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Magnetic Susceptibility of Minerals in High Magnetic Fields

By D. C. Dahlin and A. R. Rule

UNITED STATES DEPARTMENT OF THE INTERIOR



BUREAU OF MINES



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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

A/m ampere per meter

°C degree Celsius

cm³ cubic centimeter

g gram

h hour

Hz hertz

K kelvin

kOe kilo-oersted

m³/kg cubic meter per kilogram

mm millimeter

μm micrometer

pct percent

T tesla

MAGNETIC SUSCEPTIBILITY OF MINERALS IN HIGH MAGNETIC FIELDS

By D. C. Dahlin¹ and A. R. Rule²

ABSTRACT

The U.S. Bureau of Mines investigated the magnetic susceptibility of minerals as a function of magnetic field strength to determine how it might affect the potential for high-field magnetic separation as an alternative to other separation technologies. Single-mineral concentrates were prepared from specimens from the same deposit to compare magnetic susceptibilities of minerals that occur together and from specimens from different deposits to compare magnetic susceptibilities of like minerals.

A vibrating-sample magnetometer with a superconducting magnet capable of producing a magnetic field of 7.16×10^6 A/m (90 kOe) was used to measure the magnetic moment of the samples. The data were then converted to specific magnetic susceptibility data and plotted as a function of magnetic field strength. cursory studies were also completed on the effects of iron content and oxidation roasts on magnetic susceptibility in high fields.

The results showed that magnetic susceptibility is essentially constant in magnetic fields above those needed to saturate ferromagnetic constituents. Although magnetic susceptibility is influenced by iron content and by thermal treatment, the changes are not large enough to influence separations in fields above 1.59×10^6 A/m (20 kOe).

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INTRODUCTION

The U.S. Bureau of Mines is interested in the application of novel technologies to beneficiate ores that will enhance the Nation's ability to meet its mineral needs. The technology to produce ever-stronger magnets and the advent of superconducting magnetic separators in the minerals industry presents the possibility of magnetic separation of minerals in magnetic fields well above those now commonly used in high-intensity magnetic separators (on the order of 1.59×10^6 A/m (20 kOe)).

The Bureau has long been involved in the study of magnetic separation and the magnetic susceptibility of minerals (1-9).³ The object of the current research was to study magnetic susceptibility of minerals primarily as a function of field strength, and secondarily as a function of iron content and thermal alteration, to determine whether magnetic separation in the high magnetic fields now available may be a substitute for conventional separation technologies.

Superconducting magnetic separators have been used to date primarily because they offer an economic advantage rather than a technological advantage. The separators use magnetic fields and gradients of the same magnitude as conventional high-gradient electromagnetic separators, but they use less energy and often require less space. The need for higher magnetic fields has not been proven necessary or advantageous to the grade-recovery relationship (10), but the new technology conceivably could be used in place of techniques such as froth flotation that may be more expensive or environmentally less attractive.

The magnitude of the magnetic force on a particle in a magnetic field is dependent in part upon the magnetic

susceptibility of the particle. If two minerals of equal volume but different susceptibilities are exposed to the same magnetic field and field gradient, the resulting difference in magnetic forces will result in a separation of the particles if enough time is allowed. However, the efficiency of the separation is dependent on several factors, including residence time in the magnetic field, liberation of the constituent minerals, and competing forces such as gravity and friction.

Compilations of mineral susceptibility are numerous (2, 4-7, 10-15), but comparison of data from different compilations is difficult. Conflicting data may be explained by the inherent variability in mineral composition, the presence of inclusions and other contamination, and the omission of supporting information concerning the conditions under which the measurements were made.

Equations and data concerning the magnetic properties of diamagnetic and paramagnetic ions are available to calculate the magnetic susceptibilities of minerals based upon their constituent elements and molecular combinations (14). However, such calculations must be used with caution, because ferromagnetic atoms may combine to form paramagnetic minerals and paramagnetic atoms may form diamagnetic minerals (11). Tabulated data are useful for comparisons, but measurement of the susceptibilities of the specific minerals in question is more definitive, and, ultimately, separation tests provide the best information in an analysis of whether two minerals can be magnetically separated.

SAMPLES

The samples used in this study were single-mineral concentrates produced from petrographic specimens from several deposits. Because the specimens consisted of rocks or bulk concentrates that contained several different minerals, the concentration procedures involved several techniques. Crushing, grinding, and sizing for liberation were followed by gravity, magnetic, and/or acid-scrubbing methods to produce highly concentrated products. For most of the minerals, however, final concentration was by hand-picking with tweezers of single grains under a binocular microscope to ensure as clean a sample as possible. Table 1 provides chemical and X-ray diffraction analyses for each of the samples used in this study.

Specimens from the Lead Belt District, MO, Blackbird Deposit, ID, and Bornite, AK, contained a variety of

sulfides and associated gangue minerals. The Bureau's Rolla (MO) Research Center provided specimens from the Magmont Mine in the Missouri Lead Belt, from which samples of calcite, chalcopyrite, galena, pyrite, quartz, siegenite, and sphalerite were produced. The Blackbird Deposit specimens contained chalcopyrite, cobaltite, pyrite, and quartz. Samples of bornite, chalcopyrite, and pyrite were prepared from the Bornite specimens.

The Red Mountain, AK, and Emma Belle Deposit, CA, specimens contained primarily chromite and olivine. Petrographic reports listed chromite and olivine as the predominant minerals, and serpentine and kammererite (chromian clinocllore) as minor constituents. Samples of chromite, olivine, and kammererite were prepared, but it was not possible to concentrate high-purity serpentine samples.

³Italic numbers in parentheses refer to items in the list of references at the end of this report.

