

MAGNETIC SUSCEPTIBILITY FOR GEMSTONE DISCRIMINATION

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I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely in your thoughts advanced to the state of Science, whatever the matter may be.

(Lord Kelvin, Electrical Units of Measurement, 1883)

ABSTRACT

Following a review of the physics of magnetism and magnetic susceptibility, the authors present a simple method for the quantitative measurement of magnetic susceptibility on cut gemstones. The method requires a scale such as commonly used for measurement of weights of cut gemstones, a few inexpensive magnets, and a simple device to slowly place and then lift the magnet from the gemstone's surface so as to measure the force of attraction

The technique is applied to a variety of gemstones, but is focused on corundum and peridot. The authors believe that magnetic susceptibility may be able to distinguish between the magmatic or metamorphic genesis of corunda on the basis of their iron content as indicated by their magnetic susceptibility. Similarly, peridot may be categorised from its iron content based on magnetic susceptibility, and is easily distinguished from sinhalite.

INTRODUCTION

Lord Kelvin, in the quote above, clearly was arguing for quantitative measurements in the practice of science; yet for the gemmologist there are few quantitative measurements we normally make in daily practice. Principally these are

refractive index, birefringence, and density. The authors introduce a relatively simple, inexpensive way for the average gemmologist to add magnetic susceptibility to his/her arsenal of tools.

Magnetic properties of gems have been known for thousands of years, but, with the exception of magnetite, this property has had very little use in the identification of discrimination between gemstones. Magnetic properties are mentioned in passing in many gem texts going back over 2,000 years. Although there is extensive literature in the geological sciences, until recently there has been little interest shown by most modern gemmologists. However, a few gemmologists have recently started to take note. Qualitative studies began as early as that of Tisdall (1962). Koivula & Fryer (1984) gave a fine discussion of techniques they used on diamonds. Gumpesberger (2006) is the latest, examining a wide variety of gemstones.

Semi-quantitative measurements started with B. W. Anderson (1959, 1980). In the gemmological literature, quantitative measurements were reported by Rossman & Kirschvink, 1984; Haralyi (1993, 1994); Haralyi & Bosshart (2001), and Titkov *et al.* (2003).

The authors' interest in the subject was stimulated by the enthusiasm of Ms Gumpesberger based on her empirical tests with some new rare-earth magnets (Gumpesberger, 2006). Although skeptical at first, initial testing suggested that quantitative gem testing of magnetic susceptibility may now be possible. This, combined with the wide range of available mineral susceptibilities, suggested that gemstone susceptibilities might prove to be more useful in gemstone discrimination than previously thought.

Because it is mostly the rare-earth and

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transition elements that give rise to positive magnetic susceptibility in gemstones, measurement of this property complements that of optical spectra in discrimination between gemstones. It provides an approximate measure of the total content of the magnetic ions present, in practice mostly those of iron and manganese.

This paper reviews the history, discusses the science of mineral magnetism, describes a means for easily measuring a gemstone's magnetic susceptibility, and briefly evaluates such measurements for gemstone discrimination. In order to make the technique rapidly known to the gemmological community, we present only sufficient results that the potential of this technique, we hope, will be apparent, and that others will join in its use and evaluation for gemmology.

HISTORY

Early use of magnet as a gem

The phenomenal gem *magnes* was described by Pliny about 2,000 years ago. Pliny noted its ability to attract bits of iron (Eichholz, 1962). It was the magic of its attractive properties, rather than any beauty, that made *magnes* a desired gemstone for many centuries. The *magnes* of Pliny was, in most cases, an example of the mineral magnetite that had acquired permanent magnetization. A more recent popular term is lodestone. Pliny noted that its ability to attract bits of iron, or another *magnes*, provided a test for the gem; but this was to be the only such magnetic test for gems until the true nature of magnetism became understood during the 19th century.

Al Beruni, in his treatise on gemstones, written about 1040 (Said, 1989) devoted a little over two pages to *magnes*—about the same as for turquoise. He noted that jewelers used the “magnet” to separate admixed magnetite sand from panned gold concentrates. He also noted its uses for medical purposes, such as removing iron pieces from wounds, and as a medicine.

Kosminsky (1923) in his curious book, *The magic and science of jewels and stones* noted that it was popular during the Middle Ages for lover's rings due to the mutual attraction of lodestone gems. Evans (1922) noted its use as a test for chastity, adultery, and as an aid to thieves. Magnet clearly was an important gem to our ancestors. Now, we are more interested in its use for gem testing.

BASIC THEORY

Before discussing modern attempts at magnetic testing, we need to review a few

aspects of magnetic theory for better understanding of the problem and to aid the reader with little background in the subject. The subject is rather complex, so that one wishing to delve more deeply into it should consult a text such as Kittel (1956), Bates (1948), O'Reilly (1984), or the internet. Modern understanding of magnetism shows that it arises from the motion of electrons in atoms in the same way as an electrical current in a wire produces a magnetic field about the wire. Within the atom, electrons move in orbits about the nucleus, and also spin. Both of these motions produce very small magnetic dipole (oppositely charged) fields, so the electrons act as very small permanent magnets within each atom. The magnetic properties of any material are due to how the contributions of each atom interact in bulk to an applied magnetic field.

We will be primarily concerned with magnetic susceptibility per unit volume, a bulk property of all materials, since that is what we directly measure. Normally its symbol is k . It is dimensionless, defined by:

$$\text{Equation 1. } k = M_v/H$$

where M_v = intensity of magnetization per unit volume produced in the material, and,

H = magnetic field intensity applied

Often, susceptibilities are alternately expressed as specific or mass susceptibilities, symbol χ , often shortened to just susceptibilities, and defined as:

$$\text{Equation 2. } \chi = M_m/H = k/\rho$$

where ρ = density, and

M_m = magnetization per unit mass.

Although k is dimensionless, one still needs to be careful which system of units are used when comparing results. Two common systems are the older emu/cgs (centimetre-gram-second) and the now more commonly used SI (metre-kilogram-second) system. To convert k from cgs to SI units multiply by 4π . In general, we will use SI units in this paper.

