MAGNETIC SEPARATIONS IN PETROGRAPHY

Gordon C. Mathisrud, *University of Minnesota, Minneapolis, Minnesota.*

Abstract

Clean magnetic separations of mixtures of rock minerals are uncommon for several reasons including two that are important, but these have not received much attention. First, as most magnetic separators are designed, they attract larger grains more strongly than smaller grains; apparently even a difference in size of 0.03 mm. is great enough to cause trouble. Second, the different members of several isomorphous series are differently attracted by strong magnets; the series from Mg to Fe compounds shows a wide range in attractability. Magnets can probably be designed to reduce or eliminate the effect of grain-size, but one can hardly expect zoned crystals which have a range of compositions to be cleanly separated from other minerals.

The Problem

In some work done by the writer for Professor F. F. Grout at the University of Minnesota using two forms of magnetic separators, the results seemed to be peculiar in ways not clearly presented in the texts on petrographic methods. Commonly[1] an attempt is made to separate a crushed rock—a mixture of minerals—into four products of differing magnetic properties. First, a weak magnet extracts magnetite; then a stronger magnet extracts moderately magnetic minerals; and finally a very powerful magnet separates the remainder into weakly magnetic and tailings products. Some adjustments are commonly possible to adapt the magnets to the minerals at hand. In a series of separates, the grains of a single mineral are often distributed through a series of concentrates rather than in one. This has been a common experience, and is reported in a number of papers.

It soon appeared in the work at Minnesota that there was a relation between the size of grains and the apparent magnetic attraction. The separates of a certain mafic mineral had regularly smaller sizes in the less magnetic separates. On reference to the texts it was found that there is commonly a warning that the material used should be well sized, but evidently screening between two adjoining sieves in the common series, 60, 80, 100 and 200 mesh, does not give well-sized material. Tests were undertaken to see whether operating methods could be improved and to see how widely certain minerals varied in their magnetic behavior.

Principles of Magnetism

In a magnetic field, any mineral becomes magnetized by induction of

[1] Hallimond, A. F., An electromagnetic separator for mineral powders: *Mineral. Mag.*, **22**, 377–381 (1930).

two poles within each crystal. No mineral is known to be truly non-magnetic, but the magnetic strength and the character of the induced poles vary greatly with different minerals.

According to the familiar law by which magnetic poles of like character repel each other while poles of unlike character attract, minerals may be classified as diamagnetic, paramagnetic, or ferromagnetic. This classification also depends on the pole strengths of the minerals. Diamagnetic minerals are weakly repelled from the field, paramagnetic minerals are weakly attracted to the field, and the ferromagnetics are strongly attracted. Since the only abundant ferromagnetic mineral is magnetite, petrographic separations require splitting the paramagnetic minerals into three groups. These are called "moderately magnetic," "weakly magnetic," and "tailings" products. Diamagnetic minerals also fall into the tailings and for that reason will be largely omitted from the following discussions.

The magnetic strength of the induced poles, or the degree of magnetization, varies in different minerals according to a property called permeability. Permeability is numerically equal to the ratio of total magnetic strength (induced magnetism plus magnetic field) to the strength of the magnetizing field.[2]

The permeabilities of most ferromagnetic materials are of the order of several hundred, but those of paramagnetic minerals range only slightly higher than one. Since diamagnetic minerals produce an induced field opposite in direction to that of the magnetizing field, their permeabilities are always less than one. The amount of induced magnetism depends also on the strength of the magnetizing field and on the volume of the mineral particle.

Some minerals are known to be magnetically anisotropic, probably due to the crystal structure, though not much work has been done on this property. An example is pyrrhotite, which is practically non-magnetic when the hexagonal axis is oriented in the direction of the magnetizing field, but is ferromagnetic in perpendicular directions.[3]

When removed from the influence of a magnetic field, the ferromagnetic minerals retain an appreciable part of their magnetism. This part is called permanent magnetism. Probably even paramagnetic minerals also have a small amount of permanent magnetism. Hayes[4] showed that hematite

[2] A related property is called susceptibility in many texts. Susceptibility is equal to the ratio of induced magnetic strength to the strength of the magnetic field. Thus the two terms are related but not mathematically equal. The term permeability will be chieflv used in this paper.

[3] Coeterier, F., *Naturwissenschaften*, **21**, 251–252 (1933).

[4] Hayes, E. T., Ferromagnetic properties of hematite; *U. S. B. M.*, R. I. **3570**. 25 (June 1941).

retains a small amount of magnetism after being subjected to a very strong field. Although hematite is usually considered to be paramagnetic because of its very low permeability, he states that permanent magnetism is proof of ferromagnetism and suggests that the definition of ferromagnetism be based on this and related phenomena.

