# The Magnetic Properties of Archaeological Materials

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## The Magnetic Properties of Archaeological Materials

This listing has two purposes. It can help with the quantitative interpretation of magnetic surveys; the parameters here may allow interpreted magnetic moments to be converted into estimates of the mass or volume of a feature. The parameters on this list may also assist with the estimation of the magnetic anomaly that might be expected from a feature; this could help in the design of a magnetic survey.

The different parameters, variables, and constants are all in SI units (unless specifically indicated otherwise). The caret symbol indicates that the following number is a superscript; for example, 10^-4 means 0.0001, and m^3 means cubic meters. The symbols follow most closely those of Parasnis (1986).

Additional lists of magnetic parameters may be found in Carmichael (1982); a smaller list was published earlier (Lindsley, Andreasen, and Balsley 1966). However, these published parameters are generally for rocks and minerals. I have been involved with the measurements of most the parameters on the list here. Contributions from colleagues are indicated, and more would be welcome for future revisions of this report.

Most of the magnetic parameters have been measured with field procedures. For many of the measurements, a small sample was rotated near a magnetic sensor and the highest and lowest magnetic anomalies were noted. This procedure has been described by Breiner (1973, p. 34) and Parasnis (1986, p. 359). As a variant on this, the remanent magnetic poles of objects were located (with an audio-indicating magnetometer) and the magnetic measurements were made with the sample rotated to two opposite directions. In a few cases, the samples were rotated in six perpendicular directions for these measurements. Some magnetic parameters have also been determined by the analysis of spatial magnetic maps. The magnetic models have been two-dimensional prisms, or have been clusters of dipoles or rectangular prisms; least-squares fits between the calculated field and the magnetic measurements have furnished the magnetic parameters. Some measurements of magnetic susceptibility have been made with a Geoinstruments model JH-8 field meter; the readings from this small, portable field instrument are indicated below. The volumes of samples have been determined generally by the displacement of water or small seeds in a graduated container. Density has been determined by either volume and mass, or by measuring the apparent mass of a sample underwater.

The lists indicate the material or feature, along with its physical properties. This is followed by the magnetic properties, the method of measurement, the date and location of the measurement, perhaps the age of the sample, and then the individuals (in addition to myself) who made the measurements.

## Definitions and Equations

pi = 3.14159
ma = mass, kg
V = volume, m^3
d = density, kg/m^3
= ma / V

Magnetic parameters and variables:
He = strength of the Earth's magnetic field, A/m
Be = flux density of the Earth's magnetic field, nT
= uo * He
u = ur * uo = magnetic permeability
uo = permeability of a vacuum
= 400 * pi, nT-m/A
ur = relative permeability (pure number, no units)
k = magnetic susceptibility (pure number, no unit)
= ur ^ 1
k(cgs) = k / (4 * pi), convert from SI to cgs units
m = magnetic moment, Am^2 (a vector quantity)
=mr+mi
mr = remanent magnetic moment, Am^2
mi = induced magnetic moment, Am^2
Q = Koenigsberger ratio
=mr/mi
mm = magnetic moment per unit of mass, Am^2/kg
= mrm + mim
mrm = remanent magnetic moment per unit of mass, Am^2/kg
= mr / ma
mim = induced magnetic moment per unit of mass, Am^2/kg
= mi / ma
M = intensity of magnetization, A/m
= magnetic moment per unit volume
= k * He = m / V
S = strength of a monopole, Am
magnetic moment per unit of length

Field of a magnetic monopole:
Ba = 100 * S / r^2 = magnetic anomaly, nT

Field of a magnetic dipole along the line of its magnetization:
Ba = 200 * m / r^3
r = distance from the dipole or the center of the sphere to the calculation point, m

Magnetic field of a sphere, parallel to the direction of magnetization:
Ba = uo * V * M * (3 * cos^2(th) - 1) / (4 * pi * r^3)
th = angle from the center of the sphere between the direction of magnetization and the calculation point, degrees

## Modern Steel

55-gallon (0.208 m^3) drum, ma = 18.1 kg, Be = 55,260 nT.
mm = 0.44 Am^2/kg
Dipole model of a magnetic map
January 1983, New Jersey, USA

Average for steel
mm = 0.24 - 0.3 Am^2/kg
Estimate from Sheldon Breiner (1973)

Pipe vertical in the ground, ma = 2.0 kg, length = 1.55 m
mm = 10.8 Am^2/kg
Dipole model of a magnetic map.
July 1978; Valley Forge, USA.
Survey with Diana Bermingham and Harold Spaulding (Univ. of Pa.)