From atomic theory, χ and hence k can be calculated from several atomic constants, and the magnetic moment of the ions (Kittel 1956; Parks & Akhtar 1968; Verhoogen 1958), as given by equation 3:

Equation 3. $\chi = N\beta^2/3kT \sum (\mu_i^2 P_i)/W_i$ where

N = Avogadro's number,

β = Bohr magneton,

k = Boltzmann's constant,

T = absolute temperature,

μ_i = magnetic moment of the ion,

P_i = weight % of the ion, and,

W_i = atomic weight of the ion.

Solutions of 3 give fair agreement with experiment in many cases, and we will make use of this later. However, the magnetic moment of any ion is a function of its position within the crystal, neighboring ions, etc., so is not a fixed constant.

Studies have shown that there are four principal kinds of magnetic materials. The orbiting electrons of any material, when in the presence of an applied field, will precess (change in the direction of the axis of a rotating object) presenting a weak opposing magnetic field. If no other magnetic effects are present, these materials will be repelled by a magnet, and k and χ will be negative. Such materials are called **diamagnetic**. Values typically are in the range $\chi = -0.25$ to -0.5×10^{-6} cgs units. Diamond is -0.49×10^{-6} , graphite -3.5×10^{-6} , and quartz -0.49×10^{-6} . Thus, the permeability is very little different from that in a vacuum.

In some atoms and molecules there is a net magnetization generally related to electron spin, but which in bulk is zero due to thermal motion of the atoms. But, when a field is applied they can become oriented to give a small net positive susceptibility, overcoming the negative value due to diamagnetism. Such materials are called **paramagnetic**, and their susceptibility decreases as temperature increases as shown by equation 3. The prime elements contributing to this type of magnetism are the transition and rare-earth elements. The olivine (peridot), garnet, pyroxene, and amphibole mineral groups are examples. Values of k will generally range from a small positive value up to about $6,000 \times 10^{-6}$ SI.

For the transition elements it is the number of unpaired 3d-shell electrons that primarily control the magnetization. Table 1 lists the transition and rare-earth elements and the square of their average magnetic moments which determines their relative contribution to a mineral's susceptibility by equation 3.

ION	MAGNETIC MOMENT (Experimental)	MAGNETIC MOMENT SQUARED
Fe ³⁺ , Mn ²⁺	5.9	34.8
Fe ²⁺	5.4	29.2
Mn ³⁺ , Cr ²⁺	4.9	24.0
Co ²⁺	4.8	23.0
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
Dy ³⁺	10.6	112
Ho ³⁺	10.4	108
Er ³⁺ , Tb ³⁺	9.5	90
Gd ³⁺	8.0	64
Tm ³⁺	7.3	53
Yb ³⁺	4.5	20
Nd ³⁺ , Pr ³⁺	3.5	12.2
Eu ³⁺	3.4	11.6
Ce ³⁺	2.4	5.7
Sm ³⁺	1.5	2.2

Table 1. Magnetic moments of the transition and rare-earth elements, and their squares.

As can be seen it is primarily the manganese- and iron-bearing gemstones that will have the greatest paramagnetic susceptibilities of the transition elements. But many rare-earths have much higher values. Thus, magnetic testing is showing the presence, or not, of these elements, just as absorption spectra show their presence by the reaction of light to the outer electron structure of the atoms of the mineral (Fritsch & Rossman 1987, 1988). It is also clear why the rare-earth doped synthetic gems and gadolinium-gallium-garnet, $Gd_3Ga_5O_{12}$, are strongly magnetic.

Ferromagnetic materials have much larger absolute susceptibilities than diamagnetic or paramagnetic materials due to their natural alignment of magnetic moments of the individual atoms. They are further distinguished by being made up of small individual magnetic domains in which the magnetization may not be the same as in a neighbor. These ferromagnetic materials may be subdivided further into true ferromagnetic, antiferromagnetic, ferrimagnetic, and canted ferrimagnetic types. The details are not important for this paper. However, of most importance for us is ferrimagnetic magnetite with volume susceptibility ranging about 4 to 10 SI. This is about 1 million times, in absolute value, that of the diamagnetic materials. Thus a minute inclusion of magnetite can swamp the measurement of diamagnetic or paramagnetic gemstones. This becomes important in addressing magnetic properties of diamond.

To further complicate matters, magnetic susceptibility is a directional property just as is

refractive index. We have been unable to find many values of single crystal susceptibilities. Of those few, tourmaline, zircon and beryl have significant differences with direction (ICT 1930). The crystallographic orientation and symmetry of the magnetic anisotropy is not necessarily the same as that for the optical anisotropy.

Measurement of susceptibility is typically done either by induction methods where the sample material forms the core between two electrical coils, or by measuring the force exerted on the sample by an applied magnetic field. Induction methods are common, but require a sample in a fixed shape, often a cylinder, so these are not easily applied to gemstones. That leaves the force techniques which also typically require a standard shaped sample (Bates 1948, O'Reilly 1984).

Space doesn't permit going into detail of past measurement procedures. Interested readers may go to texts or the internet for details. What is important for the gemmologist to know is that it is not the strength of the magnetic field that causes a force on a substance; but the gradient of the magnetic field that represents its spatial rate of change. There is no force in a uniform field. The force is given by the vector equation (Kittel, 1956), as given by equation 4

$$\text{Equation 4. } F = 1/2 \text{ grad. } \int kH^2 dv$$

where grad.= the gradient operator and the integration is taken over the volume of the sample.

If the susceptibility, k , is independent of the magnetic field, and is homogeneous, equation 4 can be written as equation 5.

$$\text{Equation 5. } F = 1/2 k [\text{grad. } \int H^2 dv]$$

Now consider a very large and thick plate of gem material on which a magnet is placed. The gradient of the magnetic field is greatest just below the magnet's pole and drops off rapidly with distance away from the pole. Thus, the force of attraction between the magnet and material is mostly very near the contact region. This force does not vary until the magnet gets near an edge. So, if much of the material is removed from the edges, there will be no significant change in the force. There is a volume of the material beyond which the term in the bracket [] becomes essentially constant. We can then write equation 6:

$$\text{Equation 6. } F = 1/2 k[C]$$

where C = a constant.

If this condition can be met, then the

measured force of attraction is a direct measure of the volume susceptibility. This, then, is the key to easy measuring of magnetic susceptibility of gemstones; by use of a small enough magnet. It follows from equation 6 that the magnetic susceptibility of an unknown gemstone, k_g , is given by equation 7.

$$\text{Equation 7. } k_g = k_s F_s / F_g$$

where subscript s is the standard, and, subscript g is that of the gem.

