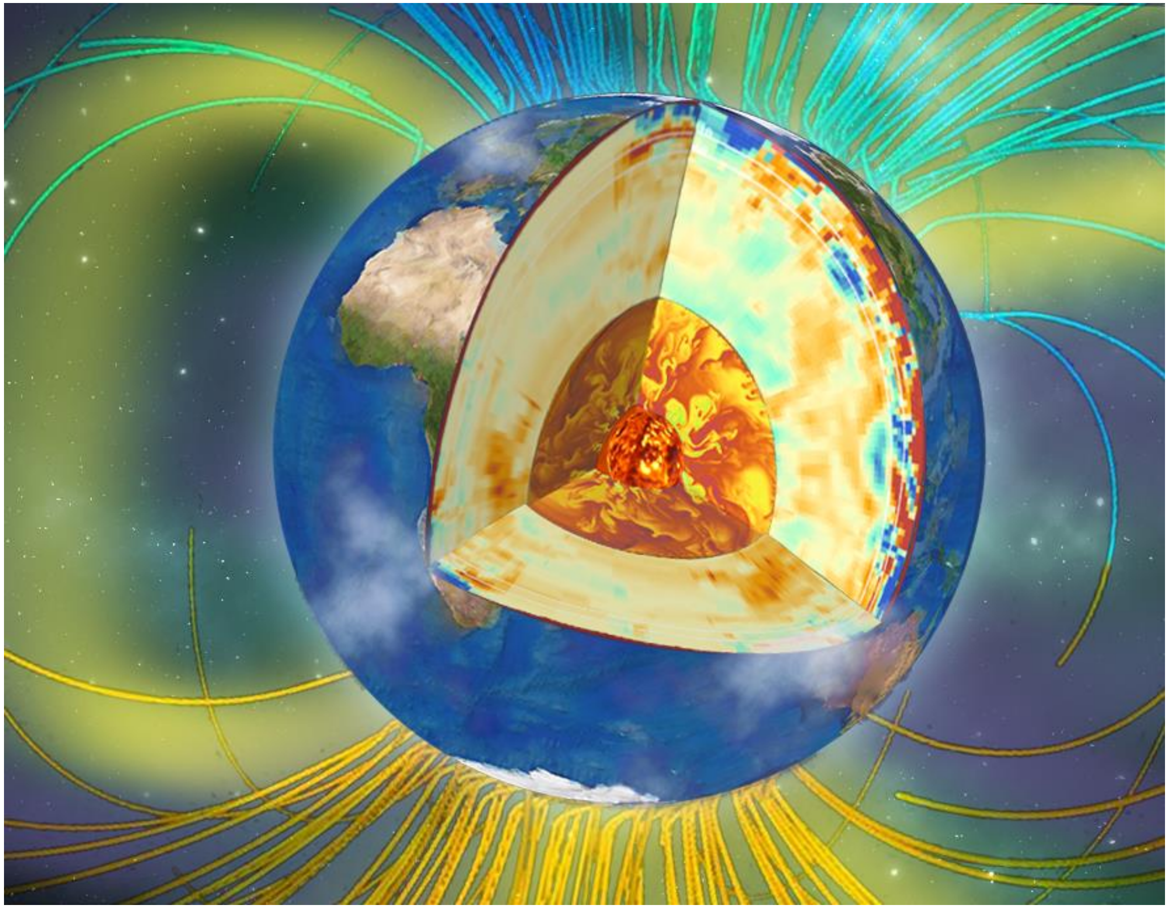
INTRODUCTION TO ARCHAEOMAGNETIC METHOD

Dr. Elina Aidona

Aristotle University of Thessaloniki, Greece

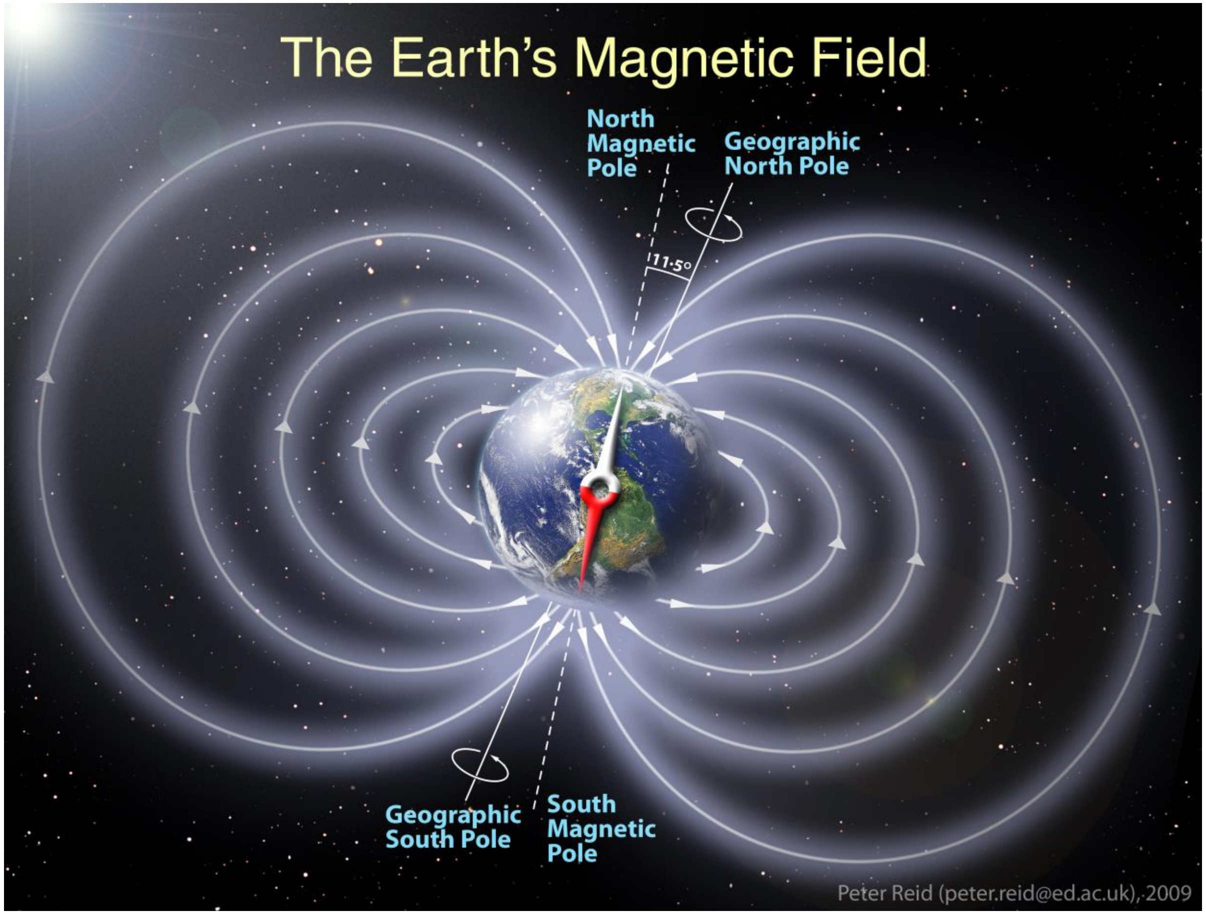
Geomagnetism



The Earth's interior is composed of a solid iron core, a liquid outer core (mostly iron) and an overlying mantle. The Earth's magnetic field is generated in the outer core by complex convective motions.

