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**MAGNETIC SUSCEPTIBILITIES OF MINERALS**

by

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## INTRODUCTION

Magnetic separation of minerals is a topic that is seldom reported in the literature for two reasons. First, separation data generally are byproducts of other projects; and second, this study requires a large amount of patience and is unusually tedious. Indeed, we suspect that most minerals probably are never investigated for this property.

These data are timesaving for mineralogists who concentrate mono-mineralic fractions for chemical analysis, age dating, and for other purposes. The data can certainly be used in the ore-beneficiation industries. In some instances, magnetic-susceptibility data may help in mineral identification, where other information is insufficient.

In past studies of magnetic separation of minerals, (Gaudin and Spedden, 1943; Tille and Kirkpatrick, 1956; Rosenblum, 1958; Rubinstein and others, 1958; Flinter, 1959; Hess, 1959; Baker, 1962; Meric and Peyre, 1963; Rojas and others, 1965; and Duchesne, 1966), the emphasis has been on the ferromagnetic and paramagnetic ranges of extraction. For readers interested in the history of magnetic separation of minerals, Krumbein and Pettijohn (1938, p. 344-346) indicated nine references back to 1848. The primary purpose of this paper is to report the magnetic-susceptibility data on as many minerals as possible, similar to tables of hardness, specific gravity, refractive indices, and other basic physical properties of minerals. A secondary purpose is to demonstrate that the total and best extraction ranges are influenced by the chemistry of the minerals. The following notes are offered to help avoid problems in separating a desired mineral concentrate from mixtures of mineral grains.

### Definitions and Disclaimers

"Ferromagnetic" refers to minerals strongly attracted to a magnet, like a piece of iron. The common ferromagnetic minerals include magnetite, maghemite, pyrrhotite, and pentlandite.

"Paramagnetic" refers to minerals less magnetic than ferromagnetic, and separable in magnetic separators with field currents up to 1.70 amps., the greatest value reached on a Frantz Magnetic Separator.

"Diamagnetic" refers to minerals that are nonmagnetic at 1.70 amps. and would be repelled by electromagnets with stronger currents.

"Best range" refers to the extraction range which contains the greatest amount of the desired mineral concentrate. In Table 1, under "Best range" the notation "dc" (depends on chemistry) indicates a large difference in extraction among the samples run for each mineral species. Generally this difference is 0.40 amp. or greater between the best-range values. We presume that the chemistry differs enough to cause the observed amperage differences.

This report is not concerned with the actual cgs (international centimeter-gram-second) units of magnetic susceptibility for each mineral, nor with the strength of the magnetic field in Gauss, Maxwell, or Oersted units. Such data are discussed by McAndrew (1957), Hess (1959), Frost (1961), and Dahlin and Rule (1993). Our main interest is the practical aspect of rapid magnetic separation of dry minerals by using a rheostat and an ammeter to adjust the strength of the magnetic field between the pole pieces. With respect to consistency among magnetic separators used, the senior author is satisfied that the Frantz Separators he used in different places (Spokane, Washington; Taipei, Taiwan; La Paz, Bolivia; Monrovia, Liberia) yielded results similar to several machines in USGS laboratories in the Federal Center near Denver, Colorado. We have no experience with other brands of magnetic separators, but the data presented in Table 1 and in Figures 1 and 2 may be used

with other machines. Data produced on other machines, if not identical, will be relatively and/or proportionally similar.

Officer (1947) used the imprecise method of passing a falling stream of grains near the pole pieces of an electromagnet, and the deflected grains fell into different collecting bottles below the variable magnetic field. Some reports discuss magnetic separations of minerals in a liquid medium (see Greene and Cornitius, 1970; Gabenisch, and others, 1971; Lumpkin and Zaikowski, 1980; and Alminas and others, 1984), or by use of paramagnetic liquids to perform separations by specific gravity (Parsonage, 1977). These methods were not used in the present study, nor were diamagnetic separations made.

The scope of this paper does not cover physical factors that may affect the magnetic susceptibility of minerals. However, the following is a brief explanation of why some minerals are magnetically susceptible, while others of similar composition are not affected by the magnetic field.

Silberberg (1998) explains that magnetic properties of minerals are affected by the chemical structure of the individual molecules. In order for a substance to be paramagnetic, it must have unpaired electrons in the molecular orbitals, while diamagnetic substances contain paired electrons in the molecular orbitals. Molecular orbitals are formed when two or more atoms are bonded covalently.

According to the filling rules for orbitals, each orbital fills first with electrons of one spin, then with electrons of the opposite spin, thus preserving stability. When a molecule has unpaired electrons, that is, only electrons of one spin, in an orbital, that molecule has a net magnetic dipole moment, which makes it paramagnetic. However, when the electrons are all paired, there is no net magnetic dipole moment and the material is diamagnetic. Ferromagnetic materials are a special case in which the individual magnetic dipole moments align in areas called domains.

