Archaeomagnetism and archaeomagnetic dating

(English version)

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Summary

This document is intended for primarily archaeologists and those with excavation responsibles, but also for persons who want to take archaeomagnetic samples for archaeomagnetic dating and those who wish to become involved with archaeomagnetism. It deals with the principals of archaeomagnetism and archaeomagnetic dating and provides useful information and recommendations for the archaeologists who want their baked structures to be investigated archaeomagnetically. In order for the archaeomagnetists to be able to construct standard diagrams of the geomagnetic field variations in the past and to improve archaeomagnetic datings in the future, the document stresses the importance of archaeomagnetic investigations of independently dated baked structures. The document also contains general information on the geomagnetic field, and the answers to frequently asked questions. The content is mainly based on textbooks given in the references and on a few web sites. Words in bold in the text are explained in the glossary.

1. Introduction

Archaeomagnetism is mainly known by the archaeologists as a dating method: archaeomagnetic dating. Archaeomagnetism of baked clays was developed in France in the nineteen thirties by Prof. E. Thellier and his wife O. Thellier. In the nineteen sixties it started to be applied as a relatively reliable and precise dating method for baked structures, particularly by M.J. Aitken in the United Kingdom. This dating method is interdisciplinary, requiring the expertise of specialists in different fields and particularly a close collaboration between archaeologists and geophysicists. It is the archaeologist who supplies the material and the information necessary to develop and to test the method and remains fundamental to improve the method. Only the archaeologist is able to determine the contextual signification of the archaeomagnetic date determined by the geophysicist. Hence, the success of an archaeomagnetic investigation depends strongly on the synergy between the geophysicist and the archaeologist, but the information obtained is valuable to both.

It is important that the archaeologists using archaeomagnetic dates have a basic knowledge of archaeomagnetism – particularly an awareness of the archaeomagnetic dating method.

2. The principle of archaeomagnetism

Materials, heated to high temperatures, acquire a **remanent magnetisation** with a direction parallel to, and an intensity proportional to, the ambient **Earth magnetic field** at the time of cooling. Measurement of this remanence allows the determination of this direction and intensity of the Earth magnetic field at the moment of cooling. Conversely, knowledge of the past variations of the Earth's magnetic field allows the dating of the last heating of the baked and burned materials, called **archaeomagnetic dating**.

3. The Earth magnetic field

The Earth possesses a magnetic field, the Earth's magnetic field or **geomagnetic field** that can be observed by its action on a magnetic compass or on a freely suspended magnetic needle. A magnetic compass, which is in reality a magnetised needle adjusted so that it can only rotate in a horizontal plane, will always orients itself in a well-defined direction corresponding to **magnetic north**. A freely suspended magnetised needle orients itself in a vertical plane, called **local magnetic meridian**, making an angle with the local horizontal plane, called **magnetic inclination**.

The geomagnetic field is completely defined in each point in space by its direction and its intensity. Its direction is determined by two angles: **declination** *D*, and **inclination** *I*. Declination *D* is the angle in the horizontal plane between the direction of **geographic north** (true north, situated on the rotation axis) and magnetic north. Hence, it is the angle between the **geographic meridian** of the place and its local magnetic meridian. The inclination *I* is the angle between the field and the local horizontal plane. The **Intensity F** of the field is its value, its magnitude. The three elements *D*, *I* and **F**, completely define the field in a place at a certain moment. The elements *D* and *I* are expressed in degrees of arc and **F** in **nanoTesla** (nT). The Earth has two **magnetic poles**: the magnetic north pole is situated at present in the north of Canada and the south magnetic pole is in Antarctica. The geomagnetic field resembles the field of a magnet with two poles (**dipole**), at the centre of the Earth that is oriented along an axis making at present an angle of about 11° with the rotation axis of the Earth.

In each point the field may be represented by a vector (arrow) reflecting its intensity and direction in space.

The field varies in space from one place to the other. Depending on the place on the Earth, the inclination *I* varies between 0° and 90°, N or S (N when the north-seeking end of a freely suspended magnet dips below the horizontal plane, which is the case for the greater part of the northern hemisphere) and attains a value equal to +90° or -90° at the magnetic poles. The declination also changes from place to place and is counted between 0° and 180° from geographic north, E or W, depending if geomagnetic north is located east or west from geographic north. The declination *D* is undefined at the magnetic poles. The intensity or the length of the field vector changes with the latitude of the place between about 25000 and 65000 nanoTesla and attains near the magnetic poles a value about twice as great as near the equator.

The geomagnetic field also varies in time. These temporal variations are known from direct instrumental measurements for *D* and *I* during the last few centuries, while the intensity **F** was only measured for the first time in 1832 by **C.F. Gauss** in Germany. The variations of the elements of the geomagnetic field from one year to the other are called **secular variation**. Globally, the intensity of the field is decreasing at a rate of about 5 % per century. As the temporal variations of the field elements differ from place to place, they need to be observed and recorded in different places of the Earth. At present the geomagnetic field is measured continuously in about 250 magnetic observatories.

Direct instrumental field observations are relatively recent, for *D* since the 16th century, for *I* since the 17th century and for **F** only since the 19th century. Fortunately, archaeomagnetism enables measurements to be made further back in time, based on the magnetic memory of rocks and baked clays.

4. Geomagnetic field records in baked clays.

All materials heated at high temperatures in the presence of a magnetic field acquire a remanent or permanent magnetisation during cooling. This remanent magnetisation can be represented by a vector, the direction of which corresponds to that of the ambient field and with a magnitude proportional to the intensity of the field. If the heating temperature is sufficiently high and beyond a critical temperature, the **Curie** or **Néel temperature** after the inventors, all remanent magnetisation acquired before is removed and is replaced during cooling by a new remanent magnetisation, called the **total thermoremanent magnetisation**, when room temperature is reached. Hence, the increase of the temperature above the Curie or Néel temperature deletes every magnetisation acquired before and consequently every memory of the ancient field. Heating at temperatures lower than the Curie or Néel temperatures will only remove parts of the remanence acquired before, and replace it by a new magnetisation during cooling in the ambient magnetic field, called **partial thermoremanent magnetisation**. In this case, the total magnetisation of the sample contains two magnetisation components, probably of different directions: a **partial thermoremanent magnetisation** obtained in the temperature interval between the maximum reheating temperature and room temperature in the present field and the residual remanence acquired before.

The main magnetic minerals contributing to the remanent magnetisation in baked clays are iron oxides, in decreasing order of importance: **magnetite** Fe_3O_4, **maghaemite**, γ-Fe_2O_3 and **haematite** α-Fe_2O_3; the Curie or Néel temperatures of which are respectively 585, about 620 and 675°C. Fine grained iron oxides are responsible for the red colour of baked clay when heated in an oxidising atmosphere or grey-black when heated in a reducing atmosphere.

If the baked materials are still in-situ, or otherwise stated if they did not underwent post-baking movements, the direction and intensity of the ancient field can be recovered by measuring the remanent magnetisation of samples oriented in a geographic coordinate system. Samples that have been moved after cooling can still be used for intensity determinations of the ancient field and even the direction of the ancient field if the position of the samples during baking is known. This is the case for the inclination of the field, which can be recovered from pottery baked in the vertical position or tiles baked in the upright position, but the declination in such materials remains undetermined.

5. Methodology of an archaeomagnetic investigation

5.1. Sampling

The determination of the direction of the ancient field requires **samples** taken from baked non-disturbed structures that remained in place after cooling and that need to be oriented with sufficient precision. Taken into account the rate of the secular variation of the field direction, which is in the order of a few degrees of arc within tenths of years, the precision of the orientation of the sample should be better than one or two degrees if possible. The samples must be oriented with regard to the local horizontal plane and geographic north. The dip of the sample and the reference direction of known geographic azimuth can be determined in different ways. (A general description explaining different methods will be added.)