But, if a major part of the strong gradient is outside the sample, you should see that the shape of the gem, its size, its distance to the magnet, and the gradient of the magnetic field in space all have a part in determining what the total force may be. It is knowing, or eliminating, these factors that in the past has presented a major problem in determination of magnetic susceptibility of cut gems, by a force or weight loss technique.

Our assumption that k was homogeneous is strictly not true for many gemstones. For example, the non-isometric ones, and those that may have concentration variations within the measured volume, will not exactly meet the restriction. However, for most species this is not expected to be a major problem due to the large range in parametric susceptibilities.

PRIOR MAGNETIC MEASUREMENT

Until quite recently, little mention has been made of magnetic testing of gemstones. Bauer (1898) did note that magnetite can be distinguished from other black stones by its strong attraction to a magnet. Goodchild (1908) noted the only gem material with important magnetic properties was iserine, a titaniferous iron ore that was used for ornamental purposes. Iserine is not a well defined mineral and this probably best referred to as a titaniferous magnetite. Walton (1952) noted that magnetite and pyrrhotite were the only gem materials affected by a bar magnet. He also noted that some minerals may be separated by the electromagnet; but here he appears to be referring to a magnetic separator for mineral grains in use for industrial purposes.

We will not go into detail of the relatively recent revival of qualitative magnetic testing stimulated, we suspect, by interest in Anderson's early work and the potential (Koivula & Fryer 1984) for its use in separating synthetic and natural diamonds. Tisdall (1962) was the earliest we have found. He suspended a gemstone on a long thread and brought a magnet close to detect any attraction. Koivula & Fryer (1984) described a number of techniques of varying sensitivity for

detecting magnetic attraction that they utilized on synthetic diamonds. This is one of the best descriptions we know of such methods.

Gumpesberger (2006) gave the latest review for qualitative testing of magnetic response, either by floating a specimen, hanging it as a pendulum, as Tisdall (1962) did, or, if strongly magnetic, by simply dragging or lifting it. She reported the ability to distinguish between the same group of gemstones as Anderson (1980), and added information on many more gemstones.

Anderson (1959, 1980) was the first gemmologist we know of to use "semi-quantitative" measurements of magnetic attraction. He used a "small" inexpensive horseshoe-shaped Alnico magnet of unspecified dimensions for a field source. An aperiodic balance was used to measure the "minimum weight that could be held by the magnet". The difference would be the maximum "pull" of the magnet. An aperiodic balance is a balance which is dampened, typically by air dampers, so as not to swing back and forth, but which settles into position from one direction. So as to avoid problems due to the balance pan being too close to the magnet, Anderson placed his gemstone on a cork pedestal.

Anderson called the weight loss, the magnetic "pull", but found that the size of a particular gem species affected the result. He, purely empirically, corrected his measurements so that a given gem species would have the same value of "magnetism"; that is magnetic susceptibility, by the empirical formula specified in equation 8.

$$\text{Equation 8. "magnetism"} = \text{weight loss} \times 100 / \sqrt{\text{weight}}.$$

From the discussion above, this formula is obviously in error.

Biswas (1974) published a short paper correlating chemical and physical properties of garnets; but his paper is largely unknown. His work covers 31 garnets in which the full chemistry is given as well as values for density, refractive index, magnetic susceptibility, and unit cell dimension. Unfortunately, he does not state how his measurements were acquired. All of Biswas' garnets were of natural origin, so had a combination of end member compositions. Values reported are in cgs units, ranging from 11.0×10^{-6} ($138. \times 10^{-6}$ SI) for a grossular to 78.6×10^{-6} ($988. \times 10^{-6}$ SI) for a spessartine. These values, we believe, are in error as they span a very small range ($\times 7.15$) for the given chemistry. Summaries from geophysical literature give a range of 13×10^{-6} SI to 5850×10^{-6} SI for the garnet group ($\times 450$).

Rossmann & Kirschvink (1984), using sophisticated laboratory equipment, measured the remnant magnetism and coercivity of natural and synthetic diamonds due to ferromagnetic inclusions. Further discussion of these properties is beyond the scope of this paper.

To our knowledge, Haralyi (1993, 1994) was the first to attempt true quantitative measurement of magnetic susceptibility on faceted gemstones as a tool for gemmologists. His unfortunate death, a few years ago, leaves some questions open with respect to details of precisely what he did. We are indebted to George Bosshart for providing several papers of which we were not aware, and photographs of his instrumentation. Haralyi followed the general approach of Anderson (1989) by measuring the loss, or gain, in weight of a gemstone as a strong magnet was brought close. He noted the problems of Anderson's empirical approach, saying "Few gems can be evaluated by the method". Haralyi used a Sartorius balance with sensitivity of 0.1 mg, and a 5.5 cm high by 1 cm diameter neodymium-iron-boron (NIB) magnet with 11.5 KGauss of magnetization in his initial work. Later he used a 5.0 cm high by 4.8 cm diameter magnet. To obtain the susceptibility of an unknown gemstone Haralyi used the following relationship:

$$\text{Equation 9. } \chi_g = (\text{Fg/Wg}) \times (\text{Ws/Fs}) \times \chi_s$$

where χ is mass susceptibility and, subscripts g and s are for the gem and standard.

Although the forces on a substance are related to its volume susceptibility, equation 9 results from equation 7 provided the gem and standard are of the same shape and volume, and are positioned in exactly the same position below the magnet. It appears Haralyi was measuring the specific susceptibility, not the volume susceptibility, and this unfortunately misleads the reader by not giving the proper units on his listed values—namely cubic centimeters per gram.

While Haralyi noted several ways to proceed from that point to obtain the magnetic susceptibility, it appears that what he did was to make many known standards (gem models) of various sizes, shapes and susceptibility by mixing magnetite into epoxy resin. By measuring the weight and loss of weight of these numerous standards Haralyi did a least squares fit to the dimensions of the standards so as to be able to calculate a standard susceptibility of an epoxy filled model that matched the dimensions of a particular unknown gem. Knowing the susceptibility of the epoxy model, one could then calculate the unknown susceptibility. This rather elaborate procedure clearly was not a

technique easily practiced by the average gemmologist. Further, magnetite is ferrimagnetic, so its susceptibility is a function of the applied magnetic field strength, making it inappropriate for use as a standard. In spite of this, his values appear to be approximately correct.