Geomagnetism

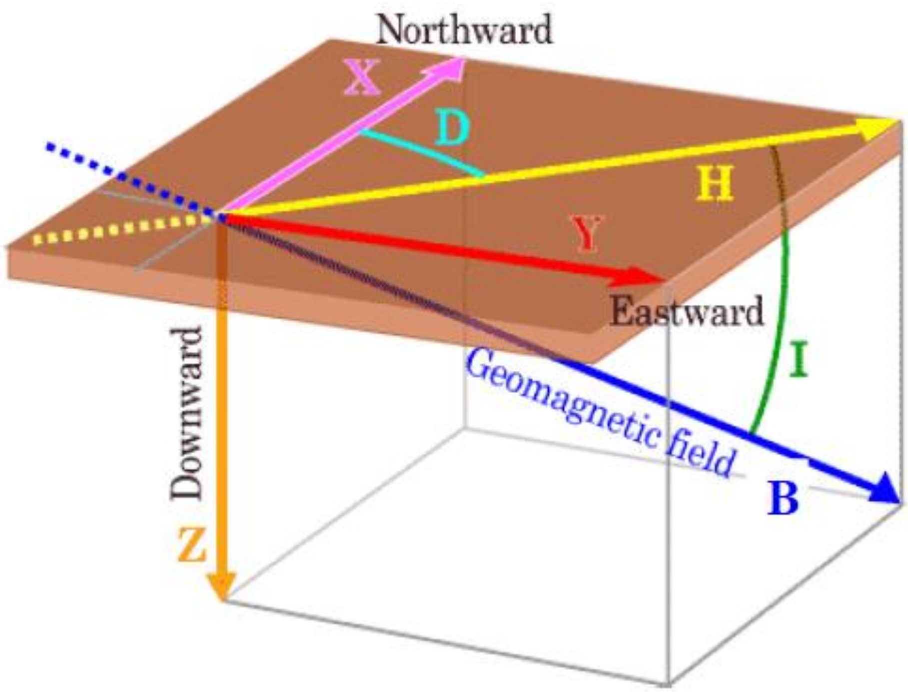
- *Earth magnetic field and the geomagnetic field components*



The major part of the GMF can be represented by a dipole, similar to a bar magnet in the centre of the Earth. However, only 80–90 % of the geomagnetic field at the Earth's surface can be ascribed to an inclined geocentric dipole. The remaining 10–20% of the observed geomagnetic field is variably distributed across the global surface. This is the non-dipole field, and it may add to, subtract from, or have no effect on the main dipole field in any given location.

Geomagnetism

- ***Earth magnetic field and the geomagnetic field components***



Declination (^{0}): The angle between magnetic north and geographic north

Inclination (^{0}): The dip of the field direction above or below the horizontal

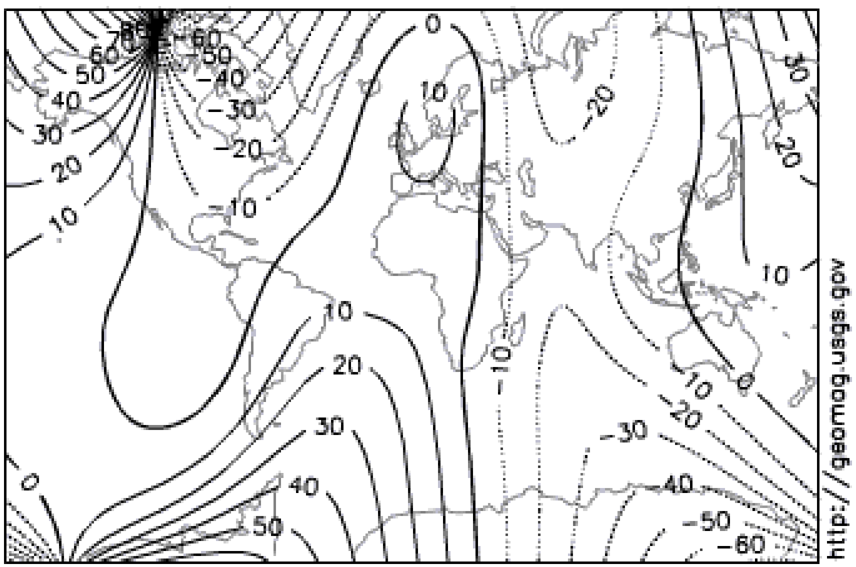
Intensity (µT): The magnitude or strength of the magnetic field