Table 1.—Chemical and X-ray diffraction (XRD) analyses of samples used in this study

Deposit and sample	Analysis, pct	XRD analysis ¹
SULFIDES AND ASSOCIATED GANGUE MINERALS		
Blackbird Deposit, ID:		
Chalcopyrite	30.7 Fe, 30.8 Cu, 34.7 S	P: chalcopyrite; BDT: covellite, pyrite, and muscovite-type mineral.
Cobaltite	5.24 Fe, 19.3 S, 29.8 Co, 43.5 As	P: cobaltite; BDT: arsenopyrite, muscovite-type mineral, and possibly calcite.
Pyrite	45.4 Fe, 0.94 Cu, 49.7 S	P: pyrite; BDT: chalcopyrite, muscovite-type mineral, and unidentified compounds.
Quartz	0.43 Fe	P: alpha quartz; BDT: unidentified compounds.
Bornite, AK:		
Bornite	13.7 Fe, 57.0 Cu, 25.6 S	P: bornite; TR: calcite and dolomite.
Chalcopyrite	26.0 Fe, 27.1 Cu, 35.3 S	P: chalcopyrite; TR: pyrite, dolomite, and unidentified compounds.
Pyrite ²	47.1 Fe, 48.4 S	P: pyrite; TR: chalcopyrite, bornite, and dolomite.
Pyrite ³	42.5 Fe, 53.8 S	P: pyrite; TR: unidentified compounds.
Butte, MT:		
Pyrite	41.4 Fe, 53.1 S, 3.26 SO ₄	P: pyrite; TR: mooihoekite and unidentified compounds.
Magmont Mine, MO:		
Calcite	0.71 Fe	P: calcite; BDT: quartz.
Chalcopyrite	28.7 Fe, 32.9 Cu, 34.8 S	P: chalcopyrite; BDT: quartz.
Galena	0.16 Fe, 13.6 S	Only galena detected.
Pyrite	44.0 Fe, 54.3 S	P: pyrite; BDT: unidentified compounds.
Quartz	1.68 Fe	Only alpha quartz detected.
Siegenite	4.04 Fe, 40.9 S, 22.9 Co, 30.1 Ni	P: siegenite; BDT: unidentified compounds.
Sphalerite	0.80 Fe, 32.9 S	P: sphalerite; BDT: unidentified compounds.
CHROMITES AND OLIVINES		
Claim Point, AK:		
Chromite	22.2 Fe, 37.9 Cr, 8.53 Mg, 4.97 Al	P: chromite; TR: unidentified compounds.
Emma Belle Deposit, CA:		
Chromite	21.6 Fe, 37.8 Cr, 7.88 Mg, 4.30 Al	P: chromite; TR: unidentified compounds.
Kammererite (clinochlore)	14.2 Fe	Only clinochlore detected.
Olivine, green	4.82 Fe, 31.8 Mg, 21.0 Si	P: forsterite; TR: chrysotile and unidentified compounds.
Olivine, orange	5.46 Fe, 31.5 Mg, 20.0 Si	P: forsterite; TR: chrysotile.
Red Mountain, AK:		
Chromite (RM1)	19.1 Fe, 39.2 Cr, 7.63 Mg, 5.07 Al	Only chromite detected.
Chromite (RM2)	14.7 Fe, 37.9 Cr, 8.88 Mg, 4.62 Al	P: chromite; BDT: unidentified compounds.
Olivine, black	4.86 Fe, 30.8 Mg, 17.9 Si	P: forsterite; TR: chrysotile-kaolinite group.
Olivine, green	5.10 Fe, 31.2 Mg, 18.1 Si	Do.
Olivine, yellow	5.10 Fe, 31.1 Mg, 19.2 Si	Do.
Sheep Hill, AK:		
Chromite (SH1)	19.6 Fe, 33.8 Cr, 6.83 Mg, 6.52 Al	Only chromite detected.
Chromite (SH2)	21.7 Fe, 36.8 Cr, 7.50 Mg, 5.66 Al	Do.
Chromite (SH3)	27.2 Fe, 25.8 Cr, 6.39 Mg, 9.42 Al	Do.
Twin Sisters, WA:		
Olivine	6.76 Fe, 30.9 Mg, 18.8 Si	Only forsterite detected.
ILMENITES		
Cascade, ID	34.9 Fe, 28.2 Ti	P: ilmenite; TR: hematite.
San Gabriel Mountains, CA	35.4 Fe, 30.3 Ti	Only ilmenite detected.
Tahawas, NY	32.8 Fe, 27.8 Ti	P: ilmenite; BDT: anatase.
MANGANESE AND TIN OXIDES AND SILICATES		
Butte, MT:		
Pyroxmangite	0.74 Fe, 37.4 Mn, 22.9 Si, 0.92 Ca	P: pyroxmangite.
Pioneer Mine, CA:		
Romanechite	0.85 Fe	S: romanechite and ramsdellite.
Tofty, AK:		
Cassiterite	4.63 Fe	P: cassiterite; TR: dravite.

See notes at end of table.

Table 1.—Chemical and X-ray diffraction (XRD) analyses of samples used in this study—Continued

Deposit and sample	Analysis, pct	XRD analysis ¹
ROASTED MINERALS		
Tahawas, NY, ilmenite:		
Roasted 700° C, 1 h	32.9 Fe, 26.9 Ti	S: hematite; M: rutile; TR: unidentified compounds.
Roasted 700° C, 3 h	32.5 Fe, 27.2 Ti	Do.
Roasted 900° C, 1 h	32.6 Fe, 26.6 Ti	P: pseudobrookite; TR: hematite and rutile; BDT: unidentified compounds.
Roasted 900° C, 3 h	32.7 Fe, 26.8 Ti	Do.
Butte, MT, pyrite:		
Roasted 500° C, 1 h	56.3 Fe, 14.0 S, 4.28 SO ₄	P: hematite; M: pyrite; TR: unidentified compounds.
Roasted 500° C, 3 h	58.0 Fe, 2.53 S, 6.41 SO ₄	P: hematite; TR: possibly Fe _(1-x) S and unidentified compounds.
Roasted 700° C, 1 h	63.8 Fe, 0.79 S, 0.52 SO ₄	Do.
Roasted 700° C, 3 h	64.6 Fe, 0.19 S, 0.07 SO ₄	Do.