Dip

The measurement of the dip of the surface of sample can be avoided by realising a horizontal surface on the top of the samples (dip equals zero). This horizontal surface can be made by pouring gypsum on top of the sample and pressing and levelling a plate (plexi-glass or aluminium) equipped with spirit levels before the gypsum hardens. Another possibility is to glue a small levelled plexi-glass plate or disk on top of the sample using a fast setting glue (e.g. Epoxy-glue).

Reference direction

Sun

zenithal distance method: theodolite,
hour angle method: solar compass

Geographical north seeker

Gyro- theodolite

Magnetic compass

It is recommended not to use the magnetic compass, as burned structures are often strongly magnetic and may cause compass deviations. If, however, the magnetic compass is used it should be put as far from the material as practicable and the local magnetic declination must be known

5.2. Sample preparation before measurement

During transport and storing in the laboratory, the samples will keep the magnetic information they contain unless they are exposed to intense magnetic fields (strong electrical currents and permanent magnets) or temperature changes that may modify the remanent magnetisation that the samples had in the field, called **natural remanent magnetisation (NRM)** or also **in-situ remanent magnetisation**. Most remanence measuring equipments require regularly shaped **specimens** (cubes or cylinders). Therefore the samples are generally cut or drilled into cubes and cylinders while retaining their reference direction. Non baked parts should be removed as much as possible, as well as disturbed parts (bio-turbated) and foreign elements (sherds, pieces of iron, etc.).

The optimal dimension of a specimen is still a matter of discussion. The larger the sample, the higher will be the precision in direction and the sample becomes more homogeneous, but the higher becomes the risk to include insufficiently baked material or foreign non-desirable elements like stones, sherds, scoria, etc. Hence, the optimum size of the specimen depends strongly on the nature (texture) of the material and dimensions of the elements it contains. It is generally determined by the instrumentation available in the laboratory concerned.

5.3. Measurement of the remanent magnetisation

The relatively weak remanence intensity of baked clays and the investigation of the ancient field direction require remanence measurement equipments of high sensitivity and great precision.

Spinner-magnetometer

The **spinner magnetometer** is based on the dynamo principle. It is equipped with a detection coil with many windings. The sample is a weak magnet rotating in the centre of this coil and induces an electrical current in it. This current is proportional to the magnetisation component perpendicular to the windings. By changing the sample position on the turntable, the other magnetisation components can be obtained in a system of orthogonal axes X, Y, Z attached to the sample. After calculation D and I are obtained, taking into account the azimuth of the reference direction and the dip, as well as the total NRM intensity.

Fluxgate-magnetometer

In a fluxgate magnetometer the magnetic field due to the sample is measured by a so called fluxgate sensor. The sensor consists of a primary drive coil and a secondary pick-up coil, both winded around a highly permeable core. The measurement is based on the proportionality between the induced voltage and temporal change of magnetic flux density. Tri-axial fluxgate sensors can be used to measure the three orthogonal components of the magnetic field (depending on the position of the sensor), but also to measure the remanent magnetisation of a baked sample.

Cryogenic Squid-magnetometer

Cryogenic SQUID magnetometers are highly sensitive instruments, measuring magnetic moments in the order of 10^{-10} Am^2. The sample to be measured is inserted in a superconducting coil. Magnetic flux enters the ring and the current drops by quantised values. Depending on the intensity of the sample several such drops (also called flux quantum jumps) are produced, their number being proportional to the magnetisation of the sample.

The NRM rarely consists of a single component, but in general it is a multi-component magnetisation and thus is the sum of several remanent magnetisations acquired at different times. All materials acquire spontaneously a remanent magnetisation after exposure to the ambient geomagnetic field, even at room temperature. The resulting remanence is called **viscous remanent magnetisation (VRM)**. One should not forget that baked structures, after their last cooling, have been exposed to the geomagnetic field during a long period of time and that a VRM is certainly present. Exceptionally, baked structures may have been struck by lightning and have been exposed to an electrical discharge accompanied by an intense magnetic field. In this case, a remanent magnetisation called **isothermal remanent magnetisation (IRM)** may be present in the structure.

5.4. Magnetic stability tests

The aim of the magnetic stability tests is to identify and to separate the different remanent magnetisation components present in the samples, to examine their magnetic stability and to determine their direction.

Magnetic viscosity test

This test aims to estimate the degree of VRM acquired by the specimens in a known field during a certain time interval. The specimens are kept during a few weeks in a known position with regard to the magnetic field in the laboratory and their remanent magnetisation measured afterwards (measurement 1). Then they are stored in an upside position during a few weeks and their remanent magnetisation is measured again (measurement 2). The half difference between the two measurements indicates the presence of a VRM acquired by the samples during the time span they spent in the upside position. The VRM is in general unstable and has to be removed in order to isolate the stable magnetisation components. Generally, two methods are used: stepwise demagnetisation in increasing alternating fields and stepwise demagnetisation at increasing temperatures. These tests are performed on a few pilot specimens, representative for the structure examined or in some laboratories on all specimens. In many laboratories several demagnetisation steps are applied to all specimens.

Stepwise demagnetisation in increasing alternating fields

The pilot specimens are submitted to a decreasing alternating magnetic field, starting from a certain value in the absence of a direct or constant field. Then the residual remanence is measured. The cycle “demagnetisation and measurement of the residual remanence” is repeated for increasing alternating field values. The resistance of the NRM against this progressive demagnetisation is a measure of the magnetic stability of the specimen. The observation of the directional variations of the NRM during this treatment may indicate the presence of several remanence components.

Stepwise demagnetisation with increasing temperatures

This test can only be applied to solid specimens or to specimens that have been consolidated with non-magnetic, high temperature resisting products. The pilot specimens are heated to a certain temperature, followed by cooling in zero field back down to room temperature. The residual remanent magnetisation is measured afterwards. The cycle “heating, cooling and measurement” is repeated for increasing temperatures until the complete removal of the NRM has been achieved. This test does not only permit determination of the stability of the NRM, and establishing the presence of multiple remanent magnetisation components, but also to determine the nature or chemical composition of the minerals carrying the magnetic remanence.

In favourable cases, from the alternating field and/or thermal demagnetisation tests, an alternating field value or temperature can be determined, needed to eliminate less stable components and to isolate the maximum of the most stable component. The latter is called **characteristic remanent magnetisation (ChRM)**, which in baked clays corresponds to the thermoremanence acquired in the ancient field direction. Having isolated and measured the ChRM of all the specimens, their analysis and calculation of the mean direction can then proceed.

5.5. Analysis of the measurements

The direction of the ChRM differs from one specimen to another for several reasons: orientation errors during sampling (generally negligible), measurement errors (generally small), incomplete removal of other remanences, inhomogeneous ChRM, presence of insufficiently baked material, post-baking movements of the baked structure and other factors like **magnetic anisotropy** and **magnetic refraction** that will be explained briefly later. A statistical analysis is needed to find the average magnetisation direction of the structure. If the individual ChRM directions have a **normal distribution**, the statistics developed by Sir Ronald **Fisher** for the treatment of vectors, can be applied. The mean magnetisation direction of the structure corresponds to the vector sum or the resultant of the ChRM's of each sample giving the same statistical weight (value) to each individual direction and eventually after elimination of outliers. Before that, the average direction of each sample was calculated, in the same way by adding vectorially the unit vectors of the specimens. The **concentration parameter k** and the **confidence factor α_{95}** are also calculated. The parameter k is a measure of the scatter of the individual sample directions around the mean direction and α_{95} is the semi-angle of the cone around the mean direction in which the true direction occurs with a probability of 95%, assuming no systematic errors are present.