Geomagnetism

- ***Earth magnetic field and the geomagnetic field components***

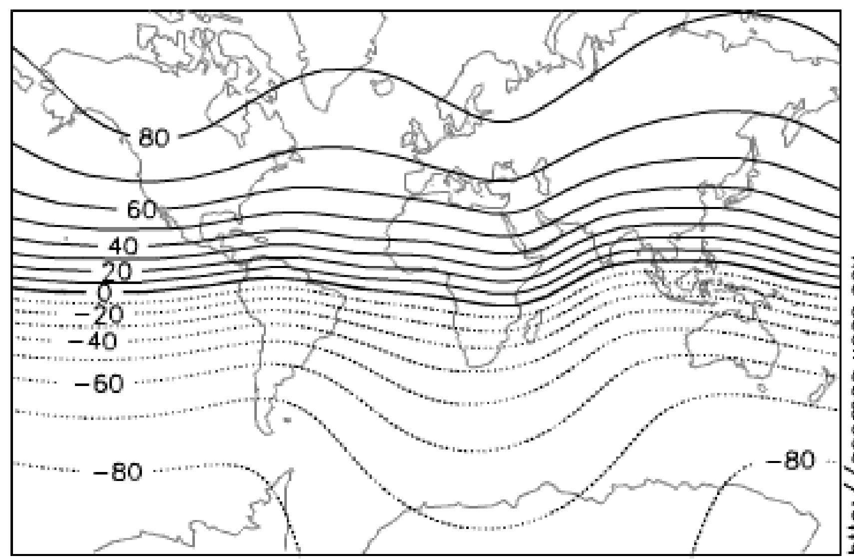
  - The Earth’s magnetic field gradually changes in direction [Declination (D), Inclination (I)] and Intensity (J)

1590
Declination (degrees east)



Model by A. Jackson, A. R. T. Jonkers, M. R. Walker, Phil. Trans. R. Soc. London A (2000), 358, 957–990.

1590
Inclination (degrees down)



Model by A. Jackson, A. R. T. Jonkers, M. R. Walker, Phil. Trans. R. Soc. London A (2000), 358, 957–990.

What is archaeomagnetism?

Archaeomagnetism is the discipline of palaeomagnetism which studies the variation of the geomagnetic field during the historical and prehistorical periods.

The principle is based on the fact that the magnetic minerals (iron and iron oxides) contained in clay-lined archaeological features, such as kilns, hearths, furnaces, burned walls and floors, or other fired structures, acquire a thermoremanent magnetisation (TRM) at the time they are heated above the so-called Curie temperatures. If the features are not reheated to higher temperatures, the direction and strength of the Earth's magnetic field at the time they were heated, is "locked in" and can then be measured in the laboratory.

Materials magnetized at the same time in the same region will normally have identical directions and the intensity of the geomagnetic field would also be the same.

What is the purpose of archaeomagnetism?

→ The establishment of accurate secular variation curves (SVC) from well dated, with other independent methods, structures. (FORWARD PROBLEM)

→ Dating of suitable archaeological material for places and periods where SVC are available. (INVERSE PROBLEM)

→ Also can provide information concerning provenance, firing conditions and temperatures.

Historical Overview

❖Ancient Greeks were the first to observe that some rocks attract iron pieces, against the gravity laws (~ 600BC). The most known is *magnetite,* and the word *magnetism* was derived from the city of Magnesia, the ancient Greek colony in Asia Minor.

❖Between 1088 and 1114 AD Chinese written texts mention the property of a magnetic needle to orient the North.

Chinese South-Pointer from Around 200 A.D

Historical Overview

- *Direct magnetic measurements* progressively started around 1600 AD in Paris, London and later in Rome.
- This was the basis of the actual *Geomagnetic Observatories where the Geomagnetic elements are continuously recorded.*
- The important change of these elements through time was quickly noticed and studied.