A uniform magnetic field is one which is everywhere constant in strength. It usually is part of a larger non-uniform field. A mineral grain in a uniform field will rotate until its poles are oriented with the field, but

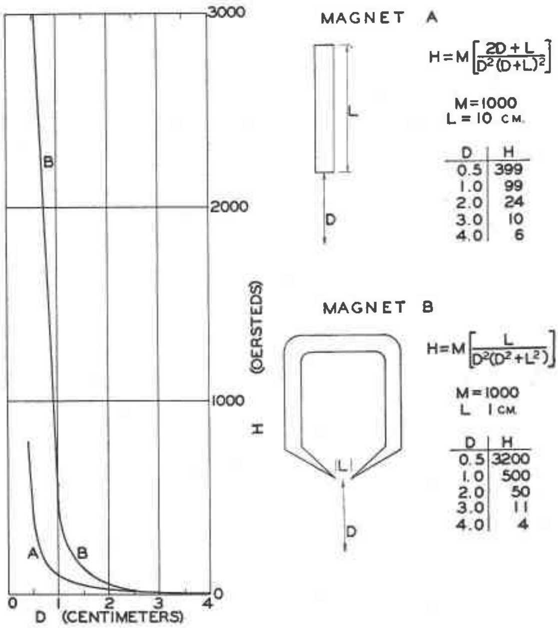

FIG. 1. Comparison of strengths (H) of two magnetic fields at varying distances from the magnets' poles.

the grain will not move to any other part of the field, because the attraction of one pole is offset by the repulsion of the other. This is illustrated by the compass in the earth's field.

Obviously, then, a non-uniform field is required to lift minerals up out of a mixture, but it must have great strength to lift a paramagnetic mineral. Such fields are produced by employing electromagnets having iron cores of various shapes. Figure 1 shows the relative field strengths of two common types of electromagnets at points at different distances from their poles. The magnets have the same magnetic moment but are different in that their poles are different distances apart and have different orientation with respect to the points considered. They show that magnet B gives a much stronger field at short distances from the magnet and also that the strength decreases extremely fast in this region. It should be emphasized that these curves are calculated from ideal point poles and do not show the considerable effect of the shape of the pole pieces.

We know that the force tending to lift a mineral grain from a table to a magnet is greater as the following variables are greater: permeability of the mineral; strength of the magnetizing field at the grain; volume of the grain; and gradient of the magnetizing field at the grain. Also that the force of gravity, tending to hold the grain to the table, is greater as the volume of the grain is greater. From these facts it can be realized that if the product of field strength and field gradient can be made a constant, the force upward will depend on permeability, and a mineral of certain permeability can be rather cleanly separated from others of different permeability regardless of the sizes of grain of ordinary crushed rocks. But, if that product is not constant, tall grains which reach up into the stronger field considerably farther than short grains on the same table, may be picked up, and the short ones will be left even though both sizes have the same permeability. This condition is illustrated by Fig. 2. Stoner[5] gives the mathematical analysis of these forces and also gives many references which may be helpful in further study of magnetism.

Ideally it is possible to screen the crushed rock into a large number of uniform sizes and change the current for each size so as to get a separation that depends on the nature of the mineral, but in practice this involves too many sizes and too many separations. A powder passing some screen, about 60 to 100 mesh, and washed to remove the fines (by settling 1 inch per minute, for 2 to 5 minutes) gives a range of sizes that is still too great for good separation.

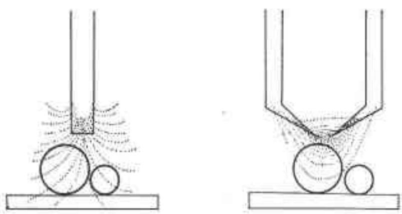

FIG. 2. Field strength and gradient are both greater at the surfaces of the larger grains.

It is possible to design pole pieces in shapes which modify the field to give approximate uniformity in the product of strength and gradient. One pole piece should have a plane surface and the other should be part of a cylinder or sphere. The uniform product of strength and gradient will occur on the axis between them. The dimensions are best determined by

[5] Stoner, E. C., Magnetism and Matter; 35–37, Methuen and Company, *London* (**1934**).

trial and error though Fereday[6] did calculate the proper shapes rather closely using theoretical considerations. Stoner[7] describes a magnet for which the force was closely uniform along the axis for a distance of 0.8 cm. Fereday's and Stoner's magnets were used for susceptibility or permeability determinations but the one made by Frantz[8] was used for separating crushed slag and probably also embodied this principle. A disadvantage is that a magnet of this type strong enough to lift paramagnetic minerals would probably be more expensive than other types.