¹P = primary phase (40 to 100 pct); S = secondary phase (20 to 60 pct); M = minor phase (5 to 30 pct); TR = trace (1 to 10 pct); BDT = barely detectable trace (<1 pct).

²Sample used at 4.3 K.

³Sample used at 217 K.

Specimens from other deposits were concentrated to provide additional high-purity mineral samples. These samples included the manganese minerals romanechite (commonly called psilomelane) from the Pioneer Mine, CA, and pyroxmangite from Butte, MT; cassiterite from Tofty, AK; and ilmenite from deposits in Tahawas, NY, the San Gabriel Mountains, CA, and Cascade, ID.

Samples of like minerals with different iron contents were selected to investigate the effect of iron as a constituent in a mineral on its magnetic susceptibility. In addition to the chromite samples from the Emma Belle Deposit and Red Mountain mentioned above, five other chromite samples from Claim Point, Red Mountain, and Sheep Hill, AK, were examined. The iron content of the chromites ranged from 15 to 27 pct⁴ total Fe. Samples of ilmenite (33 to 35 pct Fe), olivine (5 to 7 pct Fe), and pyrite (41 to 47 pct Fe) were also examined in the study.

Ilmenite from Tahawas, NY, and pyrite from Butte, MT, were used in tests to investigate the effect of an oxidation roast on magnetic susceptibility. The ilmenite sample contained 46 pct TiO₂ and 33 pct total Fe, and the

pyrite sample contained 41 pct total Fe. The samples were sized at 100 by 150 mesh (150 by 100 μm), and 5-g splits were poured loosely and evenly into open refractory boats. The samples were roasted in air in a furnace at 500°, 700°, or 900° C for 1 or 3 h and then removed and cooled in air to room temperature. They were weighed (table 2), ground lightly with a mortar and pestle to break agglomerated particles, and screened through 100 mesh before magnetic measurements were done.

Table 2.—Weight in grams of 5-g samples of ilmenite and pyrite after roasting in air

Product and roasting time	500° C	700° C	900° C
Tahawas ilmenite:			
1 h	NS	5.15	5.15
3 h	NS	5.16	5.16
Butte pyrite:			
1 h	3.64	3.23	NS
3 h	3.51	3.19	NS
NS	No sample.		

EQUIPMENT AND PROCEDURES

Magnetic susceptibility data were collected with the use of a vibrating-sample magnetometer (VSM). Figure 1 shows a schematic diagram of the primary components of

the VSM system, and figure 2 is a photograph of the system. The VSM-magnet system is a personal-computer-controlled unit that measures the magnetic moment of a small sample. The maximum weight of sample allowed by the VSM software for magnetic moment measurements is

⁴All percentages in this report are based on weight.

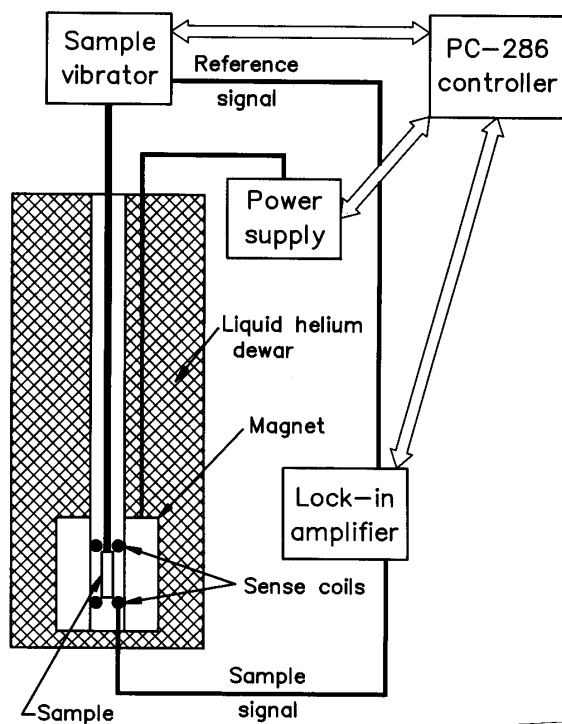


Figure 1.—Primary components of vibrating-sample magnetometer.

1 g, and the sample is limited by the volume of the sample holder to approximately 0.2 cm³.

Under test conditions, a sample is vibrated unidirectionally at constant frequency (85 Hz) and amplitude (1.27 mm double amplitude) in a magnetic field generated by a 9-T Nb-Ti superconducting magnet. The vibrating sample in the magnetic field creates a voltage signal that is proportional to the magnetic moment of the sample, and the signal is picked up by the sense coils and transmitted to the lock-in amplifier. The VSM system software translates the signal into a measurement of the magnetic moment and uses the sample weight to convert the magnetic moment to specific magnetization (M_s). As the magnetic field (H) is ramped to the selected field strength (the maximum is 7.16×10^6 A/m (90 kOe)), a graph is generated from 1,021 data points of M_s as a function of H .

For each test, a sample was pulverized, screened through 100 mesh (150 μ m), and packed tightly into the sample holder. The sample and holder were weighed

to obtain a net sample weight. The sample was then suspended from the sample vibrator on a long rod in the bore of a temperature-controlled cryostat or a "warm-bore" insert that had no temperature control and was positioned precisely between two sense coils (fig. 1). The sample and the sense coils both lay within the bore of the superconducting magnet.