An example of different magnetic properties for minerals with similar compositions is the difference between pyrite ( $\text{FeS}_2$ ), which is diamagnetic, and pyrrhotite ( $\text{Fe}_5\text{S}_6$ ) to ( $\text{Fe}_{16}\text{S}_{17}$ ), which is ferromagnetic. These two minerals have distinctly different physical properties due to the atomic structures. Pyrite has twice as many sulfur atoms as iron atoms and therefore has one more electron involved in bonding than pyrrhotite. Pyrite has filled molecular orbitals, whereas pyrrhotite is lacking the last electron, leaving an unpaired electron in the highest orbital.

Readers are encouraged to consult the above reference, or another general chemistry text, for a more complete explanation of the molecular orbital theory and its effect on magnetic properties of materials, including minerals.

### Acknowledgements

This report is based largely on an investigation of minerals available in the reference-mineral collection of the Branch of Central Mineral Resources (CMR), USGS/Denver. In addition, "fill-in" mineral samples were obtained from the Colorado School of Mines Mineralogy Museum; and from the Denver Museum of Natural History, Geology Department.

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## PARAMETERS

### Magnetic separator settings

Magnetic separators used during the study were Frantz Isodynamic Magnetic Separators, Model L-1\* . The original brass chute in each machine was replaced by an aluminum chute milled in the USGS machine shop. The isodynamic vibrator at the upper end of the chute was replaced by an asymmetric vibrator, as described by Faul and Davis (1959). The aluminum hopper was replaced by a Pyrex glass tube fitted with a spout that drops the sample into the upper end of the chute. The glass hopper is mounted on a separate mast near the upper end of the chute, and it is vibrated separately. Both chute and hopper vibrators are controlled by separate switches and rheostats on a control box.

The side slope was fixed at 15 degrees, sloping downward away from the operator. At any setting of the ammeter, the more magnetic fraction of a thin stream of dry grains, traveling down the chute, is moved laterally to the higher side of the chute. Magnetic separation takes place as the mineral grains move down the first one-quarter of chute length; then, about one-third of the way through the magnetic field, a divider in the chute keeps the magnetic and nonmagnetic fractions apart, and the two fractions are collected in separate aluminum cups at the left side of the apparatus.

If the side slope is changed to a value less than 15 degrees, then the extraction range will begin and end at lower amperages than those listed in Table 1, and the ranges shown in Figures 1 and 2 will be shifted to the left. With side slopes greater than 15 degrees, the opposite effects will take place, as shown in a chart by Hutchison (1974, p. 119) and Parfenoff (1967, p. 15). In either instance, all shifts are relative to one another, and Table 1 and Figures 1 and 2 are still useful to anyone opting to use a side tilt other than 15 degrees.

The forward (longitudinal) slope of the chute was generally about 25 degrees for most irregularly-shaped grains. This parameter is not critical. It regulates the travel speed of the mineral stream, and it was changed from time to time to help grains of different shapes to travel rapidly and smoothly down the chute, without saltation. In extreme cases, the forward slope would be about 28 to 30 degrees for platy grains, and it would be only 15 to 20 degrees for rounded grains.

The ideal situation is that of a stream of grains about 3 or 4 grains thick in which the mineral grains slide or tumble over each other as they approach the magnetic field, moving down the chute at about 2 to 3 cm. per second. The magnetically-attracted grains move out of the main stream to the higher side of the chute and form another stream of grains that moves downslope parallel to the less magnetic stream. As long as the number of grains in the separation zone is sparse, there is little danger of mechanical entrapment of nonmagnetic grains by

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\* Use of commercial names is for description only and does not imply endorsement.

the magnetic ones, and vice versa. If there is any doubt, then a second pass of each fraction at the same amperage is recommended.

The chutes in some machines develop vibrational nodes when the vibrator is used strongly. These nodes apparently are zones where some grains are bumped out of the shallow chute. The remedy for this is to decrease the intensity of the chute vibrator, resulting in longer periods of separation.

For all paramagnetic minerals, the field strength of the magnet starting at 0.10 ampere (amp.) was increased by steps of 0.10 amp. until the total extraction range for the sample was covered. For the few ferromagnetic species tested, the field strength starting at 0.01 amp. (visually estimated) was followed by passes at 0.025, 0.05, and 0.10 amp.

To speed the process, when testing a colorless mineral suspected of being diamagnetic, an initial setting of 0.50 amp was followed by a second pass at 1.00 amp., and a third pass at the highest setting, about 1.70 amps.