Haralyi & Bosshart (2001) presented susceptibility data on 24 sapphire samples from various sources that were measured using Haralyi's method. The results ran from diamagnetic to just above $+6 \times 10^{-6}$ (cm^3/gm^2), or $k = 24 \times 10^{-6}$ cgs.

Brief mention needs to be made of Hanneman's (2002) paper on "magnetic index". His "magnetic index meter" employed a rare-earth magnet attached to a pivoted arm with the magnet near the pivot. A gem was glued to a nylon thread and suspended so as to have the table contact the magnet. This assembly was rotated until the gem broke free of the magnet, and the angle was noted. Hanneman, apparently without any understanding of equation 4, calculated an assumed response of his device using Anderson's data.

Titkov *et al.* (2003) gave mass susceptibilities of Russian dark gray to black diamonds from -0.6×10^{-8} to $+36 \times 10^{-8}$ m^2/kg (volume susceptibility -26.5 to $+1590$ SI). They note that ferromagnetic inclusions were responsible for the anomalously high susceptibilities. The darker black stones had much magnetite, while the dark gray diamonds contained mostly hematite and native iron. They suggest that susceptibility measurements may be of value as a criterion of natural black color in diamond.

A U.S. patent (6281680) has been issued on an induction type device that is claimed to quickly separate synthetic from natural diamonds based on their magnetic susceptibility. From the description in the patent, the instrument appears to be nothing more than a common metal detector scaled down in size. A readout gives an indication of the probability of the diamond being synthetic. This instrument does not give a measure of susceptibility.

METHOD OF MEASUREMENT

Modern NIB magnets are extremely powerful, making possible uses not practical in the past. The illustration of the weak forces associated with diamagnetic materials can be shown, as Gumpesberger (2006) noted. Thus, a sensitive balance or scale, such as used by gemmologists, should provide sufficient accuracy for quantitative measurement of the forces involved with paramagnetic materials.

We used 1/4, 3/16, 1/8 inch diameter by 1/2 inch long, and 1/16 by 1/4 inch N42 grade NIB cylindrical magnets from K&J Magnetics. Total cost was a few dollars. Measured diameters were 6.32 mm, 4.77 mm, 3.19 mm, and 1.58 mm respectively. They are axially magnetized with the lifting force of the 1/4 inch magnet rated at 3.99 pounds of steel (1 pound Avoirdupois = 453.59 g). This is the clue to gem measurement. The NIB magnets used will easily fit within the diameter of most gemstone tables. Thus, if the small NIB magnets have enough "pull", and it fits within the table, a simple weighing of the "pull" could be made and this would represent magnetic susceptibility.

For magnets of each size the North pole was marked so that we could always measure with a known polarity, and could easily switch poles if desired. If no ferromagnetic inclusions were present in the gemstone, there will be no difference between the poles. Several percent variations in "pull" between magnets of the same size and composition were found, so it was necessary to calibrate and use the same set of magnets for best accuracy.

The authors have experimented with this technique, using an old Becker analytical balance weighing to 0.5 milligram (0.0025 ct), and a Scientech SP150 electronic scale weighing to 0.001 ct. An iron magnet holder (Fig. 1), suspended by a thread, was used to hold the magnet in position over the gemstone. We made ours from a soft iron nail drilled, as shown, so as to suspend the piece above the centre of mass of the gemstone. This magnet holder permitted ease of switching magnets, and/or reversing the polarity of the magnets.

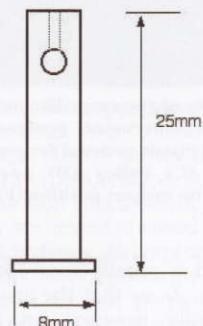


Fig. 1. Sketch of the magnet holder used.

When a conventional balance was used, the weighing pan was removed and the magnet holder with magnet substituted. Then, necessary weights were added so as to bring the whole into balance. An adjustable-height tripod was used below the magnet to hold the gemstone, and to bring it into the proximity of the magnet at or very near to the balance point. To prevent

any motion of the gem due to the magnetic forces, it was held in position with Bostick Blue Tack[®] (Blu Tac, Fun Tack) or similar material. Weights were then added to the weighing pan until the magnet broke away from the gemstone. This procedure is a bit cumbersome, but measurements can be made in a few minutes once the unit is set up.

We prefer to use a modern electronic balance where little sample motion occurs in the weighing process. In this case, the gemstone is placed on a pedestal on the scale to remove it and the magnet from the near vicinity of the scale platform. Blue Tack is again used to hold the gem in place.



Fig. 2. Photograph of the crane-like structure and scale used in the measurement process for magnetic susceptibility. (A) Plastic pedestal for gem (B) Magnet and magnet holder (C) Pulley (D) Spring (E) Coarse adjustment knob on magnet position (F) Fine adjustment knob.

We designed a small crane-like structure of aluminum (Fig. 2) so that the magnet assembly could be rapidly lowered on the thread to contact with the gemstone, and then very slowly be lifted away by means of a small screw. In order to get reproducible readings with the 8/32 machine screw used for fine adjustment, we had to suspend the small pulley from a weak spring to give sufficient compliance in the system to allow fine adjustment to function. The reader may discover improvements to this system. If the scale is tared before the magnet approaches, then one watches the reading as it goes negative to a maximum before the magnet pulls away.

The maximum negative value gives the attractive force for the particular magnet-gem used. Several readings are taken to get a good average value.

Care must be taken to have the table and the pole face in the same plane. We checked this by bringing the magnet close, but not touching, the table of the gemstone and looking across the contact area at a piece of white paper to ascertain if the surfaces were parallel. This should be done in two directions. Of course, the surfaces must be clean and free of dust, dirt, or sticky material. The fine adjustment to pull the magnet away from the gemstone must be made in extremely fine increments. A coarse adjustment will not give reproducible results. Most any scheme by which the magnet can be positioned on the gemstone's table, and then very gradually lifted off, should function. No doubt better schemes will be developed.

CALIBRATION

We first tested to verify that the "pull" was directly proportional to the square of the magnet's diameter; that is, proportional to the area of the magnet's pole. A 20.5 ct Brazilian almandine was used to provide sufficient table surface area, and high susceptibility. Figure 3 shows results for the four magnet sizes from both the balance and electronic scale measurements. Note the agreement between both sets of weighings. But what is important in this figure is the slope of the lines which are almost on top of each other.