Initial tests were done in the warm-bore insert, and because the insert has no means of temperature control, test temperatures ranged from 136 to 252 K, depending on how long the insert had been in the liquid helium dewar; temperatures in this range are described as "elevated" in this report. Later tests were run with the cryostat, and the temperature was maintained at 4.3 K, both for convenience and to conserve liquid helium. These temperatures are impractically low for current magnetic separation technology, including that which employs superconductor magnets, where the mineral stream (wet or dry) is at room temperature. Based on the Curie Law, which shows an inverse relationship between temperature and magnetic susceptibility, and the results of the initial tests, the following assumption was made: Although the magnetic susceptibility values are higher than they would be if they were measured at room temperature, the characteristics of the susceptibility curves are the same. Therefore, divergences and discontinuities in the curves that would indicate a dependence of magnetic susceptibility on field strength at room temperature also will be evident in the low-temperature results.

Specific magnetic susceptibility (X_s) is defined as the ratio M_s/H , and, consequently, X_s is the slope of the VSM-generated curve at any point along the curve. The VSM system software does not make the conversion of magnetization to magnetic susceptibility, so the data points were transferred to a spreadsheet to make the proper calculations, averaged in groups of five points as a data-reduction and smoothing function, and plotted as a curve of X_s as a function of H .

This research was concerned primarily with magnetic susceptibility as a function of magnetic field in fields above those used in current separation technologies. Therefore, values of X_s above 1.59×10^6 A/m (20 kOe) were averaged to get the tabulation in table 3. The listed standard deviation gives an indication of how constant X_s was for a given sample; a lower value (as a percentage of X_s) indicates a smaller change in X_s over the field range, and a higher value indicates a larger change. The analysis of magnetic susceptibility above 1.59×10^6 A/m (20 kOe) as a function of total iron content was done as a single-variable regression.

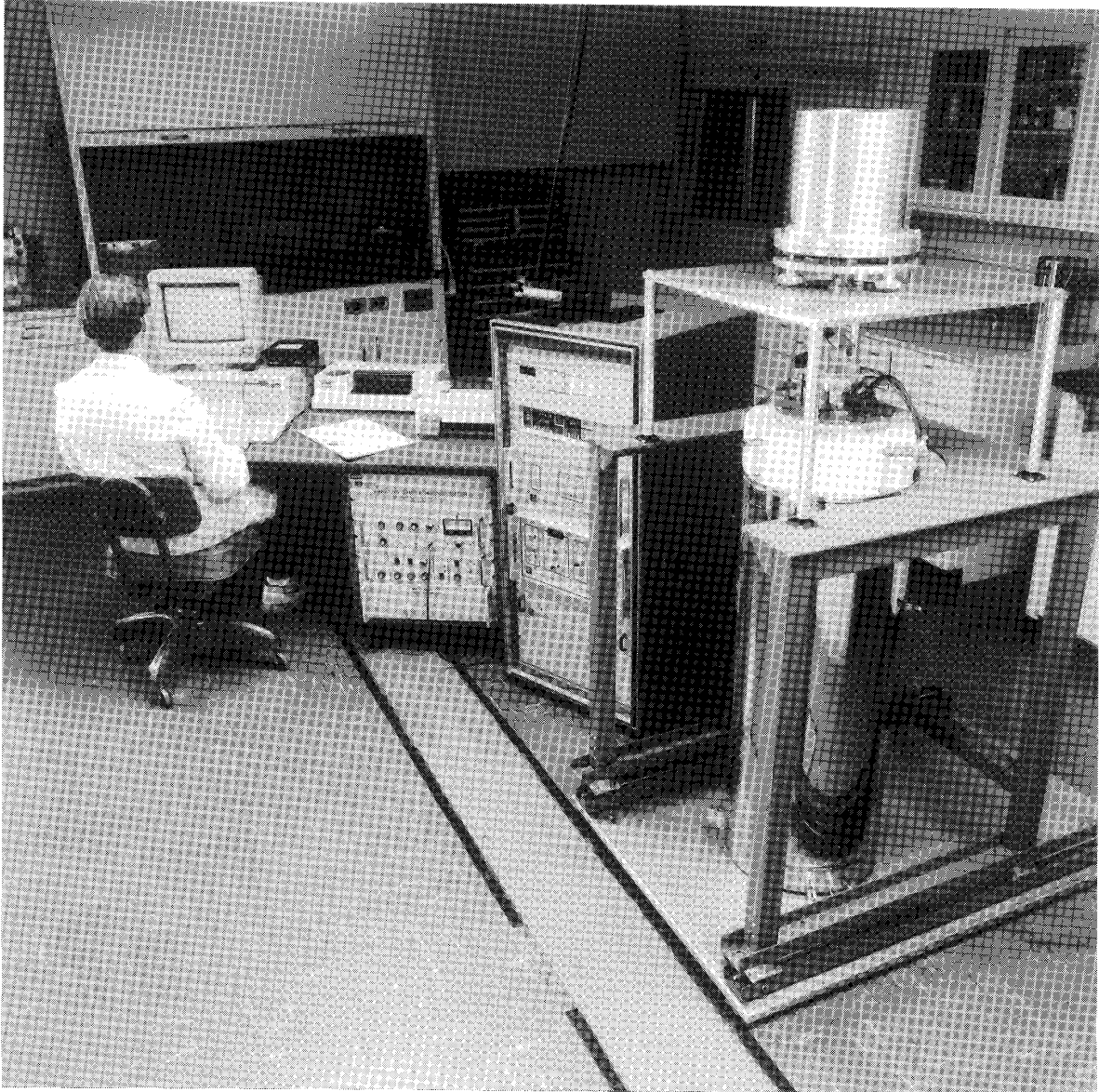


Figure 2.—Vibrating-sample magnetometer.

