

MAGNETIC SUSCEPTIBILITY OF GEMSTONES Part 2

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THE SCIENCE FUNDAMENTALS

Strong alnico permanent magnets have been around since the 1940's, and were the type of magnet used by Basil Anderson in his pioneering work on magnetism and gems about 50 years ago.

It was not until 1983 that the exceedingly high energy-density neodymium-iron-boron magnets became available and at very low cost. These new magnets permit the simple measurement of susceptibility on gems that is the subject of this section.

However, the very high energy density means that they need to be handled with care. They can damage many of the small magnetic and electronic devices we use everyday, such as your cell phones, credit cards and hotel room cards. Please keep any NIB magnet away from all such devices and away from children. Even 1/2 inch diameter NIB magnets can be a hazard because of the large forces they can exert which can propel other magnets or iron pieces at high velocity.

Along with my associates in developing quantitative measurement procedures for gemmological applications, Bear and Cara Williams of Stone Group Labs, and Claire Mitchell of Gem-A, we have published two papers on our technique; Hoover and Williams (2007), and Hoover et al (2008). These papers do not go into much detail of the basic science involved in magnetism, but give examples of the application of magnetism to gemmology. This discussion attempts to give a better understanding of the basic science involved.

Most of you, I suspect, are not very familiar with the science of magnetic properties, but having listened to Alan Hodgkinson before, many will know that some gems are attracted to a magnet but very weakly when compared to a piece of iron. What many of you may not be aware of is that all materials made up of atoms interact with a magnetic field. Some are attracted, but most are repelled. Importantly, you can now rather easily demonstrate that fact by simply floating a gem such as quartz on a small polyfoam raft and observing that a magnet repels the quartz.

The property that defines the strength of attraction or repulsion of an object to a magnet is called **magnetic volume susceptibility**.

Figure 1. illustrates how magnetic volume susceptibility is defined.

This is the property that we can now measure rather simply and at little cost.

Fig. 1 magnetic susceptibility definition

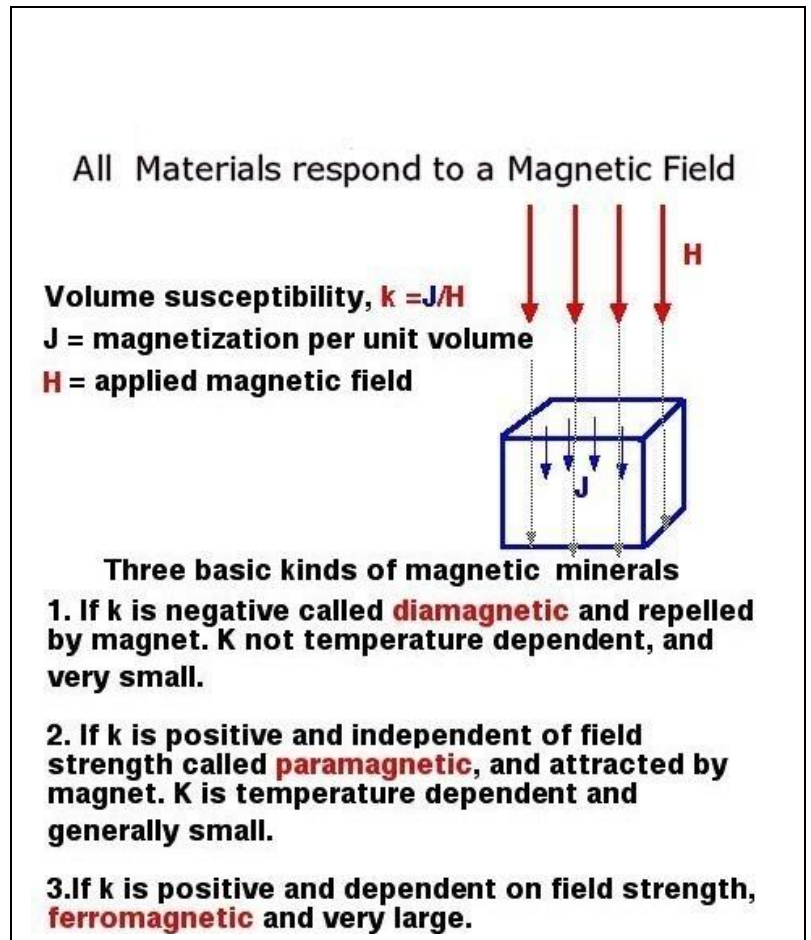


Figure 1 shows a cube of material, for illustrative purposes, shape is not important. We have an applied magnetic field H shown by the large red arrows, and this is considered to continue through the material of the box. The material comprising the box will have a magnetic field induced within it and that field is represented by the small blue arrows and designated J .