5.6. Archaeomagnetic dating

The dimension of time is essential in archaeology. Events, facts and human actions observed and recorded by the archaeologists only have historical sense if they can be situated in time (dating, absolute chronology) or be classified with respect to events before and afterwards (relative chronology). Recording of the order of events, stratigraphy, is a study of relative chronology. Later, when the archaeologist can situate an event or several events in calendar time, the relative chronology becomes an absolute chronology.

The aim of dating is to situate an event in time. In archaeomagnetism the event is the last cooling of baked clay after having been heated at high temperatures.

Archaeomagnetic dating is a relative dating technique; calibration is necessary to make it absolute (calendar). The direction and intensity of the remanent magnetisation of a sample of unknown age is compared with known ancient geomagnetic field data obtained from other well-dated baked structures. In certain cases these known data have been fixed to the time scale by absolute or relative dating techniques (^{14}C, thermo-luminescence, dendrochronology) but in most cases by purely archaeological dating (typology, context dating, historical sources, iconography, coins). The calibration error is therefore largely dependent on the reliability by which previous structures have been studied. It therefore tends to improve as more well-dated sites become available.

When α_{95} is small, i.e. when the reliability of the average direction is high, the scatter of the individual magnetisation direction small (k high) and important systematic errors absent (e.g. mass movement of the structure due to tectonic activities for instance), an archaeomagnetic dating can be attempted, based on the present knowledge of the secular variation of the ancient geomagnetic field.

Archaeomagnetic dating is only possible if the variation of the geomagnetic field of the past is known for the location of the sampling site. If a standard secular variation curve is available, the site data must be corrected to the standard reference site. A few standard curves are available for Europe and others will become available in the future (France, United Kingdom, Bulgaria, Hungary, Germany). The area validity is about 250000 km^2, but it depends on the desired precision.

A simple reduction consists in correcting the average declination and inclination found for the present day difference of the field between the sampling site and the reference site. This method assumes that the secular variation in both sites was always identical. Another method is to calculate the virtual geomagnetic pole (VGP) corresponding to the direction found in the sampling site assuming a geocentric **axial dipole field** and calculating back the field direction in the reference site. After correction, the mean direction can be plotted on the reference Bauer-diagram (inclination versus declination) and the most probable date of the last cooling can be read from this diagram.

The precision of an archaeomagnetic dating depends on several factors and remains difficult to estimate. It depends mainly on the fidelity of the record, absence of systematic errors (post-baking movements), the rate of variation of the geomagnetic field and the accuracy of the reference diagrams (these are constantly being improved). The latter depends on the precision of the independent datings of the baked structures on which the reference diagrams are based. This is why it is important for the archaeomagnetist to be able to examine baked structures that have been (or will be) dated by archaeological or other methods.

6. Applications of archaeomagnetism

- Dating of baked or burnt materials that remained unmoved since last fired. The method is based on the determination of D, I and $\mathbf{F}$ and on our knowledge of the direction and intensity of the geomagnetic field in the past.
  Materials: all materials sufficiently baked in-situ, kilns, fire places, burnt layers, accidental or intentional (war) burnt structures

- Dating of displaced materials and objects
  - If the position during their production is partially known: dating on the basis of the measured inclination and intensity
    Materials: tiles, bricks, *tegulae*, slabs in baked clay, *imbrices*, pottery
  - If the position is unknown: dating on the basis of measured intensity
    Materials: all displaced baked materials and objects

- Dating of construction or destruction phases of buildings
  Materials: burnt materials, bricks, tiles

- Determination of the firing position of materials or objects during their manufacture. It is possible to verify whether the baked materials or objects were fired in horizontal or vertical positions. Determination of the orientation of rectangular or square kilns.
  Examples: tiles (*tegulae*), bricks, slabs in baked clay (piled slabs in hypocausts), *imbrices*, pottery, amphores, vases.

- Restoration and reconstruction of broken baked objects.
  The remanent magnetisation is a marker that can be used to find the position of, for example, non contiguous sherds when assembling broken ceramics.

- Classification of fragments of fired construction materials
  Do they belong to one or several production periods spread in time.

- Contemporaneity of baked structures

- Determination of firing temperatures.

7. Palaeomagnetism

Archaeomagnetism is not limited to historical periods and can also be applied to pre-historical periods. Applied to baked clays of this period it is still called archaeomagnetism; applied to rocks one speaks of **palaeomagnetism**. Often one tries to date strata or layers in which artefacts as witnesses of human activities are found. In most cases dating is based on the normal or reversed geomagnetic field polarities recorded in the sediments. The geomagnetic field reversed many times in its history. By definition, the field is normal when the magnetic north pole is situated near to the geographic North Pole (the Earth's axis of rotation), as case for the present day field. By comparison of the polarities found (magnetozones) with the known geomagnetic polarity timescale, that is dated with precision for the last 5 million years, independent chronological markers are obtained. The last field reversal known with certainty is dated at 0.78 million years. For young sediments the comparison of the relative variations of D, I and $\mathbf{F}$ in function of depth between different drillings or outcrops results in a relative chronology. In certain cases the comparison with standard diagrams of the temporal variation of D, I and $\mathbf{F}$ can yield an absolute chronology.

Notice that the geomagnetic field is recorded in sediments as a **depositional** or **post-depositional remanent magnetisation**, when magnetised particles are aligned along the field during sedimentation or as a **crystalline remanent magnetisation**, when magnetic minerals crystallise in the presence of the Earth's magnetic field. The magnetic analysis of any deposits filling ditches or of sediments covering or filling the structures in archaeological sites may be useful in archaeomagnetism.

8. Independent datings for establishing standard secular variation diagrams

It is important that the archaeologist stays in contact with the archaeomagnetist after the intervention of the latter and after having finished the site investigation and analysis of the objects discovered in it. Moreover, it is very important the he communicates all information about independent absolute or relative dates obtained for the baked structures sampled by the archaeomagnetist and particularly any dates obtained related to the context of the structures. This information may contribute significantly to the construction of standard diagrams.

The semantics of the concepts of "absolute" and "relative" dating will not be discussed in detail. In reality, no dating technique is strictly speaking absolute. An absolute dating utilises an internal process (such as the radioactive decay of ^{14}C) isolated of all external influence (environment) and allows the event to be put into an astronomical time scale. This assumes that there was no influence of the environments at the beginning nor any subsequent evolution of the environment of the materials concerned. Relative dating, in contrast to an absolute dating, relies on data or measurements linked to the environment. Stratigraphy and purely archaeological dating, based for instance on typology or typological series, closed ensembles, or contextual dating that is linked to the site, are extremely useful for the archaeomagnetist.

One needs to draw the attention to a common error in contextual dating linked to the improper use of the term *terminus post quem*

Terminus post quem = terminus a quo: the moment from which an event took place

Terminus ante quem = terminus ad quem: a moment until, or before, which an event took place

9. An example of an archaeomagnetic dating

(will be added later)

10. Important recommendations for archaeologists, who want their sites to be investigated archaeomagnetically

The archaeomagnetist would like to be informed when an archaeologist discovers baked clays in-situ, whether the time of baking is known (to establish local standard secular variation curves) or not (to date the last cooling based on available standard secular variation curves) or even when the archaeologist plans other dating methods (confirmation or disproval of the independent datings).

The archaeomagnetic team, or other trained personal, will do the sampling of the baked clays in agreement with the site and excavation authorities responsible. Before their intervention, the baked structure may be opened and emptied - preferably without removing any baked material. It is important to avoid everything that could disturb (e.g. trampling, heavy loading) the baked structure and to leave enough non-baked material in place to better apprehend the context of the structure with its environment and to facilitate the evaluation of the intensity of baking. The archaeomagnetist needs to be informed of any material that has been replaced during excavation.

It is necessary to protect the baked clays against rain, which makes them soft, but also against long exposure to the sun (intense drying) and frost, which cause cracking and which may separate the hard and soft baked parts.