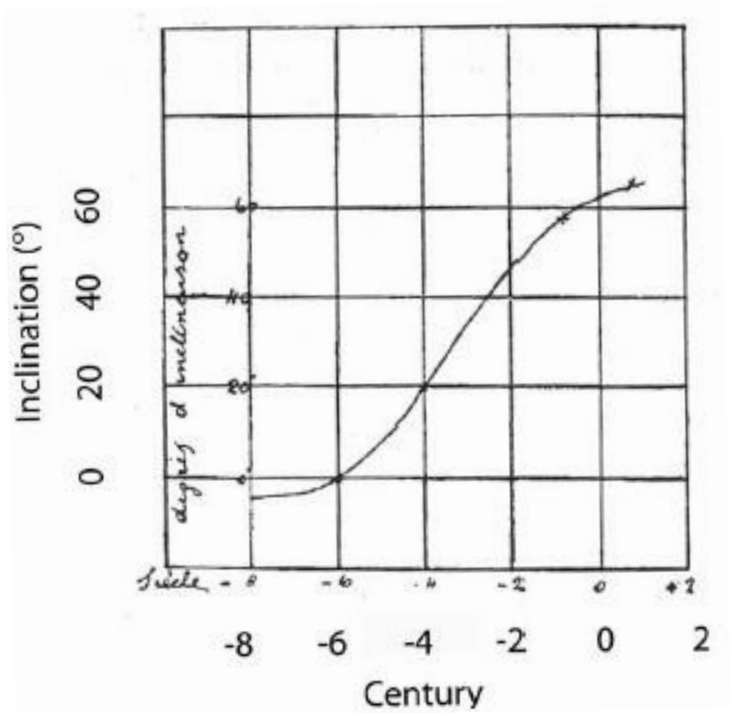
Historical Overview

- Pioneering work on archaeological artefacts began in the 17th century when Boyle (1691) demonstrated that bricks lose their magnetization when heated to high temperature and acquire a new one while cooling. The idea that archaeological materials could be used to extend the geomagnetic record over historical times was known by the last decade of the 19th century.

- Melloni (1853) measured with an astatic magnetometer the magnetization of 108 lava flows.

Historical Overview

- 1895-1900 : G. Folgheraiter performed experiments on the remanent magnetization of Roman bricks and showed that during their 2000 years life they had conserved their magnetization. He also estimated the variation of inclination between 800 BC and 100 AD. *ARCHAEOMAGNETISM HAD JUST BEEN INITIATED..*



Historical Overview

- Chevallier (1925) applied the same ideas to recover directional geomagnetic field changes from historical lavas from Mount Etna (Italy).

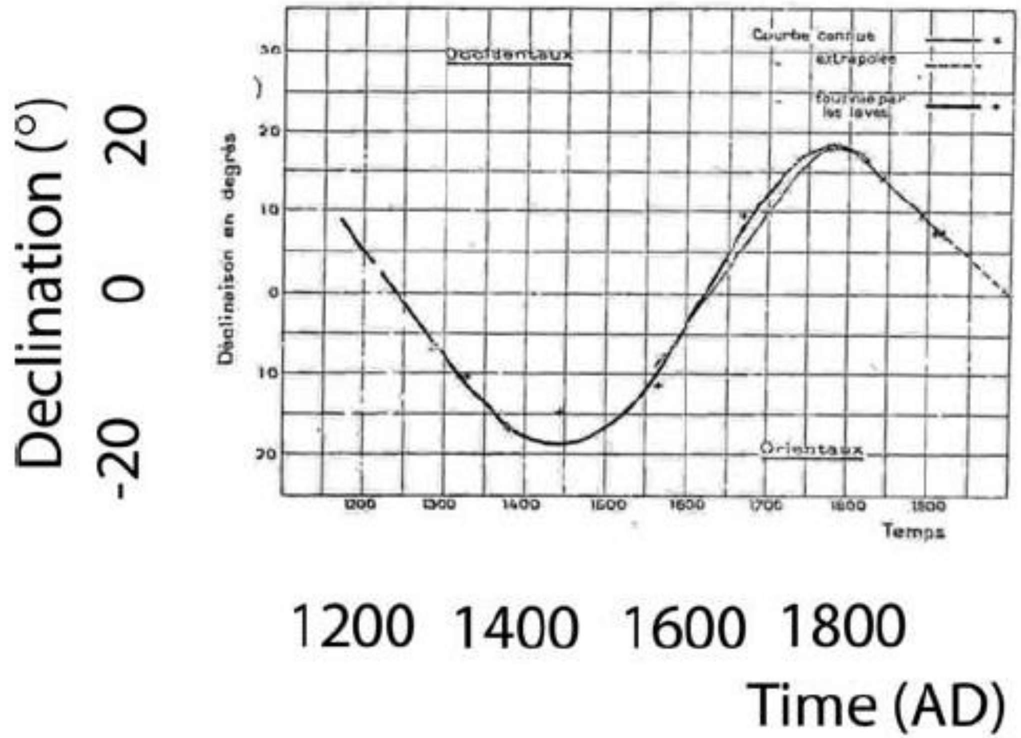


Figure 12. Secular variation of declination in Sicily as determined by *Chevallier* [1925b] based on some 100 blocks from 10 distinct lava flows (1200–1900 A.D.) seeming to suggest a "periodicity" of 750 years (though the author was careful not to conclude so based on this limited data set).

Historical Overview

- After 1940: many important scientists appeared in the areas of geomagnetism and palaeo /archaeomagnetism.
- 1942: **E. and O. Thellier** have proposed a method of sampling and published their famous method for calculating the intensity of the ancient field by using bricks aged 1465AD. This method is still used, together with some variants, but based on the same principle.

