, in addition probably to revealing other points of importance.

Prof. E. F. HERROUN, replying to some of the chemical questions that had been raised in the discussion, said that he agreed with Prof. H. Louis that if the Penryn magnetite, or the mixture of kaolin and ferrous carbonate, had been heated out of contact with air, a still greater increase in susceptibility would have resulted; but that, as all the other specimens had been heated in air, it was a fair and uniform treatment. He also agreed that by heating the magnetite containing pyrites in air some of the latter would be oxidised instead of merely losing some of its combined sulphur. In reply to another question, he said that ferrous or ferric oxides resulting from the decomposition of iron compounds, although paramagnetic, were extremely feeble in comparison with the ferro-magnetic magnetite, Fe_3O_4 : crystals of the latter may be formed artificially by using a fusible matrix. Being asked by the President for his distinction between para and ferro magnetic bodies, he said he regarded a ferro-magnetic substance as one which showed a definite K-H curve of susceptibility, while the latter was practically a straight line with paramagnetic bodies for all fields, and its value very small.

Prof. E. WILSON said that Prof. Louis had mentioned how highly magnetic was the magnetite on some of the summits of the well-known Swedish deposit, which had been estimated to contain about 200 million tons. If this magnetisation was due to lightning flashes, it would be interesting to know if the magnetite below the surface was definitely magnetic. In an experiment with bars of Arkansas magnetite and glass-hard steel of the same size, the authors showed at the meeting that, although the bar of magnetite had evidently the greater moment (by its action on a compass needle) its portative force was smaller. In answer to a question by one of

the speakers, he stated that the steel used was a carbon tool steel. He explained that the portative force depends upon the square of the magnetic induction, and that the lower permeability of the magnetite counteracted the higher moment to the extent of making its portative force smaller. Mr. F. E. Smith had remarked upon the value of the permeability of manganese steel being unity, or very nearly so, in weak fields, and that the effect of the earth's field on this steel would not appreciably affect a compass needle. Prof. Wilson said that the value of the permeability of 13 per cent. manganese steel usually quoted was 1.27, and that this figure was obtained by the late Dr. John Hopkinson in the case of a ring. If the surface of the ring is ground away, he had found the permeability of the interior portion had a value of 1.005 in a field of about 100 C.G.S. units. After prolonged heating to 530°C., its permeability may be raised to 8 or 10, or even higher. In regard to Mr. Smith's remark on the influence of the recess in the pole-faces, it is stated in the Paper that the force varies 5 per cent. between the centre of the gap and the edge of the pole-face. If the instrument had to be used for the measurement of very high permeabilities, the closeness of fit would be serious, as is well known in connection with permeameters; but the permeabilities met with in magnetite are not of such a high order as to render the method of test invalid.