No matter what material is within the cube, if it contains atoms of any sort, it will have a net induced field such as labeled by the small blue arrows.

The volume susceptibility is simply the ratio of the induced field to the applied field as shown here. Since the units are the same, the volume susceptibility is dimensionless.

This is just like refractive index, with which each of you are familiar, which is the ratio of velocity of light in vacuum to that in the gem.

None of you should feel reluctant about working with magnets because you don't understand all the science involved. All of you measure the refractive index of stones as a matter of course, yet, I would guess, few are able to understand Maxwell's equations which cover the propagation of light.

Similarly, you don't need to understand all about magnetism science to make good use of magnetic measurements.

Why should all materials react to an applied magnetic field? It is really rather simple, each atom within the material typically has many electrons orbiting and spinning around the nucleus.

So, just as an electrical current generates a magnetic field, the motions of the electrons constitute an electrical current, and thus generate a magnetic field. The electrons in essence, act like many tiny permanent magnets within each atom. It is the cumulative effect of all these tiny magnets that gives rise to the bulk susceptibility which we measure.

Remember that magnets have a north and a south pole, and that like poles repel each other and unlike attract. So, depending on the direction of the induced field, J , the material can be either attracted or repelled by the inducing field.

Since all electrons are not created equal we find that materials behave in three main ways depending on their composition. The one type you are all familiar with is the **ferromagnetic** type of material.

I'm using the term in a general sense as physicists have broken this type of magnetic behavior into several varieties. Iron and steel are familiar examples and perhaps you know lodestone. For this type, k is positive, dependent on field strength and can be quite large. For our gem work we are not interested in this kind of magnetic behavior except when magnetite or similar magnetic mineral inclusions may be present where they can give problems, or false readings.

A second type has a positive value for k , and is independent of the applied field strength, but is inversely proportional to the temperature. These materials are called **paramagnetic**.

They have rather small susceptibilities. For gem materials this can range from 0 to about $+50 \times 10^{-4}$ (SI units) for a spessartine garnet. In order to measure susceptibilities which are so small, we need the very strong NIB magnets so as to get measurable forces of attraction.

It is the paramagnetic gems that are important in what we do.

If the susceptibility is negative, the material is called **diamagnetic** and it is repelled by a magnet. While this may seem strange, and something you may not have experienced before, it is easily demonstrated by floating a diamagnetic gem on a light raft and using a NIB magnet to show repulsion.

You know that with permanent magnets similar poles repel each other, and this only means that the induced fields within the atom are aligned so as to oppose the inducing field. Diamagnetic materials have susceptibilities that are quite small. For example quartz is about -30×10^{-6} and diamond is about -6×10^{-6} . So the induced field is on the order of 100,000 times smaller than the applied.

Diamagnetic susceptibilities have little diagnostic value.

A word of caution needs to be given should any of you go to the scientific literature for research. You must watch very carefully to be sure just what measurement units are being used, and what kind of susceptibility is being discussed.

In our work we measure the dimensionless volume susceptibility and use the International System of units (SI). But, just because volume susceptibility is dimensionless doesn't mean there is no difference between units systems.

Unfortunately when working in electrical units there is a factor of 4 Pi that creeps in. If you see volume susceptibility given in the cgs system then you need to multiply by 4 Pi to get International units (SI).

But, it gets more complicated as many scientists use mass, or specific, and molar susceptibility in their work, which do have dimensions and these also will have the 4 pi problem. We don't have time to go into details, but be warned of the problem.

Now, why should some materials have a positive susceptibility and others a negative? It all depends on the nature of the electrons spinning around the individual atoms. It is found that the transition elements and the rare-earths are the elements that provide positive susceptibilities to materials which contain them.

The transition elements are the iron manganese, chromium, copper, nickel etc which also are responsible for color in many of our gems. Thus, being able to measure susceptibility gives us direct information on the quantities of these color-causing elements within our gems.

Something not easily available to the average gemmologist previously.