Upon arrival at the site, the archaeomagnetist examines the baked structure in order to estimate the degree of conservation (parts from the original structure that still remain – assessing which parts may have been tilted or displaced, structure fall-in and fall-out, etc.), the presence of disturbances (bioturbation, cryoturbation, etc.), the degree of baking and the nature of the construction materials of the structure. This examination allows the archaeomagnetist to establish an optimal sampling scheme that fully takes into account any constraints imposed by the archaeologist. The excavator must be able to examine the structure and to draw one or more sections. This may be perfectly done in coordination with the archaeomagnetic sampling. Those parts of the structure that must be removed to allow the archaeologist to make drawings or to examine deeper below the structure, are oriented before their removal and hence can still serve for archaeomagnetic analysis. The samples to be taken for the achaeomagnetic investigation should be well distributed over the structure so that they are representative of the structure and the materials present. The application of the statistics to calculate the mean magnetisation direction after measurement in the laboratory requires a strict minimum of seven samples from a structure that perfectly recorded the Earth magnetic field and that is free of post-baking movements. Therefore, if possible, 12 to 20 samples are taken per structure to increase the precision. Sometimes even more samples are taken in case the structure has to be removed to allow archaeological investigations at deeper levels. It is also useful to take additional samples for particular studies such as the effects of magnetic anisotropy and magnetic refraction. In general, archaeomagnetic measurements in the laboratory are non-destructive, except when thermal demagnetisation is applied. After finishing the archaeomagnetic examination, the samples are archived and may thus be used for other analyses and investigations in the future.

In case the site responsible plans a complete conservation of the structure in the archaeological site or elsewhere (museum), a limited sampling of small samples can be proposed in agreement with the archaeologist.

Information that the archaeomagnetist would like to receive from the person responsible for the site include: its affiliation and address, name of the site and locality, the number of the excavation sector and the archaeological/context code of the structure. If possible: a copy of the plan of the structure and eventually of the site and geographical coordinates of the structure.

11. Frequently asked questions

What is the Earth's magnetic field?

The Earth acts as a giant magnet and is therefore surrounded by a magnetic field, called the Earth's magnetic field or the geomagnetic field. The geomagnetic field resembles the field of a dipole magnet (magnet with a north and south magnetic pole at its extremities) located in the centre of the Earth and inclined by 11.4 ° with respect to the rotation axis of the Earth. This representation is somewhat simplified as the observed field can be much more complex and varies not only in space but also in time. At any point the geomagnetic field by its direction and intensity.

Is the magnetic field different in different places of the Earth?

Yes. The geomagnetic field varies from place to place in an irregular way. Hence, it must be measured in many places in order to obtain an accurate image of its geographical distribution. At the moment the field is observed in about 200 operating magnetic observatories on the continents and supplemented by marine surveys and with satellite measurements.

Does the magnetic field vary with time?

The geomagnetic field varies in time. The spectrum of variations is very large, from fractions of a second up to millions of years. There are variations of both internal and external origin. The diurnal, seasonal and annual variations are primarily of external origin and are caused by the solar activity. The sun emits particles and radiation; these are responsible for ionisations in the ionosphere with associated electrical currents and magnetic fields. The longest known cycle of external origin is about 11 years linked to the 22 year cyclicity of the solar activity. Variations of internal origin have much greater periods from a few years to millions of years. By definition, the variations of the main field of internal origin are termed secular variations. For practical reason, the secular variation is the variation from year to year. Consequently, this variation is not completely of internal origin and still contains components of external origin.

Does the geomagnetic field reverse soon?

Although a decrease of the geomagnetic field intensity is globally observed, one cannot state that the field will reverse soon. On basis of intensity measurement since the first half of the 19th century, some researchers claim that the total dipole moment of the field will become zero in about 1300 years. But the value of the present day dipole moment is still much more important than it has been for most of the time during the last 50,000 years and the trend of decrease could switch at any moment. Even if the field began to reverse, it needs probably several thousands of years (may be 3000 to 8000) to reverse completely. The field does not become completely zero during a reversal, but it is much weaker than normal and may be multipolar. Migrating animals using the Earth’s magnetic field for orientation may be disturbed to some extent. The magnetic reversals are well-known and relatively well-dated for the last 5 million years on basis of palaeomagnetic measurements and absolute dating; the last reversal known with certainty took place 780 000 years ago. It is possible and even probable that reversals of short duration occurred since that time.

What is the origin of the geomagnetic field?

The geomagnetic field finds its main origin in the liquid external core of the Earth. The most generally accepted hypothesis is that the geomagnetic field is generated by interaction between a magnetic field and the motion of the Earth’s fluid core. This liquid is an electrical conductor and when it moves in a magnetic field (interplanetary field) electrical currents are generated that are accompanied by magnetic fields. Due to the Ohmic resistance, these currents decrease in some 2000 years. Hence, there must a mechanism to regenerate the electrical currents in order to maintain the field. One of these mechanisms is a self-exciting dynamo.

What is a magnetic pole and where are they?

The **magnetic poles** are defined as the points where a freely suspended magnet is vertical i.e. where the field inclination is 90°. These points are difficult to determine as the magnetic poles are not fixed but move several tens to hundreds of kilometres due to the daily variation of the field and even more during magnetic storms. Observations by the Canadian Geological Survey and the U.S. Naval Oceanographic Office place the magnetic poles at:

North magnetic pole (in 2005): 82.7° N and 114.4° W, near Elef Ringes island (Canada)
South magnetic pole (in 2001): 64.7° S and 138.0° E in the bay Commonwealth Bay (Antarctica)

Poles based on a global analysis of the observed field limiting it self to dipole terms (dipole model) are called **geomagnetic poles**. The geomagnetic poles that correspond to the International Geomagnetic Reference Field (IGRF) for 2005 are situated at:

North geomagnetic pole: 79.7° N and 71.8° W
South geomagnetic pole: 79.7° S and 108.2°E

What is the magnetic equator?

The magnetic equator is where the inclination I i.e. the vertical field component V is zero. In contrast with the geographic equator, the magnetic equator is irregular and not fixed. North of the magnetic equator the north seeking end of a freely suspended magnet dips below the local horizontal plane and I and V are counted positive. South of the equator the south seeking end of the magnet dips below the local horizontal plane and I and V are negative.

How is the geomagnetic field recorded in baked clays?

Baked clays contain magnetic minerals (mainly iron oxides) carrying the remanent magnetisation. When a sufficiently high temperature (**Curie- or Néel-temperature**) is reached, this remanence disappears. During cooling below this critical temperature, a new remanent magnetisation is induced by the ambient magnetic field. This remanent magnetisation, called thermoremanent magnetisation, represents the field record during cooling.

Does the presence of high voltage power lines induce a parasitic remanence in archaeological baked structures?

As the electrical current flowing in these power lines is an alternating current, and the magnetic field intensity generated by this current decreases with distance, the effects of power lines on the remanent magnetisation in archaeological baked structures is generally negligible.

Does the compass needle point towards the magnetic pole?

The answer is no. The magnetic compass points in the direction of the local horizontal component H of the geomagnetic field and not to any single point.

How to convert compass readings to real geographical azimuth?

In order to convert a compass reading into real geographic azimuth, the magnetic declination of the area for the time concerned must be known. Consult local magnetic observatories or world magnetic maps edited by (NOAA, IAGA). The true azimuth is obtained by adding the local declination to the reading (= magnetic azimuth) following the conventions: declination in degrees W or negative, declination E or positive. When the declination is not known for the period concerned, but for another period, a correction, must be made based on the secular variation. An alternative way to find the declination is to take a compass reading in a known geographical direction (a compass reading of a long straight road for instance or from a known point to some remarkable point that is on the map).

Why orient archaeomagnetic samples with a solar compass or a theodolite and not with a magnetic compass?

