SQUID APPLICATIONS TO GEOPHYSICS

Proceedings Of The Workshop Held 2–4 June 1980
At The
Los Alamos Scientific Laboratory
Los Alamos, New Mexico

Edited by

HAROLD WEINSTOCK
Office of Naval Research and
Illinois Institute of Technology
Chicago, Illinois

WILLIAM C. OVERTON, Jr.
Los Alamos Scientific Laboratory
Los Alamos, New Mexico

Sponsored by
the Office of Naval Research and
the Los Alamos Scientific Laboratory

THE SOCIETY OF EXPLORATION GEOPHYSICISTS
TULSA, OKLAHOMA
1981
ABSTRACT

Two and three axis magnetometers based on RF-driven SQUIDS are now routinely used in the study of paleomagnetism. These magnetometers are both far more sensitive and much faster than any other type of rock magnetometer currently available; consequently they have made it possible to accurately measure the direction and intensity of the natural remanent magnetism in a large variety of otherwise unuseable sedimentary rocks. During the process of progressive demagnetization, however, many samples with an originally weak but apparently stable magnetic remanence become unmeasurable before the various magnetic components present have been resolved. A simple theoretical analysis shows that the detrital magnetism from either biogenic or inorganic processes could have left geologically meaningful information in these samples, and implies that two or three orders of magnitude more sensitivity (down to about $10^{-14}$ Joule/Tesla) might be of use. At this level, however, sample contamination from dust and other junk in the environment would become significant, requiring some form of air filtration in the laboratory. Similar facilities would be of use to detect small quantities of ferromagnetic minerals in animal tissue.

*Department of Geological and Geophysical Sciences, Princeton University, Princeton, N.J. 08544 U.S.A.

I. INTRODUCTION

Two and three axis RF-driven SQUID magnetometers, described in detail by Goree & Fuller (1976), have been used for approximately ten years as an analytical tool to study the fossil magnetism in rocks. Although these instruments are more expensive to buy, operate, and maintain than their astatic or spinning competitors, they more than make up for this with their extreme sensitivity ($10^{-11}$ Joule/Tesla) and speed (about 100 complete sample measurements/hour, compared to about 10/hour for other instruments). The introduction of these machines into paleomagnetic studies has made it possible to measure a weak permanent magnetization in many sedimentary rocks which were virtually impossible to work with on a large scale before. Because many of the more important fossiliferous sequences on land are only weakly magnetized, the use of superconducting magnetometers adds an entire new category of potentially useful rocks for paleomagnetic analysis. Perhaps the best example of this to date is the work of Alvarez et al. (1977) on the Cretaceous–Tertiary boundary at Gubbio, Italy. Studies of this sort are clearly important in that they can sometimes interrelate the biostratigraphic, radiometric, and magnetostratigraphic chronologies which are fundamental to the earth sciences.

In dealing with many of these biogenic sedimentary rocks, however, one often finds samples that become too weakly magnetized during progressive demagnetization to accurately measure even on the superconducting machines; typical examples of this
behavior are described in detail in the Appendix. Because it seems that some of these samples still contain potentially useful but unmeasurable information, one needs to ask what the sensitivity of an ideal rock magnetometer should be. In the analysis of this question outlined here, I will use a simplistic approach and assume that the entire remanence of such a weak sample is a result of a relatively small number of detrital single-domain magnetite crystals of uniform size. This may be a reasonable assumption for many fine grained sedimentary rocks of at least partial biogenic origin, however, because numerous organisms like chitons and magnetotactic bacteria are now known to produce significant amounts of single-domain magnetite and shed it into their environment (Kirschvink & Lowenstein 1979; Blakemore 1975; Frankel et al. 1979). Therefore, the goals of the following analysis are firstly to estimate the number of individual magnetite crystals necessary for a sample to record reliably the direction of the geomagnetic field, and secondly to estimate the total magnetic moment those grains would produce and which an ideal magnetometer should be able to resolve.

II. ESTIMATION OF THE DESIRED SENSITIVITY

In the simplest model of Detrital Remanent Magnetism (DRM) acquisition, one assumes that the individual magnetic particles are subject to the randomization process of Brownian motion, and that during the process of compaction and solidification the particle distribution in space remains the same. Each magnetic moment, \( \uparrow \), produced by a particle will then follow the Boltzmann distribution \( \exp(-E/kT) \) about the direction of the earth's field, \( \hat{B} \), where \( E = -\mu B \cos \theta \), \( \theta \) is the angle between \( \hat{\mu} \) and \( \hat{B} \), and \( k \) and \( T \) are respectively Boltzmann's constant and the absolute temperature. In other words, the probability of finding the moment \( \hat{\mu} \) in a solid angle \( d\Omega \) at an angle \( \theta \) from \( \hat{B} \) is proportional to \( \exp(\mu B \cos \theta / kT) d\Omega \).

For the present analysis, we need to know two things from the Boltzmann distribution: (1) the average projection of \( \hat{\mu} \) on the direction of \( \hat{B} \), and (2) the perpendicular variance of \( \hat{\mu} \) from the direction of \( \hat{B} \). The first quantity is the well-known Langevin function, \( L(\gamma) = \coth(\gamma) - 1/\gamma \), where \( \gamma = \mu B/kT \), while the second quantity, \( \sigma^2 \), is easily found to be \( (2/\gamma)L(\gamma) \). If there are \( N \) identical but independent magnetic particles, the variance of their resultant direction \( \sigma^2 \) about \( \hat{B} \) is approximately given by \( \sigma^2/N \), (e.g., the deviation \( \sigma_\theta \) from the true direction of \( \hat{B} \) decreases as \( \sqrt{N} \)).

