

MAGNETIC SUSCEPTIBILITY LOGGING FOR CORES

1. Overview of Magnetic Susceptibility

The magnetic susceptibility of a natural or synthetic material is a measure of its ‘magnetizability’ in the presence of a small magnetic field. Once the applied field is removed, the magnetization induced in the analyzed material reverts to the initial magnetized state of the substance. In mathematical terms, volume magnetic susceptibility (κ) is defined as the ratio between induced magnetization per volume unit of measured sample (M), and applied magnetic field intensity (H):

$$\kappa = M/H$$

Since M and H have the same SI units (A/m), κ is a dimensionless number. However, it is common practice to report volume susceptibility in what are known as ‘SI units’ (and often omitting the 10^{-5} multiplier!). When the density (ρ) of the material is known, magnetic susceptibility can also be calculated relative to sample mass. In this case we are dealing with mass-specific magnetic susceptibility (χ), obtained by dividing κ by ρ :

$$\chi = \kappa/\rho \text{ (m}^3/\text{kg)}$$

Mass-specific susceptibility values reflect the sediment magnetic composition more accurately than volume-normalized values, but core composition and coring artifacts can make this parameter unreliable when calculated on whole sections of core (see section 3).

2. Magnetic Materials in Sediments

All natural and artificial substances are magnetic, with various degrees of magnetic strength. **Ferromagnetic** substances are ‘true’ magnetic materials, and are capable of acquiring a magnetic remanence, meaning they remember the magnetic field they were exposed to. Minerals with crystalline structures that allow interactions between constituent metallic atom shells are examples of such materials. The most common ferromagnets are elemental Fe, Co, and Ni, Fe oxides such as magnetite (Fe_3O_4) and hematite (Fe_2O_3), and Fe sulfides such as pyrrhotite (Fe_7S_8) and greigite (Fe_3S_4).

Iron-bearing minerals with crystal lattices that allow only weak interactions between Fe atom shells are called **paramagnetic**, and their magnetic susceptibility is weakly *positive*. Examples of such paramagnetic minerals are Fe-Ti oxides (e.g. illmenite), Fe-Mn carbonates (siderite, rhodochrosite), iron-bearing silicates (e.g. biotite, clay minerals), or Fe sulfides (e.g. pyrite).

Minerals that do not contain Fe (e.g. quartz, calcite, halite), as well as water, organic matter, and artificial substances such as polycarbonate or polyethylene are called **diamagnetic** and exhibit a *negative* magnetization in the presence of a weak magnetic field. This is important because many paleolimnology workers assume the negative values they obtain from logging water-laden or organic-rich sediments are offset due to instrumental or procedure-related errors.

3. Continuous-Measurement Instruments

Magnetic susceptibility can be measured continuously on whole or split core sections, and discretely on individual subsamples. Continuous measurements are performed using core loggers, which utilize two types of susceptibility meters: loop sensors and point sensors. The former are used for whole core logging, the latter for split core logging. Both types of sensors are available on automated core loggers (Geotek MSCL-S and MSCL-XYZ respectively) at LacCore (fig. 1).



Figure 1. Loop (left) and point (right) sensors, mounted on core loggers (photos from <http://www.geotek.co.uk>).

Loop sensors

Loop sensors are pass-through devices of known volume. Volume susceptibility (κ) is calculated using the ratio between the volume of the loop and that of measured core. A small ratio maximizes both the strength of the signal and the measurement resolution. Mass susceptibility (χ) can be calculated using the specific gravity/density recorded by the core-logger. However, cores often contain gas and water pockets, or have gaps from the coring process, so the normalization of volume susceptibility by density can potentially yield spurious values. For this reason the LacCore MSCL-S instrument is set to report volume-normalized susceptibility values, with units of 10^{-5} SI.

The analyzed core is inside the loop for the entire length of the measuring sequence (which may contain several sections), so the susceptibility of the background is measured only at the beginning and end of the sequence, and subtracted from the bulk susceptibility by calculating the drift for each measurement point using linear regression. For long sequences, the time elapsed between the initial and final background readings can result in significant instrument drift. To reduce the magnitude of this drift, it is recommended that cores be stored at room temperature for at least 12 hours prior to logging, the magnetometer be turned on at least half an hour before measurements take place, and room temperature be constant throughout logging.