Effective Magnetron Numbers Iron Group Elements		
Ion	Number (exp)	Number²
Fe ³⁺ , Mn ²⁺	5.9	34.8
Fe ²⁺	5.4	29.2
Mn ³⁺ , Cr ²⁺	4.9	24
Co ²⁺	4.8	23
Cr ³⁺ , V ²⁺	3.8	14.4
Ni ²⁺	3.2	10.2
V ³⁺	2.8	7.84
Cu ²⁺	1.9	3.61
Ti ³⁺ , V ⁴⁺	1.8	3.24

**Table 1: IRON GROUP ELEMENTS
AND MAGNETON NO'S**

Table 1 shows some of the important iron-group elements and their effective magnetron numbers. This number is essentially the relative effective strength of the tiny magnets within each atom. In the third column I have shown the square of that number which determines the value of the bulk volume susceptibility of a gem which contains the particular element. Note that

the values are dependent on the valence state of the element. As you can see, Iron and Manganese (Fe^{3+} and Mn^{2+}) are ten times as effective as a similar quantity of Cu^{2+} .

The effective magneton numbers are not fixed numbers, but will vary to some extent depending on the type of neighboring atoms within a gem and how the atoms are coordinated within the structure.

The numbers shown above are an average of measured magneton numbers for various substances taken from Kittel (1956). What is important for the gemmologist is that the approximate susceptibility of any gem can be calculated if its chemistry is known.

Conversely, with some restrictions, the transition element chemistry can be estimated from a measurement of the volume susceptibility. The Langevin equation, which comes from atomic theory, permits us to calculate susceptibility. It is valid only for paramagnetic materials (Kittel, 1956).

Figure 2. LANGEVIN EQUATION

Calculation of Susceptibility from Chemistry

The Langevin equation

$$\chi = \frac{N \beta^2}{3kT} \sum \mu_i^2 \frac{P_i}{W_i}$$

χ = mass susceptibility
 N = Avogadro's number
 β = Bohr magneton
 k = Boltzman's constant
 T = absolute temperature
 μ_i = effective magneton number
 P_i = Wt.% of ion
 W_i = atomic wt. of ion

$$\chi = 426.5 \times 10^{-6} \sum \mu_i^2 \frac{P_i}{W_i}$$

Figure 2 is the Langevin equation. The various symbols in front of the summation sign are fundamental atomic constants, N -- Avogadro's number, k -- Boltzman's constant T -- is absolute temperature, and β -- the Bohr magneton. All these combine to give a constant which is 426×10^{-6} at room temperature (20°C). Again, this is for **paramagnetic** materials only.

This constant is simply multiplied by the sum of the square of the effective magnetic moment of the paramagnetic ions in the sample, times the weight percent of the ion divided by its atomic weight.

An example of how this is used can be found in the paper by Parks and Akhtar (1968). An example of its use for gemmological purposes is given in Hoover and Williams (2007) and Hoover et al (2008).

On the assumption that the only significant transition element in a sapphire is Fe⁺³, the susceptibility of corundum with varying iron content is calculated. This is valid for most sapphires.

From this, the iron content from a measured susceptibility of any sapphire can be estimated.

Similarly we needed the end-member susceptibility of andradite, almandine and spessartine for our garnet work. These were calculated from the Langevin equation and are shown in Table 2 below.

Table 2

Comparison of Magnetic Susceptibilities

Garnet Type	Anderson 'Magnetism Value'	Haralyi μcgs^1	Frost $\times 10^6 \text{ emu Cm}^3/\text{gm}$	Frost $10^4(\text{SI})$ (calc)	Hoover (calc) $10^4(\text{SI})$
Almandine	290-410	50-130	68 +/-2	36.9	40.7
Spessartine	250-360	40-60	81+/3	42.7	47.4
Demantoid	120-200		49+/3	23.8	30.8
Rhodolite	-	30-50	-		-
Pyrope	40-100	12-30	-		-
Hessonite	40	0.04-0.06	-		-
Grossular	-	0.25-0.50	-		-

¹Note: Haralyi's units are in question as to whether they are for mass or volume susceptibility. Frost's values shown are for mass susceptibility for end-members and also recalculated to show volume susceptibility to allow direct comparison with Hoover's values.

Anderson made the following separations:

Non-Magnetic	Magnetic
Orange metamict Zircon	Spessartine
Green metamict Zircon	Demantoid
Sinhalite	Brown Peridot
Black Diamond	Pleonaste or Hematite
Hematite ¹	Hemetine ²
Red Spinel	Pyrope

¹ Hematite is shown above to be both non-magnetic and magnetic. To clarify, hematite is weakly magnetic relative to Black Diamond but is less magnetic than Hemetine

²Hemetine is a Hematite simulant containing Iron and Titanium Oxides

Table 2 :Magnetic Susceptibilities of Garnets

We recognize that the numbers may not be the exact values, but when sufficient measurements are obtained those values can be adjusted. That we are close is supported by earlier measurements from Frost (1960) and Nathan (1964), and from our own measurements of numerous garnets.

References

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