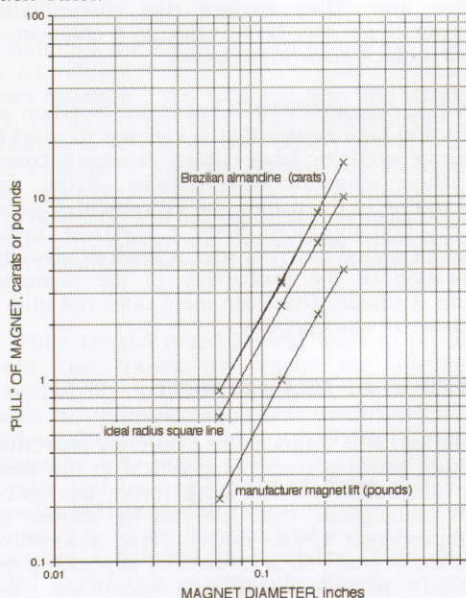


Fig. 3. Plot of magnetic attraction as a function of magnet diameter for an electronic scale and analytical balance. The manufacturer's "pull" force also shown as well as the plot of a square relationship.

Other magnets of similar type may show variations of several per cent. The 1/4 inch magnets gave "pulls" of 15.50 ct, and 15.48 ct for the two scales, showing the strength of modern magnets. An ideal curve of the radius squared is shown for reference, as well as the manufacturer's data for the pull (again see figure 3). Both our data from the almandine and the manufacturer's data show the pull increases a bit more than the square of the nominal radius. There are several possibilities for this, which we didn't investigate as they are not important for this investigation.

To determine at what magnet-gem distance the attractive force became insignificant we placed paper/cardboard spacers between the 20.5 ct almandine and the magnet; measuring the pull as the spacer thickness increased. For all magnets the force had fallen to 1% of the maximum at or less than 4 mm of separation. This gives us a minimum thickness of material for testing.

Another set of measurements were made to determine the effect of table size. A 4.40 ct spessartine, with table diameter of 4.3 mm, and a 2.57 ct almandine, with a 4.9 mm table, were used. The plots of "pull" versus magnet diameter (Fig. 4) show a square relationship for the 4.9 mm table of the almandine with magnets up to 4.77 mm diameter, and falling by about 12% with the 6.32 mm magnet. The spessartine with the 4.3 mm table was down about 9% with the 4.77 mm magnet and down 25% for the 6.32 mm magnet. These data suggest that magnets up to the table diameter may be used for measurement with little error. It should be clear that for the best accuracy one needs to use as large a magnet as possible that still fits within the table surface of the gemstone.

The last hurdle was what material to use to calibrate? Cupric sulfate and ferrous sulfate are often used as standards, and magnetic susceptibility values are known for many other transition metal salts as well. But the values are from powdered samples so that their anisotropy is unknown. With our apparatus single crystals or compact masses were needed. But, if single crystals were used we had not yet found directional values for the standards.

However, one needs to remember that the magnetic field gradient around the cylindrical magnet is not unidirectional, and becomes radial at distance if the magnet is long. Thus, the forces within the gemstone are not unidirectional, and the horizontal forces, due to symmetry about the pole, will mostly cancel—leaving a net vertical force which we measure. Without going into detail, this measurement technique will average any anisotropy to some extent.

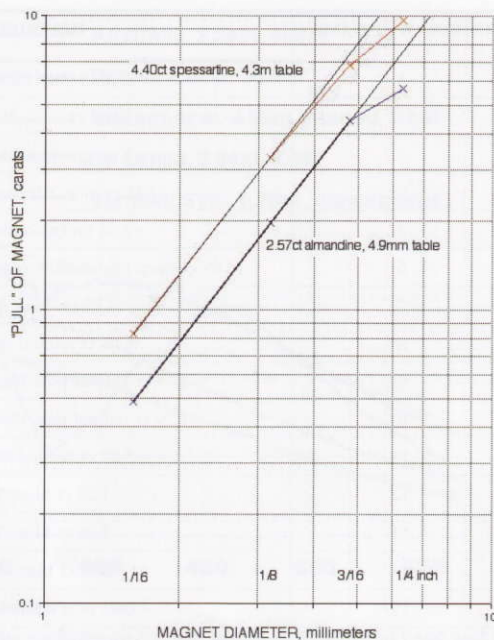


Fig. 4. Plot of magnetic attraction as a function of magnet diameter for garnets of differing table diameter.

To see if our technique was sensitive to the anisotropy of crystals, we tested several rough gem samples by grinding flats in determined orientations on the crystal and then measuring their magnetic susceptibility. Of two gemmy Brazilian dark green tourmaline samples, one gave 258 SI on the 'c' face and 255 SI perpendicular, while the other gave 245 SI on 'c' face and 255 SI perpendicular. Since the higher value is not consistent with orientation, we concluded that, for these samples, the small variation was probably due to iron zoning in the sample. Two very light colour, grey-blue Missouri River (Montana) sapphire crystals were measured. These showed no determinable anisotropy, giving 38 SI and 39 SI respectively on both their 'c' and 'a' faces. Data given in the ICT (1930) shows tourmaline with 'c' = 14 SI, and perpendicular = 9.4 SI. This must have been a low-iron specimen. A *geuda* sapphire from Sri Lanka we tested showed as diamagnetic on both 'c' and 'a' faces. Zircon has been reported as showing rather large anisotropy (ICT, 1930) at -2.1 SI for 'c' and +9.2 SI perpendicular. A red-brown zircon rough we measured on the 'c' and 'm' faces gave both as diamagnetic.

We did the same for $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$, our calibration material, by grinding flats in three orthogonal directions on a single crystal sample that we grew. As we found no measurable anisotropy on these, so we have used literature values (13.5×10^{-6} cgs, 170×10^{-6} SI) for our calibrations. Our limited investigation has shown no clear problem from anisotropy.