**Table 3.—Average specific magnetic susceptibility (χ_s) of minerals
in fields above 1.59×10^6 A/m (20 kOe)**

Deposit and sample	Temperature, K	$\chi_s, 10^{-9} \text{ m}^3/\text{kg}$		Reference figure(s)
		Average	Std dev ¹	
SULFIDES AND ASSOCIATED GANGUE MINERALS				
Blackbird Deposit, ID:				
Chalcopyrite	136	98.3	3.05	3A
Cobaltite	197	21.2	.88	3A, 6C
Pyrite	4.3	409	86.6	5E
	248	71.8	12.2	3A, 5F
Quartz	205	-7.40	1.71	3A, 6B
Bornite, AK:				
Bornite	208	131	.97	3B
Chalcopyrite	183	47.7	1.07	3B
Pyrite	4.3	172	46.6	5E
	217	11.5	1.04	3B, 5F
Butte, MT:				
Pyrite	4.3	764	175	5E
Magmont Mine, MO:				
Calcite	242	10.3	.60	3C
Chalcopyrite	248	41.4	.64	3C, 6C
Galena	250	-6.09	1.00	3C, 6C
Pyrite	4.3	157	6.21	5E
	251	2.62	.10	3C, 5F, 6C
Quartz	246	-12.4	3.36	3C
Siegenite	239	10.6	.71	3C, 6C
Sphalerite	245	3.81	.61	3C, 6C
CHROMITES AND OLIVINES				
Claim Point, AK:				
Chromite	4.3	729	19.6	5A
Emma Belle Deposit, CA:				
Chromite	4.3	1,088	55.1	4A, 5A
	136	586	25.8	4B
Kammererite (clinocllore)	167	155	4.54	4B
Olivine, green	4.3	2,088	428	4A, 5C
	161	204	4.64	4B, 5D
Olivine, orange	4.3	2,300	478	4A, 5C
	182	270	7.42	4B, 5D, 6B
Red Mountain, AK:				
Chromite (RM1)	4.3	698	78.4	4C, 5A
	143	558	3.72	4D, 6A
Chromite (RM2)	4.3	766	39.4	5A
Olivine, black	4.3	2,195	482	4C, 5C
	178	223	18.6	4D, 5D
Olivine, green	4.3	2,251	485	4C, 5C
	151	268	5.10	4D, 5D
Olivine, yellow	4.3	2,182	481	4C, 5C
	180	189	3.97	4D, 5D
Sheep Hill, AK:				
Chromite (SH1)	4.3	1,018	37.2	5A
Chromite (SH2)	4.3	869	13.7	5A
Chromite (SH3)	4.3	1,048	22.7	5A
Twin Sisters, WA:				
Olivine	4.3	2,862	674	5C
ILMENITES				
Cascade, ID				
	4.3	13,490	572	5B
	249	1,409	37.1	6A
San Gabriel Mountains, CA	4.3	13,508	732	5B
Tahawas, NY	4.3	11,264	753	5B

See notes at end of table.

Table 3.—Average specific magnetic susceptibility (χ_s) of minerals in fields above 1.59×10^6 A/m (20 kOe)—Continued

Deposit and sample	Temperature, K	$\chi_s, 10^{-9} \text{ m}^3/\text{kg}$		Reference figure(s)
		Average	Std dev ¹	
MANGANESE AND TIN OXIDES AND SILICATES				
Butte, MT:				
Pyroxmangite	252	1,199	15.4	6B
Pioneer Mine, CA:				
Romanechite-ramsdellite	232	377	2.66	6A
Tofty, AK:				
Cassiterite	244	23.4	1.36	6A
ROASTED MINERALS				
Tahawas, NY, ilmenite:				
Roasted 700° C, 1 h	4.3	2,117	568	8A
Roasted 700° C, 3 h	4.3	782	115	8A
Roasted 900° C, 1 h	4.3	1,249	98.7	8A
Roasted 900° C, 3 h	4.3	1,151	66.2	8A
Butte, MT, pyrite:				
Roasted 500° C, 1 h	4.3	1,905	515	8B
Roasted 500° C, 3 h	4.3	1,765	346	8B
Roasted 700° C, 1 h	4.3	1,113	366	8B
Roasted 700° C, 3 h	4.3	975	291	8B

¹Standard deviation.

RESULTS AND DISCUSSION

The research showed that the magnetic susceptibility of minerals is essentially independent of magnetic field in fields above those necessary to magnetically saturate ferromagnetic constituents. Discontinuities or divergences in the susceptibility data did not occur in high magnetic fields for the minerals tested. Consequently, differences in susceptibility are not enhanced, and improved separations based on magnetic susceptibility would not be expected in the high magnetic fields potentially obtainable with superconducting magnetic separators. However, because the magnetic force on particles increases with increasing field strength, mineral separations that are not possible in conventional separators may be possible in the high-intensity fields attainable with superconducting magnets.

MAGNETIC SUSCEPTIBILITY AS A FUNCTION OF FIELD STRENGTH

Figures 3 through 6 display magnetic susceptibility as a function of field strength for the constituent minerals from each of several deposits, for like minerals from different deposits, and for minerals within chemically similar groups (oxide, silicate, or sulfide). Samples from a given deposit provided results of the relative magnetic properties of the

actual minerals in that deposit. Samples of like minerals from different deposits provided comparative susceptibility data for mineral species. For most of the minerals investigated, magnetization above 1.59×10^6 A/m (20 kOe) is essentially a straight-line function of the magnetic field, and, consequently, magnetic susceptibility is independent of the field.

Some of the graphs show what appears to be good separation of the curves or divergence of the curves that would indicate the possibility of enhanced separation at a given field strength. One must consider the scale of the susceptibility axis on each graph to evaluate the differences that are shown. One reference suggests that it should be possible, at least theoretically, to separate materials whose permeabilities (and, therefore, susceptibilities) have a ratio greater than 5:1 (15). Theoretical results must be tempered by factors such as mineral liberation; the time that the minerals are exposed to the magnetic forces; and competing gravitational, frictional, and inertial forces that determine the success of a separation. The susceptibilities shown in the graphs in this report generally have ratios of less than 5:1, and these samples represent clean, liberated mineral particles.