The differences between magnetic separations in the range 1.30 to 1.70 amps are generally negligible. The value 1.70 amps shown in the current list and charts is used arbitrarily as the upper limit of the paramagnetic range, for this was the highest amperage reached in most of the machines used in this study.

After each sample run, the magnetic separator was thoroughly cleaned by a jet of compressed air to avoid contaminating following samples. Careful and patient procedures can produce satisfactory results with little or no loss of sample. Losses generally occur when separations are "forced" by using excessive feed and/or chute vibrations.

### Sample preparation and characters

The "ideal sample" used in this magnetic separation study was about 0.5 to 1.0 gram of sand in the size range of 125-150 um (micrometer) to enable adequate visual estimates of extracted fractions. If the sample was not already in this size range, then about 5 to 10 grams of the sample was reduced in a steel "diamond mortar" and in a ceramic mortar and pestle to grains that pass through a 3-1/2 inch diameter stainless steel Tyler No. 100 sieve (150 um). The fraction retained on a No. 120 sieve (125 um) was used for obtaining magnetic-susceptibility data.

In this size range, about 90 to 95 percent of the grains have few or no inclusions or locked fragments of other minerals. These grains are small enough to perform most optical-mineralogy tests; and only a small amount of these grains were required to perform tests for chemistry by wet-chemical and optical-emission spectroscopic methods, or by energy-dispersive X-ray analyses on a scanning-electron microscope. In addition, these grains may be easily ground to a powder to obtain X-ray diffraction patterns. Typically, these grains are angular and tend to tumble rather than slide down the chute of the magnetic separator.

The time involved in mineral identification (or verification) in this study was about 85 to 90 percent of the project time. Only 10 to 15 percent of the time was used for sample preparation and to actually run 1084 samples of 378 mineral species through the magnetic separator.

## DISCUSSION

### General

Chemistry is the main factor that controls the magnetic susceptibility of minerals. The difference in chemistry plays a dramatic part in the extraction of end members of a mineral series in which iron replaces magnesium, as in the olivine series. Forsterite, the magnesium-rich end-member, is extracted in the range from 0.40 to 1.20 amps, and fayalite, the iron-rich end-member, is extracted in the range from 0.10 to 0.60 amp.

Other than iron, only manganese and copper have been noted to affect minerals that are extracted in the paramagnetic range. For manganese, we can cite manganite, rhodochrosite, and rhodonite as examples. For copper, azurite, bornite, brochantite, chalcantite, chalcopyrite, chrysocolla, conichalcite, and malachite are examples. However, for iron and copper, pyrite and chalcocite are nonmagnetic exceptions, due to physical and chemical considerations. The difference between ferromagnetic pyrrhotite and nonmagnetic pyrite probably is due to chemical orbital attributes.

Niccolite, cobaltite, and skutterudite are nonmagnetic, and platinum-group minerals are not especially known to be magnetically attractable. Although rare-earth metals like neodymium and samarium are known to be used in constructing powerful magnets, minerals containing rare-earth elements are only moderately paramagnetic (see bastnaesite, monazite, and xenotime).

Some entries in Table 1 (johannite, prehnite, pyrochlore) show a wide range of extraction with a poorly defined "Best range". Therefore, under that column these minerals have the notation "dc" indicating that the best range is dependent on chemistry. Obviously, more samples for each species are required to help resolve these ambiguous results. The chemistry of each sample should be ascertained to learn which atoms or ions are responsible for greater or less magnetic susceptibility in such wide ranges of extraction.

Colorless or white minerals are generally diamagnetic; that is, beyond the paramagnetic range of the magnetic separators used. Dark-colored and opaque minerals are generally extracted at less than 1.00 amp., and less commonly at greater amperages. The exceptions include red tourmaline, red rutile, some corundum, microlite, cassiterite, and many sulfides. Variations in chemistry tend to affect the depth of color and the extraction range. Examples are chrysoberyl, chrysocolla, and johannite. Lighter-colored grains are presumed to contain less iron or copper, two elements that are responsible for paramagnetic susceptibility in some minerals.

When micro-inclusions of magnetite or other ferromagnetic minerals are present, it is difficult or impossible to determine the actual lower limit of extraction. Conversely, micro-inclusions of quartz, calcite, or other diamagnetic minerals extend the upper limits of extraction of paramagnetic minerals. Nonmagnetic weathered minerals or alteration products may extend the upper limit. Also, diamagnetic sooty minerals, such as manganese or copper oxides, which coat minerals to be magnetically separated, make upper limits of extraction difficult to determine.

