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Earth and Planetary Science Letters 265 (2008) 324–326
EPSL
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Discussion

Comment on A.J. Biggin et al., A comparison of a quasi-perpendicular method of absolute palaeointensity determination with other thermal and microwave techniques, Earth and Planetary Science Letters 257 (2007) 564–581

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Accepted 15 October 2007
Available online 22 October 2007
Editor: R.D. van der Hilst

Abstract

While Biggin et al.'s paper is an important review and critique of palaeomagnetic methods employed at present, we point out here that if the grain size selectivity of microwaves is employed, instead of just using them to heat the sample, alteration can be avoided completely, and previously unavailable grain size dependence of the magnetic moment can be recovered.

Keywords: microwaves; remanence; magnetization

Biggin et al. (2007) point out that as they are presently employed, microwaves constitute a marginal improvement on the standard thermal techniques which is not surprising in view of the fact that they are simply being used to heat the samples. We wish to argue here, that the major advantages provided by microwaves are being lost because the frequencies being used are too low with the result that it is necessary to raise the sample temperature to temperatures in excess of 300 °C where alteration becomes a problem (Walton, 1984; Walton, 1991; Biggin et al., 2007). From the results to be shown below we estimate that microwave frequencies above about 18 GHz are necessary to reverse the moments of all the grains carrying an NRM. With sufficient power the total energy necessary to do this is just equal to that absorbed by the magnetic material, so the resultant sample temperature increase will be just equal to that energy divided by the specific heat of the sample. The specific heat per unit weight for magnetite and rock are similar and are about 1 joule/gram; so typically for a 0.1 gm sample with 1% magnetite the energy required to raise the temperature of the magnetic grains to their Neel temperature is about 0.6 joule, and the sample temperature rise would only be ~6 °C, and alteration could not take place.

Furthermore, if the frequency is varied it should be possible to demagnetize the largest grains first followed by smaller grains as the microwave frequency is

DOI of original article: 10.1016/j.epsl.2007.03.016.
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0012-821X/$ - see front matter
doi:10.1016/j.epsl.2007.10.027

increased. This "microwave frequency method" would make it easy to identify overprints, and use the viscous magnetization for sample dating.

The microwave absorption mechanism involved is a second order process whereby a microwave photon creates two spin waves of equal and opposite wave-vector (Walton et al., 1993). Spin waves whose wavelength exceeds about twice the size of the particle are not possible (Hendriksen et al., 1993) except for the uniform mode that involves the coherent rotation of the spins about the anisotropy field axis; so the dispersion relations for small particles are cut-off at the corresponding wave-vector. Direct absorption of microwaves is still possible by exciting the uniform mode (Sparks, 1964), but this is uninteresting because its frequency is temperature dependent, and soon becomes lower than the microwave frequency as the particle's temperature rises. With the second order process it doesn't matter if the dispersion relations drop with temperature since two spin waves of equal and opposite wave-vector can always be found. But the gap in the spectrum has important consequences since the frequency of the microwave photon must be twice the spin wave frequency, and the minimum spin-wave wave-vector leads to a minimum frequency.

In order to be effective microwaves need to be absorbed by all the magnetic grains, and sufficient power has to be supplied to raise them to their Neel temperature in a very short time. If the frequency is too low to be absorbed by all the grains, the larger grains that are able to absorb microwaves can raise the temperature of the sample, thereby lowering the spin wave frequencies, enabling smaller grains to absorb microwaves. The average temperature of the sample, i.e. the matrix, required for complete magnetization depends on the frequency. However, sometimes the number of grains able to absorb microwaves at the frequency being used is too small, the sample temperature increase is low, and it is impossible to magnetize the sample. This is illustrated in Fig. 1 which shows results for an archaeological ceramic that was impossible to demagnetize at 14.65 GHz. An increase in frequency from 14.65 to 16.643 GHz allowed the ceramic to be demagnetized. However, the sample temperature still had to increase for substantial demagnetization to take place.