Magnetic Separators

A classification of magnetic separators according to the magnetic phenomena involved has been made by Dean and Davis.[9] In petrographic work the only type widely used is that based on attraction of particles to a pole of a permanent magnet or a direct current electromagnet. A single electromagnet with adjustable pole pieces may serve as a separator. The minerals are separated from a mixture by placing in a folded paper and moving the paper with a vertical rotary motion between the poles, shifting the paper along until the attracted grains are carried near the end of the paper and can be tipped or brushed out from the rest. More complex separators for petrographic work may be illustrated by that described by Hallimond.[10] In both these instruments, to extract a paramagnetic mineral from a mixture, the powder must be placed within about $\frac{1}{2}$ cm. from the poles where the gradient (Fig. 1) is very large. Consequently they are faulty because they separate large grains from small grains.

Previous Tests of Minerals

Several petrographers[11] have reported some data on the magnetic properties of minerals. Holmes in 1921 concluded that it is not possible to make a detailed list of minerals in order of permeability or attractabil-

[6] Fereday, R. A., *Proc. Physical Soc., London;* **42,** 251 (1930); **43,** 383 (1931); **46,** 214 (1934).

[7] Stoner, *op. cit.*, p. 80,

[8] Dean, R. S., *Annual Report of the Metallurgical Division,* Fiscal Year 1936; *U. S. B. M.*, R. I. **3331,** 45 (Jan. 1937).

[9] Dean, R. S., and Davis, C. W., Magnetic concentration of ores: *A. I. M. E.*, Milling Volume, **112,** 509–537 (1934). Also, Dean, R. S., and Davis, C. W., Magnetic Separation of Minerals: *U. S. Bureau of Mines*, Bull. **425** (1941).

[10] *Op. cit.* See also an improved Hallimond type mentioned by Evans, *Mineral. Mag.*, **25,** 474–478 (1939).

[11] Holmes, A. (From Delesse) Petrographic Methods and Calculations, 86 (**1921**).

Crane, W. R., Investigation of magnetic fields with reference to ore concentration; *Trans. A. I. M. E.*, **31,** 405–446 (1901).

International Critical Tables; VI, p. 364, McGraw-Hill Book Co. (**1929**).

Tyndall, J., Diamagnetism and Magne-crystallic Action, D. Appleton and Co. (**1888**).

ity however measured that would be generally applicable. It seems likely that this is so because most rock minerals are isomorphous mixtures and there is commonly a wide range in composition, not only in different crystals but even in different zones in a single crystal. While the differences in data recorded by the several authors can be so explained, there is little to indicate how far the magnetic attractability ranges in a single series. Tyndall[12] showed that pure lime carbonate is diamagnetic but that an isomorphous mixture of lime and iron carbonate is paramagnetic. Probably the minerals in which Fe and Mg compounds form isomorphous series will show a wide range. Several have been selected to test the ideas stated in this discussion, but the work has not been done with pole pieces properly designed to give only differences in permeability.

Experiments

A separator modelled after that of Hallimond[13] was used with constant adjustment of pole pieces and platform. The feed was satisfactory only for grains smaller than 40 mesh.

Experiment 1. A two inch fragment taken from one side of a six inch crystal of black tourmaline was crushed and screened to yield five grades. None of the material was picked up by the first magnet but the other two magnets attracted some from each size grade and left some in the tailings from each (Table 1 and Fig. 3).

Table 1. Magnetic Separation of Crushed Tourmaline

Mesh	Caught by 2nd magnet	By 3rd magnet	Tailings
30–40	80.0%	17.5%	2.5%
40–60	70.0	25.0	5.0
60–80	52.5	35.0	12.5
80–100	49.0	38.0	13.0
100–200	17.0	58.0	25.0

Clearly the supposedly uniform mineral is distributed in three separates regardless of size, and clearly the coarser grade sizes are more largely concentrated by the weaker magnet, and the finer sizes more largely by the strongest magnet and in the tailings.[14]

[12] Tyndall, *op. cit.*
[13] Hallimond, *op. cit.*
[14] Dean, R. S., and Davis, C. W., *op. cit.*

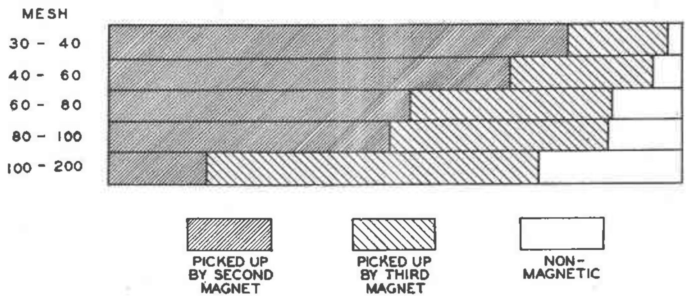

FIG. 3. Magnetic separation of crushed tourmaline.