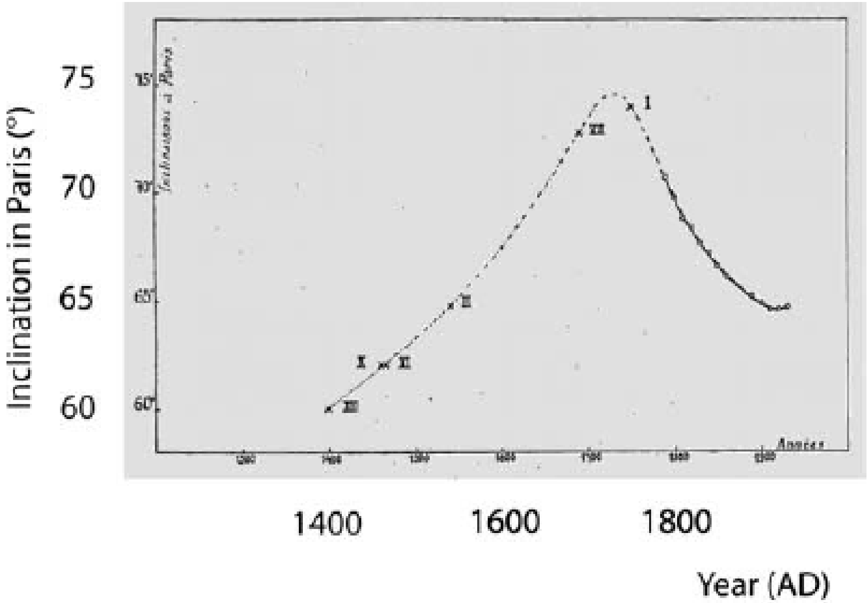


Figure 15. *Thellier*'s [1938, Figure 42, p. 74] first determination of variations of inclination in Paris from 1400 to 1900 A.D. Note that there are only six "archeomagnetic" determinations. However, three other determinations in other locations in France are in good agreement once reduced to the site of Paris.

Historical Overview

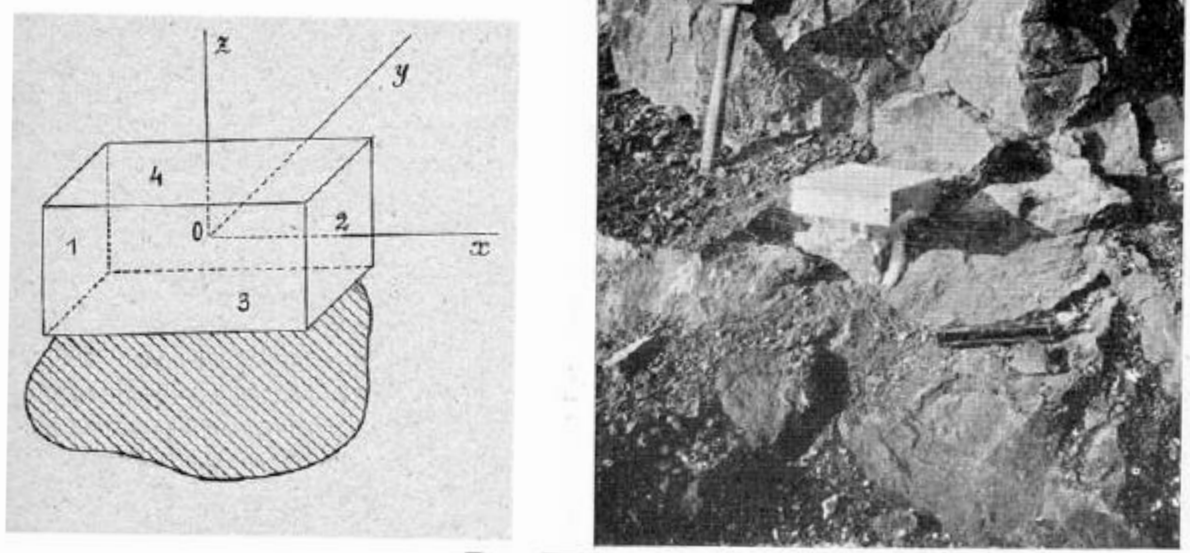


Figure 14. Method of orienting and collecting rock samples using a "plaster of Paris cap" ("chapeau de plâtre") pioneered by E. Thellier [from *Thellier*, 1938, Figures 44 and 45].