NUMBER OF SPECIMEN	DESCRIPTION	MAGNETIC SUSCEPTIBILITY (SI X 10 ⁻⁶)
1	2.26 ct dark blue, Australia	268
2	3.98 ct blue, Madagascar	108
3	~2. ct greenish-blue, Australia	82.6
4	2.41 ct blue, Chatham flux-grown	55
5	~2. ct greenish-blue, Australia	51.5
6	13.05 ct deep blue-yellow parti-colour Australia, rough	46
7	1.75 ct blue Australian	42.5
8	4.04 ct natural blue, Burma	39.6
9	1.97 ct natural pale blue, Montana rough	38
10	1.70 ct natural pale blue, Montana rough	39
11	5.84 ct natural blue, Burma	30.7
12	1.25 ct blue, Thailand	28.8
13	1.26 ct blue, Thailand	25.1
14	2.94 ct blue, Sri Lanka	4.3
15	4.08ct heat treated, Madagascar	2.6
16	5.39 ct natural blue, Tanzania	0.0
17	6.78ct blue Verneuil synthetic	Diamagnetic
18	Rough geuda, Sri Lanka	Diamagnetic

Table 2. Magnetic susceptibilities of blue sapphires.

NUMBER OF SPECIMEN	DESCRIPTION	MAGNETIC SUSCEPTIBILITY (SI X 10 ⁻⁶)
1	7.12 ct padparadscha, synthetic	257
2	~2.2 ct padparadscha, synthetic	105
3	3.12 ct Be-treated yellow, Africa	46.3
4	2.53 ct Be-treated golden	43
5	3.34 ct Be-treated yellow	34.9
6	2.56 ct Be-treated intense canary yellow	32.1
7	1.56 ct light green, Africa	22.2
8	~2.2ct padparadscha, synthetic	21.7
9	3.03 ct celadon green	17.9
10	1.60 ct light green	16.1
11	2.86 ct natural light yellow	Diamagnetic
12	1.30 ct heated canary yellow, Sri Lanka	Diamagnetic
13	1.24 ct heated canary yellow, Sri Lanka	Diamagnetic
14	1.32 ct heated golden, Sri Lanka	Diamagnetic
15	1.76 ct heated yellow, Sri Lanka	Diamagnetic

Table 3. Magnetic susceptibilities of non-blue sapphires.

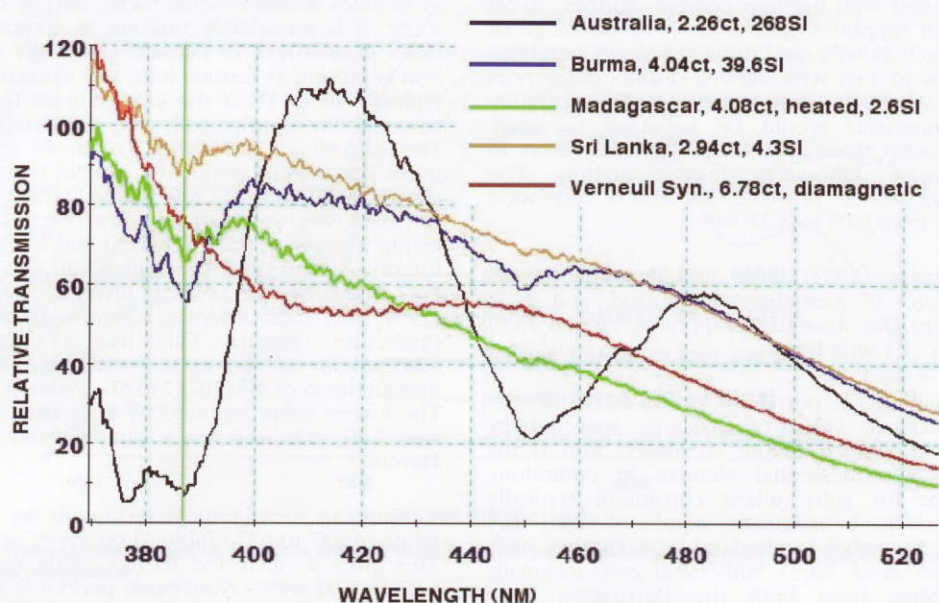


Fig. 5. Transmission spectra of five blue sapphires showing the variation in the 450 nm Fe-Fe absorption band and its correlation with measured susceptibilities.

GEMSTONE SUSEPTIBILITIES

Since Haralyi & Bosshart (2001) had looked at sapphire we also chose it for comparison purposes. Table 2 shows results for blue sapphire, and table 3 for other colored sapphires.

We show transmission spectra because they represent what one sees when viewing with a hand spectroscope. The relative value of each transmission curve was adjusted so that the 450, 388 and 377 nm absorptions are clearly seen. Ferric iron (Fe^{3+}) absorptions are spin forbidden, so normally will be weak. However, when iron concentration becomes large, pairing can occur, giving rise to Fe^{3+} - Fe^{3+} absorptions at 450 and 377 nm (Rossman 1975; Fritsch & Rossman 1988; Emmett 2003). The 450 nm peak seen in figure 5 is the most prominent iron feature in the visible range, making it a reasonable marker for comparison with susceptibility measurements. Further, it shows little anisotropy (Pisutha-Arnond *et al.* 2004), although some spin forbidden peaks may show large anisotropies (Rossman 1975). The agreement is quite striking. The dark blue Australian stone measured +268 SI and has the largest absorption. A natural blue Burmese stone, of 4.04 ct, had susceptibility of 39.6 SI, showing a distinct but much smaller 450 nm peak. A Sri Lankan stone of 2.94 ct gave 4.3 SI, and a heat-treated Madagascar stone of 4.08 ct gave 2.6 SI. They both showed very small 450 nm peaks. The Verneuil synthetic was diamagnetic and showed no 450 nm absorption. The effect of differing iron absorption in the UV

range shows a similar correlation to susceptibility in the magnitude of the 388 nm peak. Similarly, a change in slope of the transmission curves between 390 and 400 nm occurs where the high-iron sapphire has a much steeper slope than those of lesser iron content.

Clearly, as expected, our susceptibility measurements are reflecting the iron content of these sapphires. What is particularly interesting is that the variation in magnetic susceptibility between these samples is more than two orders of magnitude. While the results are intriguing, readers are cautioned about extrapolating from such limited data.