The geographical azimuth of a reference direction can be determined with precision on basis of the hour angle for the first and of the zenithal distance for the second. It is not advised to use the magnetic compass for orienting strongly magnetic baked clays. Partially because a correction must be applied for the local magnetic declination, but mainly because errors may occur due to local magnetic anomalies (of geological origin or caused by the presence of metallic masses or electrical currents in or in the vicinity of the archaeological site).

What is the precision of archaeomagnetic dating?

The precision of archaeomagnetic dating depends on several factors: the fidelity of the field record in the baked clays, the absence of post-baking movements of the structure, the rate of change of the magnetic field and the precision of the reference diagrams, which ultimately depends on the precision of the independent dating of the baked clays on which they are based. For certain periods for the last few millennia, an average precision of 25 years can be reached.

Did the geomagnetic field vary much during archaeological periods of time?

In Europe, during the two last millennia, the declination has varied in the order of about 50° and the inclination by about 20°.

12. Glossary
AARCH Glossary

Am^2
Ampère times metres squared. Unit of magnetic moment

A/m
Ampère per metre. Unit of **magnetisation** when expressed per unit of volume. Typically, the **natural remanent magnetisation** of a baked clay is in the order of 1 A/m and of a sediment 10^{-3} A/m.

Am^2/kg
Ampère times metres squared per kilogram. Unit of magnetisation when expressed per unit of weight.

Anhysteretic remanent magnetisation (ARM)
Remanent magnetisation imparted to a sample in the laboratory by a decreasing alternating magnetic field in the presence of a steady magnetic field.

Anisotropy of magnetic susceptibility
Variation of **magnetic susceptibility** with direction. Generally dominated by the form of the **ferromagnetic** grains or by alignment of elongated or flattened grains.

Antiferromagnetism
(see also **ferromagnetism**).
In a solid, the quantum mechanical exchange interaction at short distance between cations via an anion (indirect interaction) favours an antiparallel alignment of the individual magnetic moments of atoms or ions. The resulting magnetisation is zero. The magnetic susceptibility is weak. Antiferromagnetics become paramagnetic (see also **paramagnetism**) beyond the Néel-temperature. Example: Haematite (α-Fe_2O_3). Antiferromagnetics often have ferromagnetic properties due to impurities (parasitic ferromagnetism, e.g. in goethite, haematite) or because of an imperfect antiparallelism of the magnetic moments (canted antiferromagnetism, e.g. haematite).

Archaeomagnetic dating
A date obtained by comparing the values of the ancient geomagnetic field elements corresponding to the ChRM of baked clays with standard secular variation diagrams of the local geomagnetic field elements during the past.

Archaeomagnetism
(see also **palaeomagnetism**)
For the archaeologist a dating method based on the remanent magnetisation of baked clays. Study of the magnetic properties of archaeological materials (mainly baked clays) of historical or pre-historical age.

Archaic Period
Cultural period in Greece between 750 and 500 BC, subsequent to the **Dark Ages** and followed by the **Classical period**. This period is characterised by the naturalistic representation of the human figure, the formation of city-states and the rise of the aristocracy.

Azimuth
Angle between the vertical plane through the observation point and the geographic meridial plane.

Bayesian statistics
Statistical theory of Thomas Bayes. The probability of an event higher in hierarchy is calculated on the basis of the probability estimates derived from an event lower in hierarchy or from empirical data.

BP
Before present. ^{14}C dating before its correction in calendar years.

Bronze-age
Denotes a time period in the development of human society subsequent to the **Stone-age.** Period of advanced metalworking when techniques of smelting copper from natural outcrops, and bronze alloys, were developed and produced. The starting date differs from culture to culture: in Britain the Bronze-age lasted from 2200 to 700 BC; in central Europe from 1800 to 700 BC; while in the Aegean it is associated with the **Minoan period.** The Bronze-age is followed by the **Iron-age**.

Byzantine period
Cultural period between 324 AD and 1453 AD denoting the supremacy of the Byzantine Empire in south-eastern Europe, Syria, Egypt, Israel, and North Africa. Byzantium – the other name for the east-Roman Christianised empire – rose from the Roman empire and disappeared with the invasion of the ottoman Turks.

Capping
The capping or also topping of a kiln comprises the material used as temporary covering for the open end of the **superstructure**. Its purpose was to prevent the loss of heat but also in the case of reducing firing, to prevent oxygen intrusion.

Carolingian
Denotes a time between the 8^{th} and 10^{th} century AD when a dynasty of Frankish rulers (amongst them Charles the Great) and their successors ruled parts of Europe (mainly territories in the present day France and Germany, Austria).

Coercivity
Magnetic field that must be applied to a material to change its magnetisation to the opposite direction. The coercivity depends inter alia on grain size and grain shape. When remanent magnetisation is concerned, one speaks about coercivity of remanence.

Coercivity spectrum
A variety of grain sizes and shapes exist in a sample or specimen. Hence the coercivity is rather a distribution of values than a single value. This is called coercivity spectrum.

Characteristic remanent magnetisation (ChRM)
Remanent magnetisation obtained after removal of less stable remanent magnetisation components. It represents in general the record of the Earth magnetic field at the moment of cooling of a baked clay (see also **remanence**).

Chemical remanent magnetisation
Remanent magnetisation acquired during the crystallisation of magnetic minerals in a magnetic field

Classical Period
Cultural period in Greece between 500 and 336 BC subsequent to the **Archaic period** and followed by the **Hellenistic period**. Development in politics (Pericles), culture (Sophocles, Euripides) and philosophy (Socrates, Plato) culminated in Athens.

Combustion chamber
Part of a **kiln,** where the fire burnt and from which hot gases percolated upwards through the raised oven floor to the overlying **oven**. In single chambered sunken kilns it is also called oven-pit.

Concentration parameter *k*

Estimate of the concentration parameter κ of **Fisherian statistics.** Indicates the statistical distribution of points on the surface of a sphere and therefore it is a scatter estimate of for **ChRM** directions. The concentration parameter is given by $\kappa \approx k = (N\text{-}1)/N\text{-}R)$, where N is the number of directions and R the modulus of the vector sum of all unit vectors. A mean ChRM direction of a site should have values of $k > 80$ to be considered as a reliable result.

Confidence factor α_{95}

Semi-angle of the cone of confidence around the mean direction in which the true directions occur with a probability of 95%. It is calculated from the following formula $\alpha_{(1\text{-}P)} = \cos^{-1}(1\text{-}(N\text{-}R)/R[(1/P)^{1/N\text{-}1}\text{-}1]))$ where N is the number of directions, R the modulus of the vector sum of all unit vectors and P equal 0.05 at a probability level of 95%. For a mean direction of an archaeological site α_{95} should not be more than 2°. In order to assess the accuracy of a mean direction, the **concentration parameter *k*** should also be considered. The confidence factor α_{95} decreases with an increasing number of samples.

Context dating

Relative dating of an archaeological structure or object, based on other archaeological findings around it of known age.

Cryogenic magnetometer

Instrument to measure the remanent magnetisation of rock and baked clay samples based on certain superconducting properties. The sample to be measured is inserted in a superconducting coil in which it induces a persistent electrical current. This current is send to another coil via a magnetic flux transformer. The amplified current is then detected by a sensor called **SQUID-sensor**, in reality a weak magnetic field detector. In a three axes cryogenic magnetometer, three orthogonal pairs of superconducting coils measure simultaneously the three orthogonal vector components of the magnetisation. Its main advantages compared to the spinner magnetometer are its high sensitivity, short response time and a signal independent of the velocity with which the sample is inserted in the detection coils.

Crystalline remanent magnetisation (CRM)

Remanent magnetisation acquired during the crystallisation of magnetic minerals in a magnetic field.