Where the total range of extraction extends from 0.10 to >1.70 amps., and the best range is >1.70 amps., we may presume contamination by a ferromagnetic mineral. For the samples that showed this effect, the extraction range is reported as >1.70 amps. For samples that showed a range from 0.50 or 1.00 amps to >1.70 amps, probably some contamination was involved. Often, we cannot be sure of this, even after microscopic examination of the mineral, so the whole range is reported.

Based on careful study of one sample split into four contiguous size ranges (63-90 um, 90-106 um, 106-125 um, and 125-150 um), the magnetic extractions of the several samples, visually estimated, were essentially the same. Differences among the four size ranges were (+/-) 1 to 4 percent for six different mineral species. In another test using rhodochrosite in the 125-150 um size range, the extraction range was 0.10-0.30 amp. and the best range was 0.15-0.30 amp. Similar grains in the 180-250 um size range were extracted in precisely the same total and best ranges.

For isomorphous series, such as dolomite-(Fe), (extraction range 0.40-0.60 amp.), and dolomite, (extraction range >1.70 amps.), a single sample containing both species may show extraction (of apparently one mineral) throughout the whole paramagnetic range.

### Variations based on chemistry

The fact that many iron-bearing minerals are either ferromagnetic or paramagnetic is well-known for some time. Also "well-known" are reports that minerals containing nickel, cobalt, platinum metals, and rare-

earth metals are also paramagnetic, and may even be ferromagnetic. This is apparently based on magnetic susceptibilities of the native metals, but in a chemical compound such as a mineral, the presumption that the same magnetic property will be found in the mineral is not often true because of the way that atomic bonding affects the magnetic susceptibility. We discovered that other metals such as manganese, copper, chromium, niobium, and tantalum, when occurring as major components of minerals, may enhance the magnetic susceptibilities of some members of a mineral series.

As a result of this study we can see that iron-rich end members of some mineral series (or families) such as olivines, pyroxenes, amphiboles, tourmalines, garnets, and epidotes, are more magnetic than minerals in the series with less iron. We have less confidence in making the same statement for mineral series that contain manganese, copper, chromium, niobium, and tantalum because there are far less minerals with these elements than with iron.

Table 1 shows an alphabetic listing of 378 minerals whose identities are known by physical and chemical testing listed above and including UV light responses, radiation testing, microchemical testing, and even blowpipe analyses.

Figure 1 presents the data of Table 1 in graphic form, in the order of increasing best-range-of-extraction for each mineral. In Figure 2, the data are arranged to show the best range of extraction for several mineral families arranged in alphabetic order. The most striking examples of strong magnetism dependent upon iron content can be seen in the amphibole, epidote, mica, spinel, tourmaline, and variscite families. Less striking are the families of minerals containing manganese as the major component.

Not shown in Figure 2 are the copper minerals that cross family lines, such as antlerite, brochantite, chalcantite, malachite, and azurite which are moderately paramagnetic compared to similar minerals with alkali or basic metals. In the foregoing examples, minerals lacking iron were chosen for comparison. Similar minerals with appreciable iron content were not available. If we consider sulfides with major iron and copper, such as chalcopyrite and bornite, we find that the magnetic susceptibilities are not additive. These minerals are moderately paramagnetic and, like pyrite, may be affected by physical and chemical constraints.

## CONCLUSIONS

1. The data presented in Table 1 and Figures 1 and 2 are based on testing 1 to 18 samples per mineral species. Obviously, the greater the number of samples, the better the reliability of the data.
2. An attempt was made in Figure 2 to gather species into mineral groups or families to try to show how chemistry influences the range of extraction of related minerals. Certain metals substituting for others do alter the magnetic susceptibility of minerals. Iron substituting for calcium or magnesium is the best example. In Figure 2, we can see that iron-bearing carbonates are more magnetic than other species that are iron-free. Also, in the olivine group, iron-bearing species are more magnetic than olivine that is iron-poor.
3. Another metal that appears to affect the magnetic susceptibility, perhaps not as strongly, is manganese. In Figure 2, this conclusion is supported again by the carbonate and olivine groups wherein manganese carbonate (rhodochrosite) and manganese-rich olivine (tephroite) are more magnetic than other species in the two groups.
4. Metals like nickel, cobalt, chromium, platinum, and others were thought to enhance magnetic properties of minerals where they constituted major amounts. However, in this study there was no evidence that these metals were effective in this regard. More samples of minerals bearing these metals will be needed to confirm or alter this conclusion.
5. A case may be argued for copper being effective in making minerals magnetic, considering that chalcopyrite, bornite, antlerite, brochantite, azurite and malachite are extracted in the early to middle part of the



paramagnetic range. An exception is chalcocite ( $\text{Cu}_2\text{S}$ ), which is diamagnetic; but this is probably due to physical and chemical effects, similar to pyrite.

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