Horse shoe, ma = 0.3 kg
mm = 0.17 Am^2/kg
Dipole model of a magnetic map.
February 1993; Jamestown Island, USA.
Excavation and mass by Audrey Horning (Williamsburg)

Bolt, ma = 2.1 kg
mm = 1.07 Am^2/kg
Dipole model of a magnetic map.
February 1993; Jamestown Island, USA.
Excavation and mass by Audrey Horning (Williamsburg)

Bottle cap, ma = 0.0033 kg
mm = 0.21 Am^2/kg
Dipole model of a magnetic map.
August 1993; Simferopol, Crimea.
Survey with Tatyana Smekalova (St. Petersburg State Univ.)

Nail, ma = 0.0094 kg, length = 0.10 m, diameter = 0.004 m
mm = 0.11 Am^2/kg
Dipole model of a magnetic map.
August 1993; Simferopol, Crimea.
Survey with Tatyana Smekalova (St. Petersburg State Univ.)

Nail, ma = 0.0099 kg, length = 0.10 in, diameter = 0.004 m
mm = 0.91 Am^2/kg
Dipole model of a magnetic map.
August 1993; Simferopol, Crimea.
Survey with Tatyana Smekalova (St. Petersburg State Univ.)

Car, range for a variety of passing cars
m = 300 - 850 Am^2
Magnetic base station readings of distant moving cars.
June 1992; Petersburg, Virginia, USA.

Train, apparently independent of length.
m = 9 - 17(10^4) Am^2
Magnetic base station readings of distant trains.
June 1992; Petersburg, Virginia, USA.

## Historical Iron

Lump of cast iron, ma = 0.0113 kg, d = 5900 kg/m^3
mrm = 9.36(10^-3) Am^2/kg
mim = 1.31(10^-3) Am^2/kg
Q = 0.7
Rotation of sample.
August 1975; Les Forges du Saint-Maurice, Canada; 18th century.

Lump of cast iron, ma = 0.0445 kg, d = 6600 kg/m^3
mrm = 4.36(10^-2) Am^2/kg
mim = 4.74(10^-2) Am^2/kg
Q = 0.9
Rotation of sample.
August 1975; Les Forges du Saint-Maurice, Canada; 18th century.

Part of a spike, ma = 0.17 kg, d = 6100 kg/m^3
mrm = 1.56(10^-2) Am^2/kg
mim = 2.68(10^-2) Am^2/kg
Q = 0.6
Rotation of sample.
August 1975; Les Forges du Saint-Maurice, Canada; 18th century.

Mortar shell, US Civil War, diameter = 8 inch (0.203 m), ma = 21.1 kg
mrm = 3.8(10^-4) Am^2/kg
mim = 2.1(10^-2) Am^2/kg
Q = 0.02
Rotation of sample; contains soil inside.
October 1992; Petersburg, Virginia, USA; 1863.

Fragment of mortar shell, ma = 4.3 kg, thickness = 0.0044 m
mrm = 1.4(10^-2) Am^2/kg
mim = 2.4(10^-2) Am^2/kg
Q = 0.6
Rotation of sample.
October 1992; Petersburg, Virginia, USA; 1863.

Fragment of Hotchkiss shell, ma = 0.7 kg, size = 0.0056 by 0.0051 m
mrm = 5.6(10^-3) Am^2/kg
mim = 2.3(10^-2) Am^2/kg
Q = 0.2
Rotation of sample.
October 1992; Petersburg, Virginia, USA; 1863.

Fragment of Coehorn shell, ma = 1.1 kg, diameter = 0.203 m
mrm = 1.1(10^-2) Am^2/kg
mim = 1.9(10^-2) Am^2/kg
Q = 0.6
Rotation of sample.
October 1992; Petersburg, Virginia, USA; 1863.

## Iron Slag

Mixture of iron and glass slag, m = 0.035 kg, d = 3600 kg/m^3

mrm = 6.9(10^-3) Am^2/kg
mim = 1.37(10^-3) Am^2/kg
Q = 0.6
Rotation of sample.
August 1975; Les Forges du Saint-Maurice, Canada; 18th century.

Iron and frothy slag, ma = 0.173 kg, d = 3300 kg/m^3

mrm = 1.06(10^-3) Am^2/kg
mim = 3.1(10^-4) Am^2/kg
Q = 3.4
Rotation of sample.
August 1975; Les Forges du Saint-Maurice, Canada; 18th century.