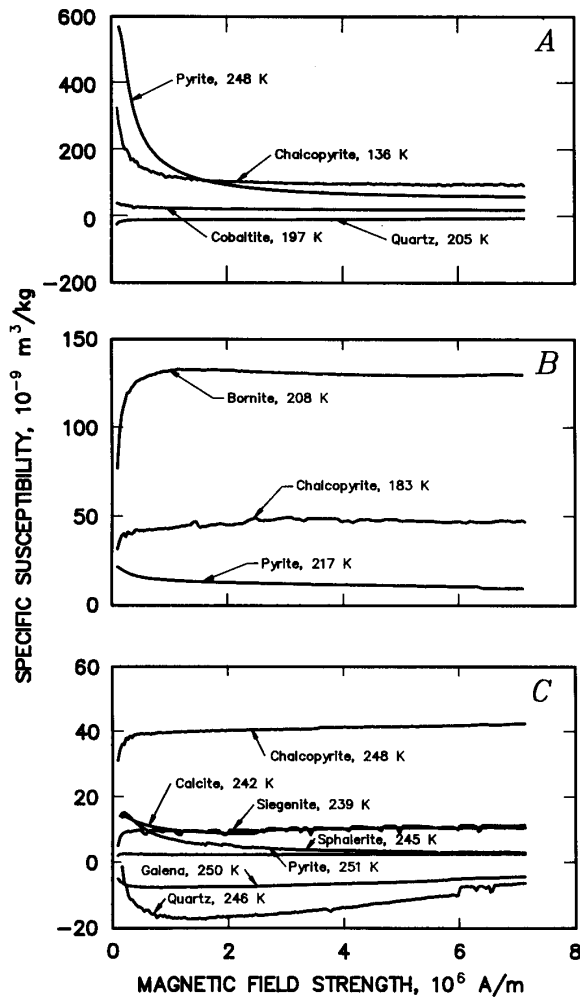


Figure 3.—Magnetic susceptibilities at elevated temperatures of sulfides and gangue minerals from three deposits as a function of magnetic field strength. A, Blackbird Deposit, ID; B, Bornite, AK; C, Magmont Mine, MO.

Many of the susceptibility curves show a sharp decrease in the susceptibility of a mineral from the start of the test to the field range of 7.96×10^5 A/m (10 kOe) that can be attributed to saturation of small amounts of iron or other ferromagnetic constituent in the sample. After this component was saturated, the net magnetization of the remaining elements of the mineral was recorded, and the susceptibility was approximately constant through the rest of the field sweep.

The data for olivine at 4.3 K (figs. 4A, 4C, and 5C) show that susceptibility decreases as the magnetic field increases above 1.59×10^6 A/m. However, the susceptibility moves closer to that of chromite, and, consequently, separation of the two minerals would be more difficult. The phenomenon disappeared at elevated temperatures (figs. 4B, 4D, and 5D).

Although magnetic susceptibility as a function of temperature was not specifically investigated in this research, the effect can be seen in comparing the results from the warm-bore insert and the cryostat (figs. 4 and 5C-F). As would be expected from the Curie Law, the susceptibilities measured at higher temperatures (136 to 252 K) were lower than those measured at 4.3 K. The effect is more pronounced in some minerals than in others. For example, chromite has a higher magnetic susceptibility than olivine at room temperature, and these two minerals can be separated in conventional separators. Chromite still has the higher magnetic susceptibility in the 136- to 182-K range (figs. 4B and 4D), but at 4.3 K, olivine has a higher magnetic susceptibility than chromite (figs. 4A and 4C).

MAGNETIC SUSCEPTIBILITY AS A FUNCTION OF IRON CONTENT

An important influence on magnetic susceptibility is the inclusion of contaminant minerals in a concentrated sample and/or the variation in mineral composition due to isomorphous substitutions. These may have a large effect on the measured susceptibility and, consequently, on the potential for magnetic separation.

The effect of iron as a constituent in the mineral composition on the magnetic susceptibility of minerals in high magnetic fields was investigated with chromite, ilmenite, olivine, and pyrite samples. Based on very few data points, linear-regression analysis indicated that the magnetic susceptibility of chromite, olivine, and ilmenite increases with increasing iron content, while for pyrite the opposite is true (fig. 7). Other research has suggested that susceptibility is proportional to the square root of iron content (3, 16). With the small number of data points in this study, linear and power regressions gave essentially the same results.

MAGNETIC SUSCEPTIBILITY AS A FUNCTION OF OXIDATION ROAST CONDITIONS

If the composition of a mineral is altered by oxidation during roasting, the magnetic susceptibility of the mineral changes, and, consequently, the roasted product is more amenable or less amenable than the unroasted mineral to