The next experiment (Experiment 2, below) confirmed the conclusions of this in every way but only two sizes were used, 40–60, and 80–100. In each case the finer material seemed to be less magnetic, but the differences should probably be attributed wholly to the design of the magnets. Data for these minerals are not here listed as they simply support the conclusion drawn from tourmaline.

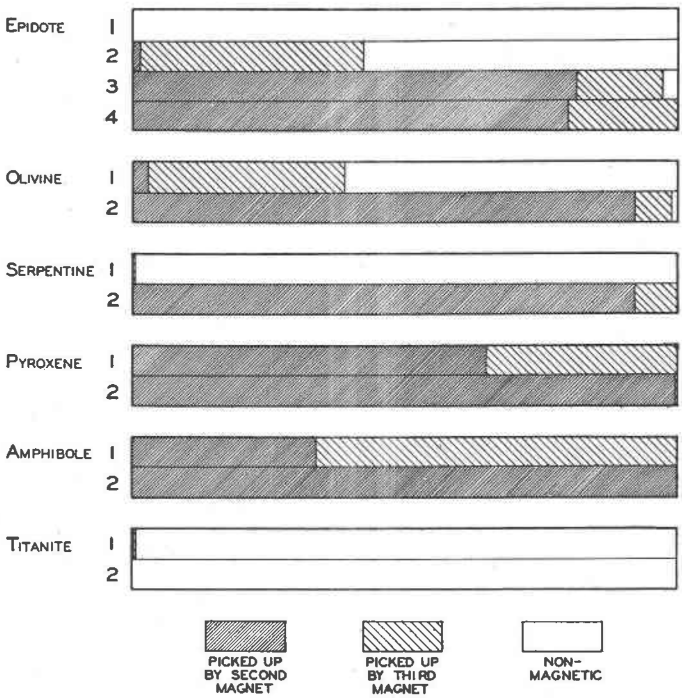

FIG. 4. Magnetic separates of several minerals.

Experiment 2. Several minerals forming isomorphous series from Mg to Fe extremes were tested at 80 to 100 mesh sizing to show how differently the ferruginous and magnesian varieties behave in a magnetic separator of the Hallimond type. Grains ranged from 0.140 to 0.173 mm. in diameter. Samples were those that happened to be available in the Department of Geology at the University of Minnesota. A correction was made for any impurity found by microscopic examination of the sized material. None of the minerals yielded any separate to the first magnet, which is intended to take out the ferromagnetic minerals. Table 2 and Fig. 4 show the distribution through the rest of the separator.

TABLE 2. MAGNETIC SEPARATES OF SEVERAL MINERALS

		Magnet 1	Magnet 2	Magnet 3	Tailings
Epidote	1	none	0	0	100
	2	"	1.1	40.8	58.1
	3	"	81.4	15.8	2.8
	4	"	79.8	20.2	0
Olivine	1	"	2.7	36.0	61.3
	2	"	91.8	6.9	1.2
Serpentine	1	"	0	0.2	99.8
	2	"	92.0	8.0	0
Pyroxene	1	"	64.5	35.5	0
	2	"	99.6	0.4	0
Amphibole	1	"	33.6	66.4	0
	2	"	100.0	0	0
Titanite	1	"	0.3	0.3	99.4
	2	"	0	0	100.0

Epidote group. Specimen 1, zoisite, east of Rainy Lake, Ontario. Specimen 2, green, fibrous, from pegmatite at Dewey, Montana. Specimen 3, dark green, from Ute Creek, Colorado. Specimen 4, very dark, from Sulzer, Alaska.

Olivine group. Specimen 1, light green, Carolina. Specimen 2, dark gray-green, Mooihoeck, Bushveld.

Sepentine group. Specimen 1, green, and 2, dark green; localities unknown.

Pyroxene group. Specimen 1, diopside, light gray-green, Ariege, France. Specimen 2, augite, black, Hybla, Ontario.

Amphibole group. Specimen 1, actinolite, and 2, hornblende; localities unknown.

Titanite. Specimen 1, medium brown, unknown locality. Specimen 2, dark brown, Westport, Ontario.

The magnetism of titanite was investigated because it has been supposed to show marked variability.[15] The differences in color do not seem related to such a variability. No magnetic samples are available here except some in which magnetism results from opaque inclusions.

Summary

This paper covers two points, namely, that with most magnets used in petrographic or mineral separations, the material must be accurately sized, but that the difficulty might be overcome by a different design of the pole pieces; and that, in an isomorphous series grading from an Mg compound to an Fe compound, the Fe compound is much more strongly attracted as might be expected, and in zoned crystals a clean magnetic separation of that mineral from another is hardly to be expected.

[15] Tyler and Marsden, Report of Committee on Accessory Minerals: *Div. of Geol. and Geog., Nat. Research Council* for 1936–7, p. 13.