Curie, Pierre

French physicist (Paris 1859 – Paris 1906). He studied the magnetism of materials as a function of temperature and deduced from it the “principle of symmetry”: the symmetry of elements of causes of physical phenomena must be found back in the effects. He deduced from it also the law, $\chi = C/T$, expressing the decrease of the magnetic susceptibility of paramagnetics with increasing temperature, known as the Curie-Weiss law. With his wife Marie Curie he studied the phenomenon of radioactivity and discovered with his brother Jacques, piezoelectricity. He obtained the Nobel Price in 1903.

Curie-temperature T_C
Temperature below which, magnetic moments of **ferromagnetic** materials are parallel. Beyond this critical temperature they become **paramagnetic**.

Dark Ages
Cultural period in Greece between 1100 and 750 BC, subsequent to the **Mycenaean age** and followed by the **Archaic period**. Greece was occupied by the Dorians during this period.

Dating
Determination of a date, in absolute chronology with regard to the Christian reference system (before Christ BC, after Christ AC; before or after our era)

Declination (D)
Angle between geographic north (true north) and magnetic north. Also angle between geographic north and the magnetic remanence of a sample.

Demagnetisation
Action to eliminate the remanent magnetisation of a sample.
alternating field demagnetisation
Demagnetisation by applying a sufficiently high alternating magnetic field which decreases smoothly towards zero.
thermal demagnetisation
Demagnetisation by heating above the Curie-or Néel-temperature followed by cooling in zero magnetic field to room temperature

Depositional remanent magnetisation
Remanent magnetisation acquired by sediment at the (air) water/sediment interface, by alignment of magnetic particles. This remanence is not fixed until the particles are immobilised. This remanent magnetisation may not be preserved at geological timescales due to bioturbation or other disturbing factors (see also **post-depositional remanent magnetisation)**.

Detrital remanent magnetisation
General expression for the remanent magnetisation acquired by field alignment of magnetic particles during the deposition of a sediment (see **depositional** and **post-depositional remanent magnetisation**)

Diamagnetism
In materials with paired electrons (even number of electrons). All materials brought in a magnetic field show the effect of diamagnetism often masked by other more important effects of **paramagnetism** or **ferromagnetism**. Diamagnetic susceptibility is weak and negative. Examples: the most important constituents of rocks (quartz, feldspar, calcite).

Dipole field
The Earth magnetic field resembles to the field of a magnet placed at the centre of the Earth and inclined with respect to the Earths rotation axis. It is characterised by a magnetic north and South Pole (dipole). Other forms of fields, designated multipolar fields, are called non-dipole fields.

Earth magnetic field
see **geomagnetic field**

Exhaust vent
One ore more holes on top of the **superstructure** through which gases can escape into the atmosphere. At certain stages these holes were either open or closed in order to increase or decrease draught upwards.

Ferrimagnetism
(see also **ferromagnetism**)
The quantum mechanical exchange interaction favours a parallel or antiparallel (via an anion) alignment of the magnetic moments as domains and one observes a resulting magnetisation. Ferrimagnetics become paramagnetic above the **Néel-temperature** T_N. Examples: magnetite Fe_3O_4 ($T_N = 585$ °C) and maghaemite γ-Fe_2O_3 ($T_N \approx 620$ °C).

Ferromagnetism
Magnetic state in a solid with unpaired electron spins (odd number of electrons) and atomic distances such that the quantum mechanical exchange interaction causes an alignment of the individual atomic magnetic moment as domains. Each domain has a maximum magnetisation, called spontaneous magnetisation. Ferromagnetics have a strong **magnetic susceptibility**, a strong **remanent magnetisation** and show the property of **hysteresis**. Ferromagnetics

become paramagnetic above the **Curie-temperature** T_C. The transition elements iron (Fe), nickel (Ni) and cobalt (Co) are ferromagnetic.

Fire-tunnel

Part of a **kiln**, connecting **stokehole** and **combustion chamber**. Also named flue, and sometimes, furnace or praefurnium. A part of the fire burnt at this place, with the flames directed towards the combustion chamber.

Fisherian-statistics

Statistics applied to a population of vectors when they are normally or Gaussian distributed in azimuth. It is used in archaeomagnetism to describe the spatial distribution of magnetisation directions. The probability density function is called Fisher-distribution (after Sir Ronald Fisher), which is a bivariate distribution as there are two variables, declination and inclination. The probability for an observation falling in a small element of area δA at an angular distance ψ from the true mean direction is given by $P_{\delta A}\ \delta A = \kappa / 4\pi \sinh(\kappa)\ e^{\kappa\cos(\psi)}\ \delta A$, with δA being $\sin(\psi)\ d\psi\ d\varphi$, where φ is the azimuth (or longitude) of the observation about the mean direction and ψ the co-inclination (or co-latitude). The Fisher distribution assumes that declinations are randomly distributed and that the inclinations are exponentially distributed.

The Fisherian-statistics allow to define an error of the population true mean **ChRM** direction, called the cone of confidence at given probability; in general 95% (see also **confidence parameter**, **concentration parameter**).

Fluxgate-magnetometer

In a fluxgate magnetometer the steady magnetic field due to the sample is measured by a so called fluxgate sensor, which works on the induction principle, similar to a transformer. The sensor consists of a primary drive coil and a secondary pick-up coil, both winded around a highly permeable core that does not exhibit hysteresis. Alternating voltage is applied to the primary coil and induces a secondary alternating voltage in the pick-up coil. The presence of a sample causes an additional steady magnetic field. This field is superposed to the field that is caused by the primary coil. The sum of both is detected by the secondary coil. The voltage change per time at the pick-up coil is analysed by splitting the signal with Fourier-analysis into harmonics. The amplitude of the second harmonic is proportional to the steady magnetic field produced by the sample and which is only present if a steady field is present. Tri-axial fluxgate sensors can be used to measure the three orthogonal components of the magnetic field, but also to measure the remanent magnetisation of a baked sample.

Gauss, Carl Friedrich
German mathematician (1777 - 1855), known for his works on physics and mathematics. He did for the first time an absolute measurement of the intensity of the geomagnetic field and a global analysis of the geomagnetic field, called **spherical harmonical analysis**. He is also known for the law of Gauss, which allows defining an error at a given level of confidence for the estimation of the true mean of a series of observations.

Geographic meridian plane
Plane containing the local vertical and the rotation axis of the Earth.

Geographic north (pole)
Point on the surface of the Earth in the northern hemisphere, situated on the Earths rotation axis.

Geomagnetic field
Magnetic field of the Earth. Resembles the field of a centric magnetic dipole inclined about 11.4 ° to rotation axis of the Earth. It is defined in each place at a certain instant of time by its direction and intensity. The geomagnetic field is divided in an interior part (the main part), which is caused by fluid movements in the outer fluid core of the Earth and other sources in the upper Earth mantle and the Earth's crust, and an exterior part which is caused by currents in the ionosphere and magnetosphere. A complete mathematical description of the potential of the total magnetic field was developed by **C.F. Gauss** based on **spherical harmonics.**

Geomagnetic poles
Poles based on a global analysis of the observed geomagnetic field limited to dipole terms. The geomagnetic poles corresponding to the International Geomagnetic Reference Model (IGRF) of 2005 are situated at:

North geomagnetic pole: 79.7° N and 71.8° W
South geomagnetic pole: 79.7° S and 108.2°E

Goethite
Antiferromagnetic mineral. Acicular or fibrous, but in general isometric and of irregular form. Colour: brown-black, yellowish brown to red it has a yellow-brown to yellow-orange colour. Metallic to ashy reflectance. Hardness 5 to 5.5. Very common as alteration product in certain soils and sediments. Remains stable in soils of the temperate and humid climate zones. Identified in 1806 as a new mineral named in honour of the German poet Johann Wolfgang von Goethe, also a great collector of minerals.