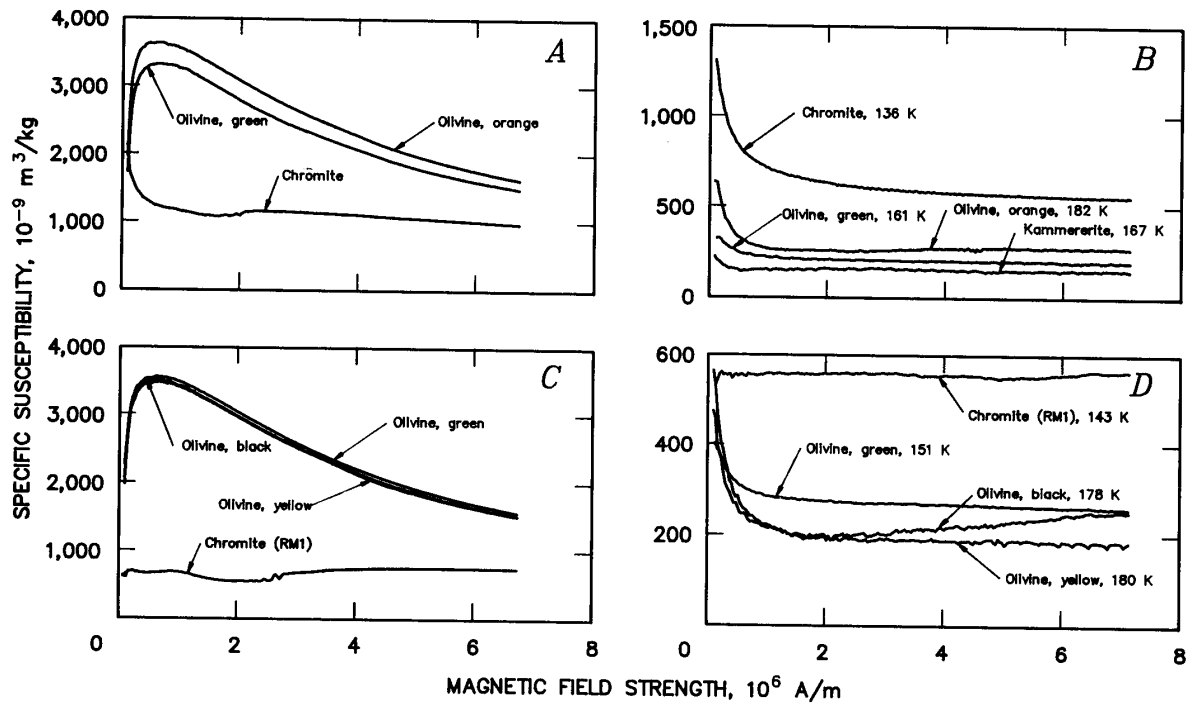


Figure 4.—Magnetic susceptibilities of chromites and olivines from two deposits as a function of magnetic field strength. A, Emma Belle Deposit, CA, at 4.3 K; B, Emma Belle Deposit, at elevated temperatures; C, Red Mountain, AK, at 4.3 K; D, Red Mountain, at elevated temperatures.

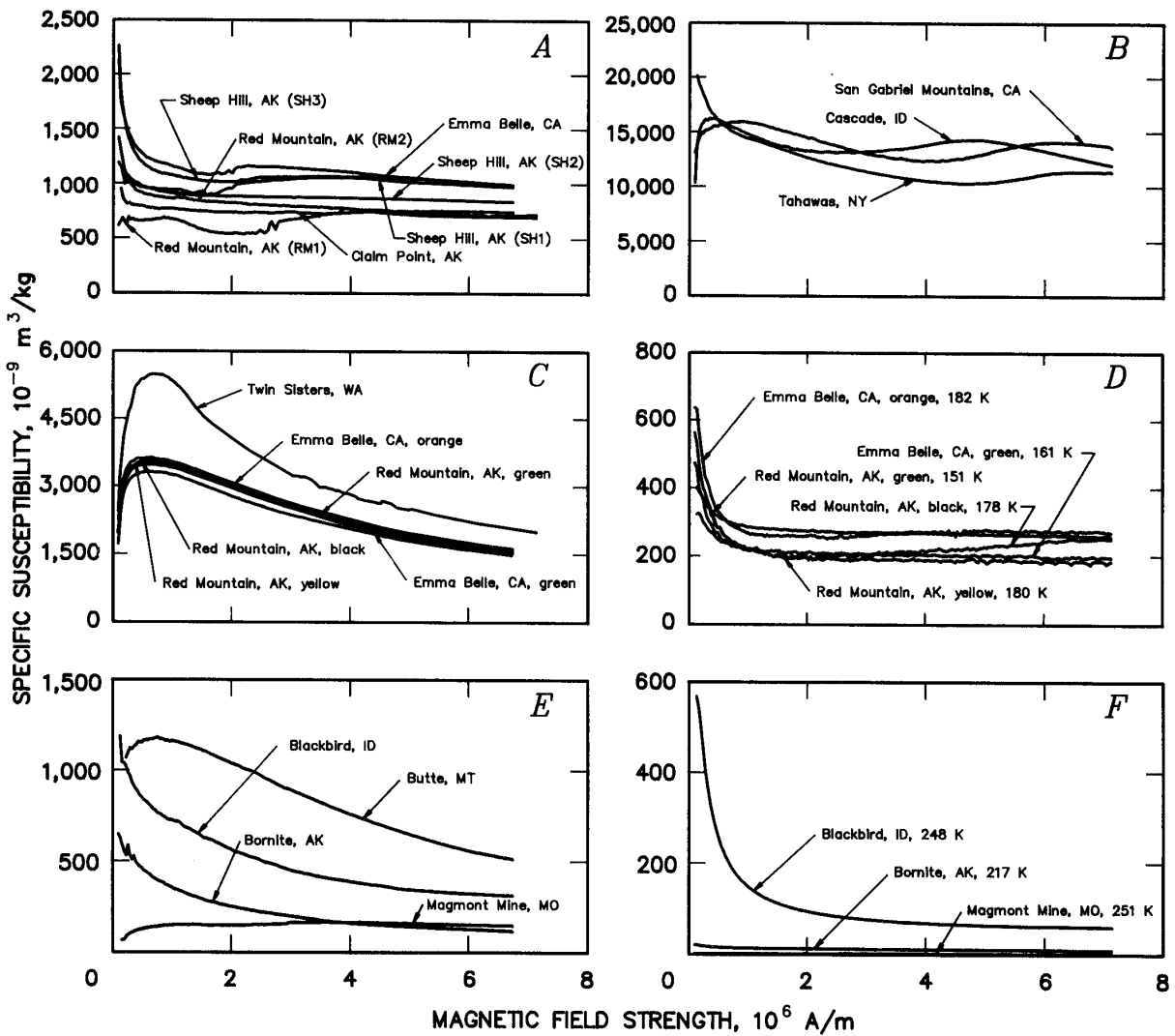


Figure 5.—Magnetic susceptibilities of like minerals from different deposits as a function of magnetic field strength. A, Chromites at 4.3 K; B, ilmenites at 4.3 K; C, olivines at 4.3 K; D, olivines at elevated temperatures; E, pyrites at 4.3 K; F, pyrites at elevated temperatures.

magnetic separation. Samples of ilmenite from Tahawas, NY, and pyrite from Butte, MT, were roasted in air to alter their composition, and then the changes in their magnetic susceptibilities were measured.