Block of slag, ma = 1.3 kg

mrm = 4.8(10^-3) Am^2/kg
mim = 1.0(10^-3) Am^2/kg
Q = 4.8, k = 0.1
Rotation of sample.
September 1996; Snorup, Denmark; 400 AD.
Survey with Tatyana Smekalova (St. Petersburg State University)

Nine samples from Snorup, Denmark

Q = 11 - 212
Laboratory measurement by Boris Pisakin (Petrophysical Dept., St. Petersburg State University).

Circular blocks of slag from Snorup, Denmark

| location | F | B8 | Ba | Bc | E16 | E24 | E25 |
|---|---|---|---|---|---|---|---|
| diameter, m | 0.75 | 0.7 | 0.85 | 0.65 | 0.75 | 0.70 | 0.70 |
| thickness, m |  |  | 0.15 | 0.20 | 0.29 | 0.25 | 0.36 |
| d, kg/m^3 | 3600 |  |  |  |  |  |  |
| ma, kg | 67 | 78 | 112 | 51 | 175 | 165 | 225 |
| mm, Am^2/kg | 0.0124 | 0.0094 | 0.0084 | 0.0075 | 0.0142 | 0.0094 | 0.0089 |
| k | 0.026 |  |  |  |  | 0.063 | 0.0055 |
| Q | 28 |  |  |  |  | 9.4 | 160 |

Measured by models of magnetic maps.
September 1996; Snorup, Denmark; approximately 400 AD.
Survey with Tatyana Smekalova (St. Petersburg State Univ.)
Measurements of k and Q by V. V. Gernik (Geological Institute, St. Petersburg State University). Excavations and mass by Olfert Voss (Nationalmuseet, Copenhagen).

## Ceramic

Modern roof tiles, average 5, d = 1740 kg/m^3, ma = 0.075 kg

mrm = 7.2(10^-4) Am^2/kg

mim << mrm

k (JH-8) = 0.0006

Measured by rotating samples.

December 1987; Guajara Mound, Brazil.

Burial urns, Be = 27,860 nT

| number | 7000-0-1 | 7000-0-3 | 7000-0-9 | 7000-0-13 |
|---|---|---|---|---|
| height, m | 0.7 | 0.7 | 0.7 | 0.4 |
| diameter, m | 0.6 | 0.7 | 0.6 | 0.6 |
| mr, Am^2 | 0.0380 | 0.0654 | 0.041 | 0.0037 |
| mi, Am^2 | << mr | 0.0127 | << mr | << mr |
| Q | | 5.2 | | |
| k (JH-8) | 0.006 | 0.006 | 0.0055 | 0.008 |

Measured by rotating urns.

December 1987; Guajara Mound, Brazil.

Burial urns, Be = 27,835 nT

| type | Epaulets | Geometric |
|---|---|---|
| height, m | 0.54 | 0.56 |
| width, m | 0.48 | 0.45 |
| ma, kg | 22 | 18 |
| mrm, Am^2/kg | 1.06(10^-3) | 4.9(10^-4) |
| mim, Am^2/kg | 1.4(10^-5) | 1.4(10^-4) |
| Q | 75 | 3.5 |
| k | 0.0011 | 0.011 |
| k (JH-8) | 0.008 | 0.004 |

Measured by locating remanent magnetic poles and measuring field.

November 1988; Guajara Mound, Brazil.

Pot sherds

| number | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| ma, kg | 0.123 | 0.148 | 0.131 | 0.436 |
| V, m^3 | 70(10^-6) | 79(10^-6) | 87(10^-6) | 262(10^-6) |
| d, kg/m^3 | 1760 | 1870 | 1510 | 1660 |
| mrm, Am^2/kg | 3.6(10^-3) | 9.7(10^-4) | 4.5(10^-5) | 7.9(10^-4) |
| mim, Am^2,kg | 8.1(10^-5) | << mrm | 2.9(10^-4) | 9.6(10^-5) |
| Q | 44.6 | | 0.2 | 8.2 |
| k | 0.003 | | 0.010 | 0.004 |
| k (JH-8) | 0.015 | 0.006 | 0.002 | 0.005 |

Measured by rotating sherds, Be = 54,470 nT.

December 1987; Guajara Mound, Brazil.

## Brick

Modern brick, average of 5, 20th century
k (JH-8) = 0.0012
Measured with JH-8 susceptibility meter.
February 1991, Millville, New Jersey, USA.