Anderson (1959) commented that the 450 nm iron absorption was best seen in Australian sapphire followed by, in order, those from Montana, Siam, Kenya, Kashmir, Burma, and Ceylon (Sri Lanka). Our limited susceptibility data, presented in tables 2 & 3, are in partial agreement. Schmetzer *et al.* (1983) showed spectra with analytical data for five (5) yellow sapphires that showed similar correlation with the strength of the 450 nm band and iron content. Two Sri Lankan sapphires these authors show had 0.05, and 0.11 wt% Fe, two Umba (Tanzanian) sapphires had 0.50 and 0.42 wt% Fe, and an Australian sapphire had 0.75 wt% Fe. Schmetzer & Schwarz (2004) gave chemical and spectroscopic data covering 152 orange sapphires, both natural and treated, from Sri Lanka, Ilakaka (Madagascar), and Songea (Tanzania). The 450 nm iron band is well

correlated with the iron content. Further, 26 Sri Lankan sapphires gave a Fe_2O_3 in the range of 0.03 to 0.25 wt%, and the 42 Songean sapphires of 1.04 to 1.80 wt% showed distinct differences in these populations. Susceptibility measurements would be expected to easily distinguish these populations without resort to expensive laboratory instrumentation. The Ilakaka stones, however, showed a very wide range from 0.05 to 3.22 wt%.

Pearson (1982) gave iron content for 13 sapphires (7 Australian, 3 Thailand, and 2 Sri Lankan). The Australian sapphires ranged from 0.62 to 1.1 wt% iron.

Equation 3 permits us to calculate the approximate value of magnetic susceptibility from known corundum chemistry. Iron is the principal nonessential element in corundum, except for ruby when chromium typically exceeds it. In magmatic sapphires Fe_2O_3 may reach 2 weight% (Sutherland 1998; Hughes 1997; Emmett *et al.* 2003). Sutherland gave magmatic sapphires from both the Barrington Tops (Australia) and West Pailin (Cambodia) deposits as reaching up to about 2 wt% Fe_2O_3 . From equation 3, and assuming all iron as ferric with no other magnetic ions, standard densities and the magnetic moment of ferric ion (Table 1), the calculated susceptibility is 287 SI, for 2 wt% Fe_2O_3 . The largest susceptibility we measured in sapphire was for the dark blue Australian stone (Fig. 6) which gave 268 SI.

The complex chemistry of corundum, with varying amounts of chromium, titanium, ferric and ferrous iron substituting in the lattice, makes exact conclusions about its chemistry from a single value of magnetic susceptibility impossible. At best one might be able to estimate probable iron content. However, it appears that, in many cases, one may be able to suggest that a corundum is of magmatic or metamorphic origin. However, much additional work is needed to determine the statistical variation between corundums of differing locals, and genesis.

Table 3 gives results on the 15 other colored sapphires we measured. These limited data show a wide variation in susceptibilities of synthetic padparasha, and that all the beryllium-treated stones measured gave intermediate values. The Sri Lankan stones all showed minimal susceptibilities.

Another example of how magnetic susceptibility can be used to investigate gem chemistry is the case of peridot. The olivine group minerals, forsterite to fayalite, are well studied by earth scientists. Peridot, with near 8 to 10% forsterite composition, is found world wide

in nodules within basaltic rocks, and in dunitic rocks. It is remarkably uniform in composition (Ross *et al.* 1954). In peridot, essentially all the iron is present as ferrous iron, and manganese is typically about 1% of the iron content. Thus, its susceptibility is principally due to ferrous iron. The deposit at San Carlos (Arizona) supplies much commercial peridot. A sample from there shows FeO of 9.46 wt% (Ross *et al.* 1954). Koivula (1981) summarized a few other analyses giving a range of 8.24 wt% FeO and 0.3% Fe_2O_3 for one sample and the highest at 10.37 wt% FeO. The largest FeO content given by Ross *et al.* (1954) was 10.26 wt% for a sample from Akita Prefecture (Japan). This has a calculated susceptibility of 16.9 to 18.7×10^{-6} cgs, versus a measurement of 18×10^{-6} (746 SI) (Vernon 1961). The lowest value reported by Ross *et al.* (1954) was 7.49 wt% iron for a sample from Oahu, Hawaii.

From our measurement technique we find a range of 447 to 637 (Table 4) on seven samples. This gives a calculated ferrous oxide range of 6.27 to 9.02 wt%. Norwegian peridot is known for its fine color, and low iron content (Arem 1987; O'Donoghue 1994). Our measurement of Norwegian peridots gave a range of 448, to 475 for their magnetic susceptibility, indicating an iron content of 6.27 to 6.67 wt%. Notably, a Pakistan stone had low susceptibility as well. Chinese and Egyptian stones are at the high end of iron content. Our results are in line with those reported by others and indicate the potential of susceptibility measurements in peridot for indirect measurement of the iron content.

Table 4 also shows measurements on three sinhalites.

NUMBER OF SPECIMEN	DESCRIPTION	MAGNETIC SUSCEPTIBILITY (SI $\times 10^{-6}$)
1	2.14 ct peridot, Zabargad, Egypt	637
2	4.42 ct peridot, China	622
3	13.79 ct peridot, Zabargad, Egypt	531
4	48.15 ct peridot, Burma	490
5	2.80 ct peridot, Norway	475
6	2.60 ct peridot, Norway	448
7	2.91 ct peridot, Pakistan	447
8	11.02 ct sinhalite, Sri Lanka	120
9	2.47 ct sinhalite, Sri Lanka	108
10	3.02 ct sinhalite, Sri Lanka	Diamagnetic

Table 4. Magnetic susceptibilities for peridot and sinhalite.