X-ray diffraction and chemical analyses showed that the roasted samples contained hematite and rutile at 700° C and pseudobrookite, hematite, and rutile at 900° C (table 1). Table 3 and figure 8A show that the magnetic susceptibility of the unroasted sample was approximately an order of magnitude greater than that of the roasted samples ($11,264 \times 10^{-9} \text{ m}^3/\text{kg}$, compared with 782 to $2,117 \times 10^{-9} \text{ m}^3/\text{kg}$).

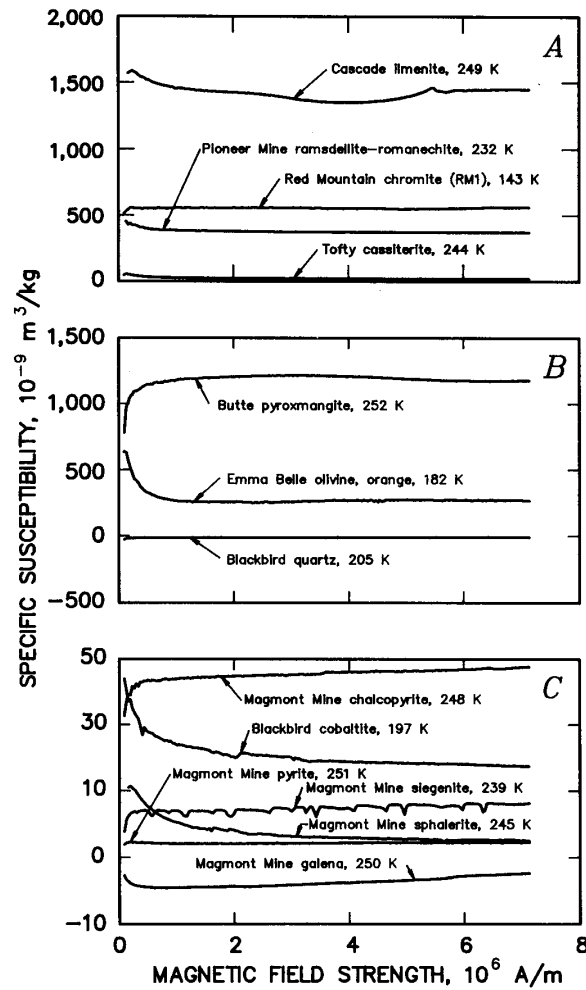


Figure 6.—Magnetic susceptibilities at elevated temperatures of selected minerals as a function of magnetic field strength. A, Oxides; B, silicates; C, sulfides.

The pyrites were oxidized to hematite with traces of pyrrhotite (Fe_{1-x}S). Pyrrhotite is highly magnetic (ferri-magnetic), and traces of it in the roasted samples were enough to raise the X_s values above that of the unroasted sample (table 3 and fig. 8B). However, above $1.59 \times 10^6 \text{ A/m}$ (20 kOe), the differences were small ($764 \times 10^{-9} \text{ m}^3/\text{kg}$ for the unroasted sample, compared with 975 to $1,905 \times 10^{-9} \text{ m}^3/\text{kg}$ for the roasted samples).

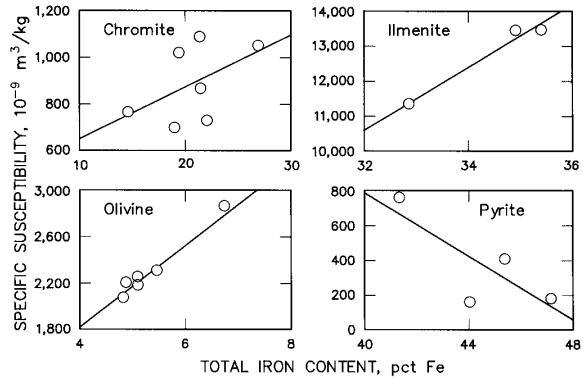


Figure 7.—Magnetic susceptibilities of four minerals predicted by total iron content at 4.3 K.

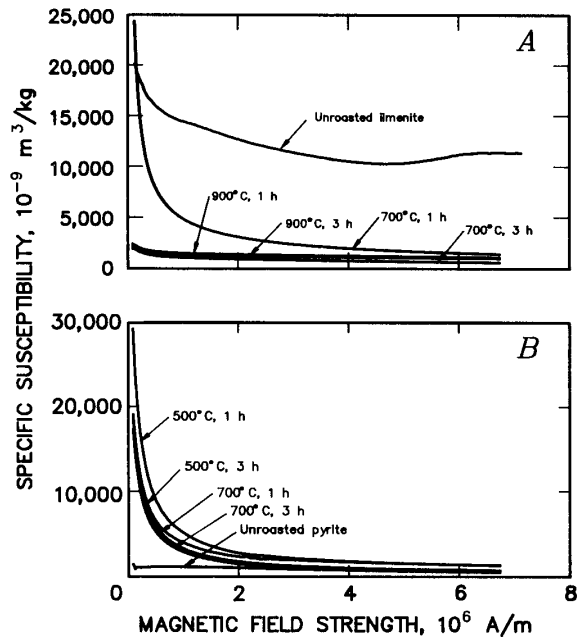


Figure 8.—Effect of roasting in air on magnetic susceptibilities of two minerals at 4.3 K as a function of magnetic field strength. A, Tahawas ilmenite; B, Butte pyrite.

CONCLUSIONS

The results of this research showed that the magnetic susceptibility of minerals is essentially independent of magnetic field strength after saturation of ferromagnetic constituents. Consequently, novel magnetic separation technology based on enhancement of mineral susceptibilities in high magnetic fields is unlikely.

Mineral susceptibilities are influenced by iron content and by changes in composition due to thermal alteration, but in fields above 1.59×10^6 A/m (20 kOe), no divergences or discontinuities are apparent that would suggest enhanced separation characteristics.

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