Modern brick, V = 795(10^-6) m^3, ma = 1.60 kg, d = 2010 kg/m^3
mm = 4.7(10^-4) Am^2/kg with Be = 54,200 nT
k (JH-8) = 0.003
Model magnetic map with rectangular prism.
April 1992; Millville, New Jersey, USA; 20th century.

Brick foundation, about 45 percent of wall by volume is brick.
k = 0.006
Measured from two-dimensional model of measurements.
September 1991; St. Mary's City, Maryland, USA; 17th century.

Bricks, average of 4
V = 1.60(10^-3) m^3, ma = 3.1 kg, d = 1945 m^3/kg
mrm = 2.2(10^-3) Am^2/kg
mim = 1.4(10^-4) Am^2/kg
Q = 15.7
k = 0.020, k (JH-8) = 0.001
September 1991; St. Mary's City, Maryland, USA; 17th century.

## Fired Earth

Parts of U-shaped stoves exposed by excavations

Be = 28,070 nT, assume d = 1700 kg/m^3

| location | excavation 5S | profile 3 | other |
|---|---|---|---|
| V, m^3 | 1.75(10^-3) | 0.85(10^-3) | 0.55(10^-3) |
| mrm, Am^2/kg | 1.94(10^-4) | 3.73(10^-3) | 2.18(10^-3) |
| mim, Am^2/kg | 6.75(10^-4) | 1.17(10^-3) | 0.46(10 -3) |
| 4 | 2.9 | 2.2 | 5.1 |
| k | 0.017 | 0.089 | 0.035 |

Measured magnetic field by rotating to 6 perpendicular faces.

November 1985; Teso dos Bichos, Brazil.

Fired clay, encountered by excavations

k (JH-8) = 0.0055 (surrounding soil had k = 0.0035)

November 1988; Guajara Mound, Brazil.

Fired earth, not exposed by excavations, 5 estimates

k = 0.0035, 0.005, 0.020, 0.015, 0.018

Measured by two-dimensional models of magnetic maps.

November 1988; Guajara Mound, Brazil.

Kiln, dimensions about 4.7 by 3.2 m, and 1.3 m tall (after excavation)

m = 135 Am^2

Measured by multiple dipole model of magnetic map.

1993; Kanaka, Crimea; medieval kiln N2

Measurements with Tatyana Smekalova (St. Petersburg State Univ.)

Kiln, dimensions about 3.5 by 3.5 m

m = 104 Am^2

Q = 2 - 20 (sample measurement after excavation of nearby kilns).

Measured by prismatic model of magnetic map (no excavation)

August 1997; Choban-Khule; medieval kiln alpha.

Measurements with Tatyana Smekalova (St. Petersburg State Univ.)

Kiln, dimensions about 2.5 by 3.5 m

Visible at excavation surface; unknown fraction remains.

m = 2.3 Am^2

Measured by prismatic model of magnetic map.

June 1997; Tell Banat, Syria; perhaps 2300 BC

Measurements with Tatyana Smekalova (St. Petersburg State Univ.)

Brick clamp (at-surface brick kiln)

k (JH-8) = 0.005

February 1993; Jamestown Island, Virginia, USA.

## Rocks

Metamorphic or igneous stone, V = 450(10^-6) m^3
M = 1.6 A/m
Measured by rotation of hand sample.
March 1976; Quirigua, Guatamala
Metamorphic or igneous stone, V = 570(10^-6) m^3
M (remanent) = 4.0 A/m
M (induced) = 0.44 A/m
Q = 9.2
Measured by rotation of hand sample.
March 1976; Quirigua, Guatamala.
Fine-grained basalt, d = 3000 kg/m^3, ma = 0.6 kg
mrm = 7.2(10^-4) Am^2/kg, mim    mrm
Measured by rotation of hand sample.
January 1983; Rojdi, India.
Gabbro (probably), d = 2900 kg/m 3, ma = 0.685 kg, Be = 43,050 nT
mrm = 1.09(10^-4) Am^2/kg, mim = 3.7(10^-4) Am^2/kg
Q = 0.3, k = 0.031
Measured by rotation of hand sample.
January 1983; Rojdi, India.
Coarse-grained basalt, ma = 0.57 kg, Be = 42,980 nT
mrm = 1.16(10^-2) Am^2/kg, mim = 6.4(10^-3) Am^2/kg, Q = 1.8
Measured by rotation of hand sample.
January 1984; Rojdi, India.
Fine-grained basalt, ma = 2.11 kg
mrm = 1.06(10^-2) Am^2/kg, mim = 1.41(10^-2) Am^2/kg, Q = 0.7
Measured by rotation of hand sample.
January 1984; Rojdi, India.
Basalt, ma = 0.715 kg
mrm = 6.3(10^-3) Am^2/kg, mim = 3.2(10^-3) Am^2/kg, Q = 1.9
Measured by rotation of hand sample.
January 1984; Rojdi, India.
Triassic sandstone, ma = 1.6 kg, Be = 53,850 nT
mrm = 1.1(10^-5) Am^2/kg, mim = 5.5(10^-6) Am^2/kg, Q = 1.9
k (JH-8) = 5(10^-5)
Measured by rotation of hand sample.
October 1995; Manassas Battlefield, Virginia, USA.
Granitic, ma = 1.51 kg, d = 3010 kg/m^3, Be = 55,870 nT
mrm = 1.9(10^-4) Am^2/kg, mim = 2.7(10^-4) Ant^2/kg, Q = 0.7
Measured by rotation of hand sample.
November 1979; Pluckemin, New Jersey, USA.
Gabbro (possibly), ma = 7.7 kg
mrm = 7.9(10^-5) Am^2/kg, mim    mrm
Measured by rotation of hand sample.
September 1981; New Windsor Cantonnment, New York, USA.