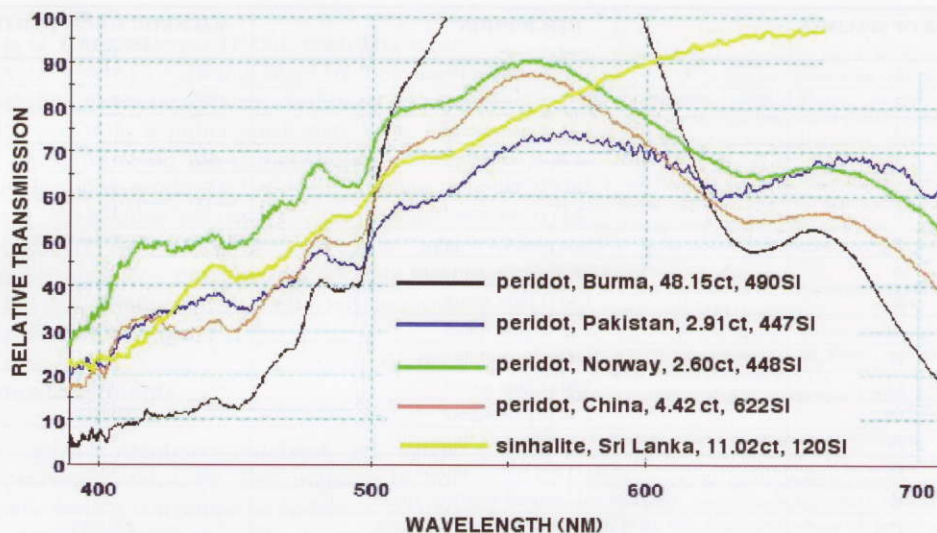


Fig. 6. Transmission spectra of 4 peridot and one sinhalite showing the variation in spectra and the corresponding measured susceptibility.

Hodgkinson (2006) has shown that sinhalite could be distinguished from peridot by the qualitative difference in their attraction to a magnet. Sinhalite (MgAlBO_3), if pure, would be diamagnetic, but the brown to yellow colours of typical gem material are due mostly to ferrous iron (Farrell & Newnham 1965), so are weakly magnetic. Farrell & Newnham (1965) and Henn (1994) noted the similarity of their visible spectra, arising from weak spin forbidden transitions in both gemstones. Hodgkinson (2006) noted that dark colored gems might be distinguished from peridot by their spectra, but many could not be distinguished. However, the large anisotropy shown in the polarized spectra (Farrell & Newnham 1965) would indicate that caution should be used for such identification. Figure 6 shows transmission spectra in the visible range for four (4) peridots and one (1) sinhalite from table 4.

The iron absorptions in the 450 to 500 nm range do not appear to be diagnostic from these data. The principal difference in the spectra is the weaker absorption at the far red end of the spectrum for sinhalite. However, the susceptibility measurements show that, for this limited sample, there would be no problem in distinguishing between the two from magnetic measurements.

Table 5 gives susceptibility measurements on

21 other gemstones. Note the wide range of tourmaline, which would be expected.

CONCLUSIONS

Much has been left out of this discussion in order to keep the paper as short as possible. Yet much remains to be done for the full implication of susceptibility measurement to be known. Our hope is that sufficient information has been given that interested readers will be able to implement the procedure so that much additional data will be generated and made available.

We would strongly encourage anyone interested in this technique to give it a try, as it is not really difficult. The authors will do their best to assist readers in what way they can.

We see two principal areas where added research is particularly needed. The first is in identification of optimum calibration standards that easily would be available to the gemmologist, and magnetic susceptibility of which is well defined. This includes identification of any problems related to anisotropy. Although our measurements are in fair agreement with those of other more conventional techniques, and are in line with that expected from calculation, we believe additional work is necessary.

NUMBER OF SPECIMEN	DESCRIPTION	MAGNETIC SUSCEPTIBILITY (SI X 10 ⁻⁶)
1	20.5 ct almandine, Brazil	4460
2	2.57 ct almandine	1640
3	4.41 ct spessartine	2770
4	1.36 ct tsavorite	47.2
5	3.42 ct tsavorite	30.7
6	2.44 ct tsavorite	12.3
7	Large pink CZ rough	1075
8	1.40 ct ceylonite, Sri Lanka	483
9	1.58 ct blue spinel	1250
10	2.23 ct blue spinel	1030
11	6.78 ct red spinel, Burma	160
12	1.89 ct blue spinel	151
13	1.52 ct pink spinel	65.2
14	2.25 ct red spinel, Burma	51.1
15	3.08 ct red spinel, Burma	48.6
16	4.32 ct red Verneuil synthetic spinel	23
17	~5 ct dark green tourmaline, Brazil	258/255
18	~4 ct dark green tourmaline, Brazil	245/255
19	4.5 ct light blue-green tourmaline, Brazil	98.2
20	~2 ct green tourmaline, Nigeria	28.3
21	~2 ct medium green tourmaline, Nigeria	28.3
22	1.5 ct chrome tourmaline	0.0
23	5.65 ct pink beryl	Diamagnetic
24	3.87 ct golden beryl	Diamagnetic
25	4.33 ct kunzite	Diamagnetic
26	4.65 ct red-brown zircon rough	Diamagnetic

Table 5. Magnetic susceptibilities for various gemstones.

The second major area is in compilation of a sufficient number of measurements for the numerous gem species and localities, so that adequate statistics are obtained to define the range of values for given gem varieties and for each locality. This will involve a major effort on the part of gemmologists with access to gemstones with well documented credentials with respect to their source. The major laboratories would be expected to play a principal part in this effort.

Measurements on natural and synthetic diamonds should go a long way towards determining to what extent this simple technique may be able to assist in distinguishing between the two. However, the magnetism of diamond is due to ferromagnetic inclusions (Rossman & Kirschvink, 1984; Titkov *et al.*, 2003), not paramagnetic ions substituting for carbon.

Although ferromagnetic inclusions have not been addressed in this paper the reader should be well cautioned that such may be present in

gems that are measured, and their consequences may not be minor. Any gems that are not eye clean should be carefully examined so as to note a possible problem. It should be clear that such inclusions would obviate any inference of ionic chemistry based on calculations from equation 3.

Improvements in magnetic apparatus that will give better or more precise readings are to be expected. We have a number of ideas that we will be pursuing along that line.

There is a complex and intimate relationship between colour, valence of transition element/s, ion position within a crystal and near neighbors, and whether colour is allochromatic or idiochromatic in nature (Fritsch & Rossman, 1987, 1988). The magnetic properties are similarly affected. Heat treatment and diffusion will affect the magnetic properties of gemstones, just as it does their colour. We expect that detailed studies may assist in selecting gemstones for treatment, and possibly assist in detection of treatment.

The results of Anderson (1980), and empirical results of Gumpesberger (2006), regarding what gem varieties may be distinguished by their non-quantitative magnetic tests are confirmed by our results; but from a rather small data base. We plan on focusing on the garnet group, among others, in future work. We believe the ability to place a quantitative measure on the magnetic susceptibility of a gemstone, easily and inexpensively, does provide an important new means for discrimination that can only improve as our data base improves

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