The loop sensor integrates the magnetic signal over a longer segment of core than the actual length of the loop, resulting in the susceptibility record being smoothed over the interval the loop is sensitive to. Each data point should thus be treated as a weighted running average of the susceptibility distribution over the spatial resolution of the loop. For a detailed account of the convolution of the magnetic susceptibility signal by loop sensors see Nowaczyk (2001).

Point sensors

Point sensors are magnetometers that make measurements while in contact with the sample surface. Typically, these are plane surfaces of longitudinally split cores wrapped in plastic film, or U-channel boxes (see U-channel magnetometry procedure for details). The measured surface must be horizontal and level, otherwise magnetic susceptibility measurements do not reflect sedimentary susceptibility values, due to extreme sensitivity of the sensor. Compared to the loop sensor, which integrates the magnetic signal over tens of centimeters, the point sensor records the magnetic response of small volumes of sediment, at sub-centimeter resolution. The susceptibility reading is reported as normalized by a defined volume, characteristic of each instrument. The point sensor measures background (air) values before each reading, therefore errors caused by instrument drift can be corrected with a high degree of precision.

Loop vs. point vs. single-sample sensors

There are advantages and disadvantages in using the two types of magnetic susceptibility sensors. Loop sensors can be used on whole core sections as soon as they are collected, so they are present aboard the majority of oceanographic research vessels. They offer a first view of major sedimentary units, and are used for correlating between cores collected in the same basin.

Point sensors offer increased spatial resolution, but are only sensitive to a small volume of sediment, and yield larger uncertainties in susceptibility values due to lack of control on normalizing volume. If susceptibility is measured by both loop and point sensors, an inter-instrument calibration should be performed by means of regression analysis.

Both types of continuous measurement techniques are powerful tools for initial core sediment characterization and basic interpretation, and should be corroborated with the other records obtained from core loggers (gamma density, P-wave velocity, electrical resistivity, etc.).

For detailed magnetic studies however, it is recommended to subsample core sections and measure susceptibility (and possibly other magnetic properties) on discrete samples. Individual samples do not suffer from magnetic signal convolution effects, and offer the option of normalizing the magnetic parameters by sample mass. Single-sample magnetic susceptibility can be measured on a Kappabridge susceptometer at the Institute for Rock Magnetism (IRM). For more details see <http://www.irm.umn.edu/IRM/Home.html> or contact irm@umn.edu.

4. Basic Interpretation and Caveats of Core-Logger Magnetic Susceptibility Records

In sedimentary environments, magnetic susceptibility is directly proportional to the magnetic mineral content of sediments, so it can be used as a non-destructive, first order assessment of the concentration of iron-bearing magnetic minerals.

In lake sediments, magnetic iron mineral assemblages are mixtures of particles of different origins, the most common being detrital and endogenic. Detrital magnetic minerals are transported into the lake basin by water or wind, whereas endogenic minerals are formed *in situ* by biological and chemical processes. For this reason, susceptibility alone should not be used as a minerogenetic or environmental fingerprinting tool unless a site-specific calibration demonstrates that magnetic susceptibility is a reasonable proxy for other measurements at that site. If magnetic minerals are present in low quantities, their concentration will be diluted by other sedimentary components. For example, if sediments are rich in diamagnetic substances (calcite, quartz, water, or organic matter) the bulk magnetic susceptibility will be negative, as noted above. If the concentrations of the diluting substances can be determined, their contribution to the susceptibility can be subtracted from the bulk value in order to obtain the concentration of the ferromagnetic component.

For a more accurate interpretation of the magnetic sedimentary record, magnetic susceptibility obtained from core logging can be complemented by long-core magnetic remanence measurements. The IRM has recently acquired a U-channel magnetometer that can be used for this purpose (see LacCore U-channel magnetometry procedure).

5. Useful Magnetic Susceptibility Resources

Dearing, J., 1999, Magnetic susceptibility. In Walden, J., Oldfield, F. and Smith, J. P. (eds.), Environmental magnetism: a practical guide. Technical Guide, No. 6, p. 35-62. Quaternary Research Association, London, UK.

Geotek MSCL manual (<http://www.geotek.co.uk/sites/default/files/manual.pdf>)

Nowaczyk, N. R., 2001, Logging of magnetic susceptibility. In Last, W. M., and Smol, J. P. (eds.), Tracking environmental change using lake sediments, vol. 1, Basin analysis, coring, and chronological techniques, p. 155-170. Kluwer Academic Publishers, Dordrecht, Netherlands.

Thompson, R., and Oldfield, F., 1986, Environmental Magnetism, Allen and Unwin, London, UK, 227 p.