Rocks (continued)

Garnet gneiss (possibly), ma = 1.36 kg

mrm = 2.72(10^-4) Am^2/kg, mim = 6.6(10^-4) Am^2/kg, Q = 0.3

Measured by rotation of hand sample.

September 1981; New Windsor Cantonnment, New York, USA.

Granodiorite (possibly)

k (JH-8) = 0.02

December 1991; Green Spring Park, Virginia, USA.

## Soils and Sediments

Beach sand with garnet and magnetite, d = 2400 kg/m^3
k (JH-8) = 0.03 - 0.06
May 1991; Cape Cod, Massachusetts, USA.

Beach sand containing magnetite
k (JH-8) = 0.0035
February 1993; Jamestown Island, Virginia, USA.

Residual soil over limestone
mm = 5(10^-5) Am^2/kg
Measured by rotating soil sample; limestone was non-magnetic.
April 1978; Baq'ah Valley, Jordan.
Measured with Patrick McGovern (Univ. of Pennsylvania).

Silty soil
k = 0.0075
Measured by magnetic model of grave voids.
June 1997; Tell Banat, Syria.
Measured with Tatyana Smekalova (St. Petersburg State Univ.)

Silty soil, Be = 46,150 nT
Soil of White Monument earthen mound, 21 m tall, 61,000 m^3
k = 0.0037
Measured with topographic model of magnetic map and lab. sample.
June 1997; Tell Banat, Syria, 2300 BC
Measured with Tatyana Smekalova (St. Petersburg State Univ.)

## Miscellaneous

Fly ash (ash from coal-burning), V = 7.69(10^-4) m^3
M = 30.2 A/m
September 1985; Bound Brook, New Jersey, USA.

Well, bored, with iron or steel pipe
S = -116.5 Am
Measured with monopole model of magnetic map.
October 1995; Manassas Battlefield, Virginia, USA.

Well, dug, contains iron debris
S = -193.4 Am
Measured with monopole model of magnetic map.
January 1994; Petersburg Battlefield, Virginia, USA.

Magnetic noise caused by overhead wires to electrified buses
B = 10 nT at a distance of about 500 m
Measured with total field magnetometers; model with 35 A current.
October 1992; Simferopol, Ukraine.
Measurements with Tatyana Smekalova (St. Petersburg State Univ.)

Archaeological materials from the site of Neapolis

| Material: | k |
|---|---|
| fired layer | 0.02 |
| pit filling | 0.0075 |
| unfired brick | 0.0013 |
| natural gravel | 0.001 |

Measured in laboratory.
October 1993; Simferopol, Ukraine.
Measurements by Tatyana Smekalova (St. Petersburg State Univ.)

Further archaeological materials from the site of Neapolis

| Material: | k (JH-8) |
|---|---|
| igneous rock | 0.007 |
| roof tile | 0.005 |
| reddish orange fired earth | 0.001 |
| black fired earth | 0.0005 |
| gray ash | 0.0005 |
| ancient topsoil | 0.00015 |
| yellow clay | 0.0001 |
| limestone | <0.00001 |

April 1993; Simferopol, Ukraine.

Central dipole of the Earth, r = 6.37(10^6) m, ma = 5.97(10^24) kg
m = 7.94(10^22) Am^2; nun = 1.33(10^-2) Am^2/kg
From: Frank D. Stacey, *Physics of the Earth,* 1977, p. 333

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