We now want to estimate \( N \) such that \( \sigma_\theta \) will be less than some specified angular error from \( \hat{B} \). For most paleomagnetic samples, the orientation accuracy for a sample in the field is typically on the order of 1-5° (Collinson et al. 1969), so to get 95% confidence 1.96\( \sigma_\theta \) should at least be less than 5° or 0.09 radians. The relationship is then:

\[
1.96 \sqrt{\frac{2L(\gamma)}{YN}} < 0.09
\]

or

\[
N > 1009 \frac{L(\gamma)}{\gamma}
\]

(1)

A typical single-domain magnetite grain such as one produced by a chiton or magnetotactic bacterium is large enough such that the ratio \( \mu B/kT \) (\( \gamma \)) in the earth's field and at room temperature is roughly between 1/2 and 10. Using 5 as typical, \( L(5) = 0.83 \) and by eq. (1) it would take about 168 such particles in the sample to obtain the desired accuracy. Finally, the moment of this assemblage is simply given by \( N_\mu L(\gamma) \), which works out to about \( 5.7 \times 10^{-14} \) Joule/Tesla. Numbers of the same order of magnetitude are found for other grains of single-domain size. A related analysis using the Fisher distribution yields similar results.

III. DISCUSSION

The SQUID magnetometers currently employed in paleomagnetic studies can reliably measure moments down to about \( 5 \times 10^{-11} \) Joule/Tesla (Goree & Fuller 1976), so it is clear by comparison with
the above analysis that a 1,000-fold improvement in their current sensitivity would be of use before the physical limits governing the magnetization of a sample are approached. To actually use a machine of this sensitivity, however, would probably require the elimination of airborne contamination or other sources of dust which could be more magnetic than the rock itself. The question of whether or not a machine of this sensitivity and sample volume can be built is best left to the other contributors at this symposium. In conclusion, however, one must stress that the magnetization process in real rocks is usually far more complex than the simple analysis used here, and it is rarely an easy matter to determine either the age, origin, or the geologic significance of any magnetic remanence detected. Many factors including thermal metamorphism and/or chemical alterations can destroy a rock’s primary magnetism and can leave misleading secondary components behind. Although a more sensitive instrument could aid in the detection of some of these weak magnetic components, the problem faced by the paleomagnetist of interpreting what each component means remains the same.

ACKNOWLEDGMENTS

I thank R.B. Hargreaves for helpful discussions during preparation of this manuscript, and D.P. Elston and E.M. Shoemaker of the U.S. Geological Survey in Flagstaff, Arizona for use of their laboratory facilities. This work was supported in part by NSF grants SPI79-14845 and EAR78-03204.

REFERENCES


---


APPENDIX

The two sets of figures above provide an illustration of progressive thermal demagnetization of two weakly magnetized sedimentary rocks. The direction and intensity of the natural remanent magnetism (NRM) in each 30 gram sample was measured first, and then they were repeatedly heated to progressively higher temperatures, cooled in a low-field environment, and remeasured. Results from each sample are shown both with a vector
diagram (left column of figures) and a stereographic projection (right column of figures). On the vector diagrams, the declination curve represents the projection of the magnetic vector into the plane of the bedding, while points on the inclination curve show the corresponding vertical vs. horizontal components of the vector at each demagnetization temperature. Numbered units along these axes represent a moment of $10^{-11}$ Joule/Tesla ($10^{-8}$ emu). The stereographic projection shows the direction of the remanence vector after each demagnetization step. Open symbols represent negative (upper hemisphere) inclinations. Numbers next to each point refer to the demagnetization temperature in °C.

Sample OHA-32 (upper pair of diagrams) is a pale-grey micrite from the top half of the late Precambrian Série lié de vin in the High-Atlas mountains of Morocco, near Oumein (30.78°N, 8.28°W).

Thermal demagnetization up to 260°C removes a magnetic component directed to the north and down which is probably of recent origin. The magnetic vector remaining above this temperature dips shallowly downwards to the E-SE. Unfortunately, the intensity at this stage is barely measurable; consequently very little can be inferred from this part of the demagnetization process. Sample LZX-102.1 (lower diagrams) is a similar fossiliferous light-grey micrite from lower Cambrian carbonates at Zhurinsky Mys, on the Lena River of east-central Siberia (60.93°N, 125.97°E). Upon demagnetization, the magnetic vector moves in direction away from that of the present geomagnetic field towards an upwards, W-SW position. Sequential directions as viewed on the stereonet fall along a great circular arc indicating that only two components exist, but the moment remaining after the 450°C demagnetization step is again approaching the sensitivity limit of the superconducting instrument.

---

**HOW SENSITIVE SHOULD A MAGNETOMETER BE FOR USE IN ROCK-, BIO-, AND PALEOMAGNETISM? — J. L. Kirschvink**

**DISCUSSION**

**FOSTER**—If you take an ordinary, off-the-shelf second-order gradiometer and place it on a table top in a cheap shielded room, you can drive your sample volume up by a factor of 1000, giving you the sensitivity needed for the paleomagnetic case.

**KIRCHVINK**—One problem when doing paleomagnetic stratigraphy is that one is dealing with thousands of samples, perhaps tens of thousands of samples. So, if we must collect boulders each time we enter the field, that in itself becomes impractical.

**FOSTER**—It is not as bad as you think. The problems that you have generally involve sample preparation. The oil companies obtain big cores and resection them into small cylinders, or worse yet, you get big blocks. If you cut down your sample preparation time (and improve your throughput) by taking various-sized samples, placing them on table tops in a clean lab environment without using a sample holder, you can solve your problem.

**GOREE**—There is a problem with using gradiometer systems because it is very difficult to couple the samples to pickup coils. One of the advantages of using a rock magnetometer is that a sample fits inside the coil. If one places a sample outside the coil, one loses considerable sensitivity and one can't increase the sample volume to get around this.