Haematite

Antiferromagnetic mineral. Common in oxidised volcanic rocks and sediments formed in an oxidising environment. It is a final product of prolonged oxidation of **magnetite** or **maghaemite**. It is also formed by dehydration of **goethite**. Formed from a solution by precipitation in certain sediments (red sediments) and in hydrothermal veins. Very common in tropical and subtropical soils. The name is derived from the Greek word *aima*, meaning blood. Mentioned by the Roman poet Vergilius in the 1st century BC in the Eneid. Also called oligist from the Greek work *oligos*, meaning very few, because it contains a lower percentage of iron compared to magnetite. Colour: steel grey to black. In powder form it has a red cherry or blood colour to reddish brown. Metallic reflectance. Hardness between 5 and 6.5. It occurs in massive forms (*greneuse, terreuse*) or as fibrous concretions, or also as an aggregate of laminar crystals or in rose like form. Occurs also as hexagonal platelets, but in general isometric and irregular form. Iron ore. Utilised as a precious stone, colourant, abrasive and as a polishing product.

Hellenistic Period

Cultural period in Greece (336-146 BC) between the conquest of the Persian Empire by Alexander the Great and the establishment of Roman supremacy.

Inclination (I)

Angle between geomagnetic field and the local horizontal plane. Also the angle between the remanent magnetisation of a sample and the horizontal plane.

Intensity (F, M)

The value or magnitude (F) of the geomagnetic field expressed in Tesla. Also the value or magnitude (M) of the remanent magnetisation of a sample expressed in A/m or Am^2/kg.

International geomagnetic reference model (IGRF)

Model for the global **geomagnetic field** of interior origin. It is based on **spherical harmonics**, but taking also into account the temporal field variation to the **secular variation**.

Iron-age

Denotes a time period in the development of the human society when iron working was the most sophisticated form of metalworking. Its hardness, high melting point and the abundance of iron sources favoured its use. The Iron-age is subsequent to the Bronze-age. The Iron-age lasted in Britain from around 500 BC to 500 AD or until the Roman conquest (43 AD – 303 AD). In central Europe it lasted from about 800 BC until the Roman conquest.

Isothermal remanent magnetisation (IRM)
Remanent magnetisation acquired by a sample after the application of a constant or steady field and removal of the field

Kiln
Ancient fire place for producing pottery, glass ware, tiles, bricks, but also for melting metal. It consists of a **stokehole**, a **fire-tunnel,** a **combustion chamber**, the **support**, the **raised oven-floor**, the **oven**, the **superstructure**, **exhaust vents** and the **capping**.

Laplace equation
Partial homogeneous differential equation used for the estimation of scalar, irrotational potential fields (free of sources), such as the **geomagnetic field** at the Earths surface (or between surface and ionosphere). The Laplace equation can be solved by the expansion of the potential into **spherical harmonics.**

La Tène
A continental Iron-age culture beginning around 450 BC and ending with the Roman conquest. Named after a Swiss lake site.

Maghaemite
Ferrimagnetic mineral. Utilised in certain magnetic recording tapes. Alteration product, present in certain soils.

Magnetic anisotropy
Variation of magnetic properties with direction.

Magnetic dipole
Ensemble of two equal magnetic charges of opposite sign.

Magnetic domains
Regions in a solid, where the magnetic moments of the atoms are parallel, separated by walls. They form spontaneously to minimise the potential energy of a magnetised material.

Magnetic field
Force field in the vicinity of a magnet or electrical current. Also **magnetic induction** in vacuum. Unit is A/m. The unit of the Earth magnetic field is the unit of induction or Tesla.

Magnetic hysteresis

The magnetisation induced in a sample by a magnetic field lags behind the field. After removal of the field the sample possesses a remanent magnetisation.

Magnetic meridial plane

Local vertical plane containing magnetic north.

Magnetic minerals

Rock magnetic properties

Mineral	Chemical formula	Magnetic susceptibility 10^{-8} m^3/kg (*)	Tc , Tn °C	Saturation magnetisation at room temperature kA/m	Saturation magnetisation at room temperature A m^2/kg
magnetite	Fe_3O_4	578	580-585	480	92
maghaemite	γFe_2O_3	500	~620 590-675	380	85
haematite	αFe_2O_3	25	675	~2,5	0,5
goethite	$\alpha FeOOH$	0.5-1.5	120	~2	~1

Crystallographic properties

Mineral	Chemical formula	Crystallographic system	Unit cell diameter (A)	Density kg/m^3	Transformation temperature
magnetite	Fe_3O_4	cubic inverse spinel	8.396	5.197	
maghaemite	γ-Fe_2O_3	Cubic or tetragonal spinel	8.337 (a) 24.99 (c)	5.074	250 →750°C
haematite	α-Fe_2O_3	rhombohedric	5.034 (a) 1.375 (c)	5.271	
goethite	α-FeOOH	orthorhombic	9.956 (b) 3.021 (c) 4.596 (a)	4.264	250-400°C

(*) these values are indicative, the magnetic susceptibility depends strongly on grain size

Magnetic moment

Expresses the magnetic intensity of a magnet. A couple of forces acting on a magnet put perpendicular to a uniform magnetic field with a magnetic flux density equal to the unit. The unit of the magnetic moment is Am^2

Magnetic multipole

Ensemble of even-numbered equal magnetic charges of opposite sign. A quadrupole is an ensemble of two north and two south poles. About 5% of the interior geomagnetic field are caused by multipolar fields

Magnetic poles

Points on the surface of the Earth, where the observed magnetic inclination is +90° (magnetic north pole) or -90° (magnetic south pole) and where the horizontal component of the geomagnetic field is zero. The magnetic poles are currently situated at:

North magnetic pole (in 2001): 81.3° N and 110.8° W, near Elef Ringes island (Canada)
South magnetic pole (in 2001): 64.7° S and 138.0° E in the bay Commonwealth Bay (Antarctica)

Magnetic susceptibility

Measure of the ability of a sample to acquire a magnetisation in a magnetic field (magnetisability). Ratio of the magnetisation **M** induced in the sample over the inducing magnetic field **H.** $k = \mathbf{M}/\mathbf{H}$.

Magnetisation (M)

Magnetic moment per unit of volume (**A/m**) or per unit of weight (**Am^2/kg**) of a magnetised sample. In the presence of magnetic field it is the sum of two components:

- **Remanent magnetisation** (magnetisation that remains when the magnetic field is removed)
- **Induced magnetisation** (magnetisation that disappears when the magnetic field is removed)

Magnetite

Ferrimagnetic mineral. Very common in the majority of volcanic, metamorphic and sedimentary rocks. Is also produced by certain bacteria: intracellular by magnetotactic bacteria and extracellular by iron reducing bacteria. Named after Magnès, who after Plinius the old discovered stones that attracted iron. According to another version the denomination magnetite should come from the locality of Magnesia in Macedonia where it was discovered. Magnetite forms granular to compact masses, more rarely it crystallises into tetrahedrons and dodecahedrons. The colour is black with blue metallic reflectance. In powder form the colour is black. Strongly magnetic mineral. Iron ore. Hardness from 5.5 to 6.

Merovingian
Denotes a time when the Merovingian dynasty (dynasty of Frankish kings) who ruled territories in the present day Germany and France from the 5^{th} to the 8^{th} century AD.

Minoan period
Cultural period in Greece between 2000 and 1400 BC, subsequent to the Early Bonze age (2900-2000 BC) and followed by the **Mycenaean age**. The Greek Bronze-age civilisation was centred in Crete and the surrounding islands. The terrible eruption of the Santorini volcano around 1600 BC may be to certain extend responsible for the disappearance of the Minoan civilisation in Crete.

Mycenaean age
Cultural period in Greece between 1100 and 600 BC, subsequent to the **Minoan period** and followed by the **Dark ages**. This period was characterised by high cultural achievement, being the basis of myths and heroes later on.

Natural remanent magnetisation (NRM)
The in-situ remanent magnetisation of rocks and other materials like baked clays.