From a very rough extrapolation of the results it appears that increasing the frequency to ~17.5 GHz should accomplish the same degree of demagnetization with a minimum increase in sample temperature, i.e. 17.5 GHz photons would be absorbed by a substantial majority of the grains contributing to the NRM. Unfortunately our amplifier had no output at this frequency.

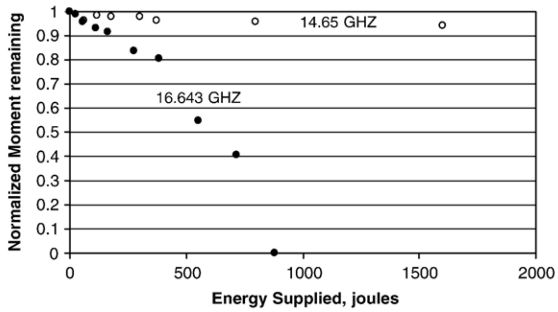

Fig. 1. Demagnetization of the NRM in a pre-Columbian sherd at the two frequencies indicated on the chart. The energy shown is that supplied to the cavity at a power of 66 W. The actual energy absorbed by the sample is about a fifth of the amount shown. The sample temperatures for the 14.65 GHz measurements were all ~85 °C, whereas those at 16.643 GHz increased steadily to 138 °C, showing that there were insufficient grains absorbing microwaves at 14.65 GHz to raise the sample temperature to enable the grains to absorb microwaves, but that at 16.643 GHz the increase in sample temperature with the consequent decrease in spin wave energies was enough to do so.

But the frequency required can easily be calculated: from the size of grains blocked on a 1 second time scale at room temperature, and the magnetite dispersion relations (Alperin et al., 1967), the frequency required to demagnetize all the blocked grains can be calculated to be 13. 33 GHz, and since two photons must be supplied a 26.6 GHz amplifier would be required. A considerably lower frequency should be adequate for palaeointensity measurements, though, because grains with relaxation times on the order of a year or less carry uninteresting viscous moments. The volume of a grain blocked for 1 year is $\sim((\ln(\omega * 1\ \mathrm{yr}))/(\ln(\omega * 1\ \mathrm{s}))) = 1.94$ times the volume of a grain with the same anisotropy blocked at room temperature, and the frequency required becomes 9. 21 GHz, and an 18.4 GHz amplifier would be sufficient, in agreement with the rough estimate above.

The power required has to be sufficient to raise the grains from room temperature to their Curie temperature without any additional contribution from heating of the matrix, thus the 0.6 joules required must be supplied before any appreciable heat flow into the matrix has occurred. From an analysis of unpublished experimental data we estimate this requires a time less than 0.1 s. The efficiency of the system appears to be about 10%; so a minimum of about 60 W is required.

Thus it appears that in order to optimize the energy transfer from the microwaves to the magnetic grains, i.e. for the largest possible fraction of the available power to be consumed in only heating the magnetic grains, thereby minimizing heating of the matrix, the power has to be applied for less than 0.1 s. Of course, in order to be able to reverse the moments of all the grains, a frequency above about 18.5 GHz is necessary and a minimum power about 50% higher than the 40 W that was available to us. Ideally more power would be advisable to compensate for any deficiency in coupling to the cavity.

The frequency selectivity of the grain sizes involved is a feature of microwaves that has not been explored experimentally at all, and we would like to propose the following radically different protocol, that we wish to refer to as "the microwave frequency method" for accessing the palaeointensity:

a) Using a power level sufficient to raise the absorbing grains above their Neel temperature, magnetize, and then demagnetize at a low frequency, thereby determining the contribution to the moment of the larger grains, and the ancient field producing the moment.
b) Then, increasing the frequency in stages, access the contribution to the NRM of the rest of the grains.

Such a microwave frequency method has the advantage that it can easily identify overprints (which cannot be done at present) and, in particular allows the viscous overprint (which is the last to be removed) to be used for dating the sample, and last but by no means least it eliminates any possibility of mineral alteration.

Acknowledgements

We wish to thank CONACYT of Mexico for the support provided under grant no. 46213, and D. Walton thanks NSERC of Canada for support for travel to Mexico.

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