Néel, Louis
French physicist (Lyon 1904 – Brive-la-Gaillarde 2000). He discovered new types of magnetism, ferrimagnetism and antiferromagnetism completing in this way the theories on magnetism by **P. Curie**, P. Weiss and P. Langevin. Also known for his theories on the remanent magnetisation for single and multidomain particles. He proposed models of self-reversal for certain reversals observed in rocks. He obtained the Nobel Price in 1970.

Néel-temperature T_N
Temperature below which magnetic moments of **antiferromagnetic** and ferrimagnetic materials are antiparallel. Beyond this critical temperature they become paramagnetic.

Normal (Gaussian) distribution
When number of values are distributed around the mean value as a bell-shaped curve.

nT
NanoTesla (1 nanoTesla = 10^{-9} Tesla). Unit of magnetic induction (flux density). Also unit of the intensity of the geomagnetic field. After Nikola Tesla (1856 - 1943)

Oven
Chamber in which pottery or other material was stacked for firing and into which hot gases and flames rose from the underlying **combustion chamber** through the raised **oven floor**.

Palaeomagnetism
Study of the behaviour of the geomagnetic field during geological times based on remanent magnetisation of rocks.

Paramagnetism
In materials with unpaired electrons and when the atoms or ions, carrying a magnetic moment, are diluted (gas or ions carrying a magnetic moment in silicate matrix). The susceptibility is weak and positive. Examples: materials with rare Earth or transitional elements: clays, pyroxene, amphibole

Partial thermo-remanent magnetisation (pTRM)
Remanent magnetisation of a sample at room temperature, acquired in a temperature interval $[T_1;T_2]$ (with $T_2 \leq$ Curie- / Néel-Temperature and $T_1 >$ than room temperature) in the presence of a magnetic field.

Post-depositional remanent magnetisation (pDRM)
Magnetic remanence acquired by a sediment after its deposition, when all magnetic particles are fixed in the sedimentary matrix. This remanent magnetisation is preserved over geological timescales.

Raised oven floor
Also called false floor. The raised oven floor covered the **combustion chamber** and upon it vessels or other ware to be burnt was stacked for firing. It was built of portable components such as bars, positioned at certain intervals, but also of solid clay perforated with vent-holes. In both cases hot air coming from the combustion chamber was able enter the **oven**.

Relaxation time
The time in which the remanent magnetisation decreases by $1/e$ of its initial value.

Remanence
Partial persistence of a phenomenon after disappearance of its cause. Remanent magnetisation of a material is the magnetisation that remains after removal of the inducing magnetic field.

Roman period

Period of the Roman supremacy in Europe and the Mediterranean, lasting from 27 BC until 378 AD.

Sample

In archaeomagnetism, a piece or fragment of baked material taken in an in-situ baked structure.

Secular variation

The interior geomagnetic field is also a function of time. The field slowly changes its direction and intensity. This temporal change is known as secular variation. The secular variation has been discovered by the English mathematician and astronomer H. Gellibrand (1597-1637) in 1634. The secular variation can be graphically represented in a Bauer-plot (inclination vs. declination), named after L.A. Bauer (1865 - 1920). Basis of archaeomagnetic dating.

SQUID-sensor

The SQUID sensor or Superconducting Quantum Interference Device can be regarded as a ring with superconducting properties. Once a circulating current I is stimulated in the ring, it flows for ever as the resistance is nearly zero and the current can only be changed through an external magnetic field (from a sample). When the external magnetic field is strong enough the circulating current reaches a critical value I_c, the SQUID becomes resistive, magnetic flux enters the ring and the current drops by quantised values $\Delta I = n\Phi_0$ ($n\Phi_0$ denotes multiples of the flux quantum $\Phi_0 = \hbar/2e = 2.07 \times 10^{-15}$, $\hbar$ = Planck's constant and e = electron charge) below I_c. As the current dropped below I_c, the superconducting state is achieved again. Further increase of the external magnetic field yield multiple flux changes. A critical current equal to $0.75\Phi_0$, causes the circulating current to change polarity. The number of polarity changes is proportional of the magnetic field produced by the sample and hence to its remanent magnetisation.

Specimen

Cylindrical or cubic piece cut from a **sample** by drilling or sawing, respectively.

Spherical harmonics

The spherical harmonics are a common solution of the **Laplace equation**. C.F. Gauss (1839) used them for the mathematical description of the global geomagnetic field. He could show, that the total Earth's magnetic field is composed of external an internal fields which have certain geometries (**magnetic dipole**, **magnetic multipoles**). The IGRF model is based on spherical harmonics.

Spinner magnetometer

Instrument to measure the remanent magnetisation of rocks based on the dynamo principle. The sample is rotated in the centre of a coil. During rotation the field lines of the magnetic moment of the sample cut the coil and induce in it an electromagnetic force (signal) according to the law of Faraday. The amplitude of the signal is proportional to the magnetic moment of the sample and its phase determines the direction of the magnetic moment.

Spherical harmonics

The spherical harmonics are a common solution of the **Laplace equation**. **C.F. Gauss** (1839) used them for the mathematical description of the global geomagnetic field. He could show, that the total Earth's geomagnetic field is composed of external an internal fields which have certain geometries (**magnetic dipole**, **magnetic multipoles**). The IGRF model is based on spherical harmonics

Stokehole

A hollow dug into the ground from which fuel was put into the fire burning in the combustion chamber of a **kiln**. Also called stoke-pit. If the kiln is built at the surface one can speak about a stoking area.

Stone-age

Denotes a time period in the early development of the human society before the use of metals, Weapons and tools were made from stone. Began in Europe around 2 million years ago and ended around 4000 BC. It can be subdivided in three periods Palaeolithic, Mesolithic and Neolithic.

Superparamagnetism

Ferromagnetism of very small particles (in the order of 30 nm and smaller) that have **relaxation times** on the laboratory time scale.

Superstructure

Free-standing temporary or permanent walling of the **kiln** above the ground, this term applies also to the kiln structure above the level of the **raised oven-floor**.

Support

Protruding, recessed or raised structure, temporary or inbuilt located in the **combustion chamber** of a **kiln,** to support the mechanical stability of the overlying **raised oven-floor**. If located in the centre of the kiln as single standing element, also called *pedestal*.

Theodolite
Survey instrument equipped with an objective used in geodesy to measure horizontal and vertical angles and in astronomy to determine the **azimuth** and the apparent height of a celestial body.

Total thermo-remanent magnetisation (tTRM)
Remanent magnetisation of a sample at room temperature after cooling from a temperature higher than the **Curie**- or **Néel-Temperature** in a magnetic field.

Typology
Relative dating method in archaeology based on classification of things according to their characteristics.

Vector
The geomagnetic field as a force can be represented in each point of the Earth’s surface as a vector (arrow) the orientation of which defines the direction and sense of the action of the field and the length of which symbolises the intensity.

Virtual axial dipole moment (VADM)
Intensity of an imaginary axial (along the Earth's rotation axis) centric (located in the centre of the Earth) dipole that would produce the estimated archaeo-/palaeointensity at the sampling site. It is calculated from the archaeo-/palaeointensity of a sample as estimated by measurements in the laboratory and the magnetic co-latitude of the sampling site. check

Virtual dipole moment (VDM)
Intensity of an imaginary dipole (located in the centre of the Earth) that would produce the estimated archaeo-/palaeointensity at the sampling site. It is calculated from the archaeo-/palaeointensity and the palaeoinclination of a sample as estimated by measurements in the laboratory and the geographic co-latitude of the sampling site.

Virtual geomagnetic pole (VGP)
Geographic position of a geomagnetic north/south pole related to an imaginary dipole (located in the centre of the Earth) which would produce the observed ChRM in a sample. The VGP is calculated from the mean ChRM direction of a sample and the geographic coordinates of the sampling site.

Viscous remanent magnetisation (VRM)
Remanent magnetisation acquired spontaneously by a sample after an exposure to a weak magnetic field.

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