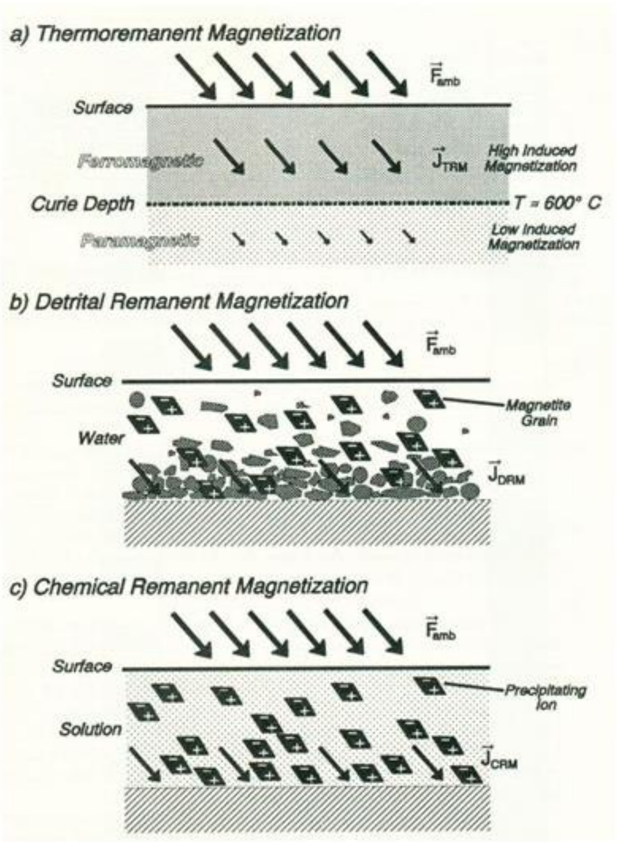
Historical Overview

- Archaeomagnetic studies were firmly established through the work conducted by Émile Thellier and his students between 1930 and 1960 (Thellier, 1936, 1938; Thellier and Thellier, 1959). During this period, these researchers explored and described the magnetic properties of baked clays, developed sampling techniques for recovering archaeomagnetic materials from the field, and designed and developed laboratory equipment and techniques for analyzing archaeomagnetic samples.

- By 1960, these methods had been greatly refined, and archaeomagnetic studies were undertaken in various parts of the World (mainly Europe, Japan, Soviet Union and later America).

Physical background

Types of remanent magnetization



When the materials cool below the Curie temperature, strong magnetization occurs, parallel to the Earth's ambient field

! Crystals cannot rotate, the collection of magnetic moments is oriented in the direction of the ambient magnetic field

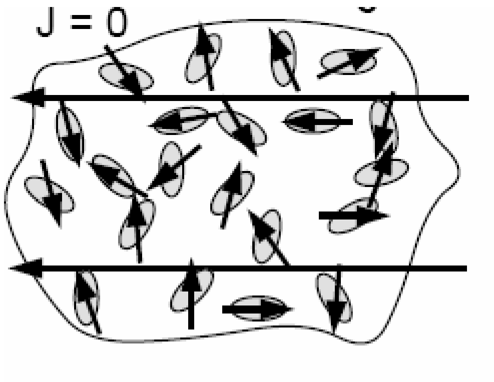
As sediments settle out in water, small mineral grains rotate so that their magnetic domains preferentially orient with the ambient field.

As ions are precipitated from solution, their magnetic domains align with the ambient field.

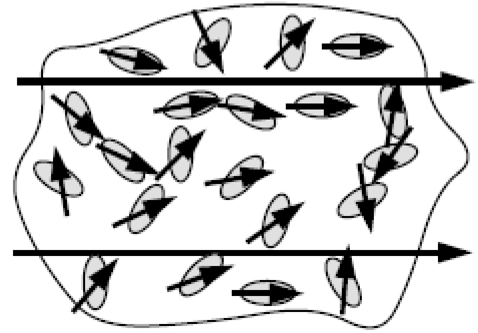
Physical background

Acquisition of Thermoremanent Magnetization (TRM)

Unbaked

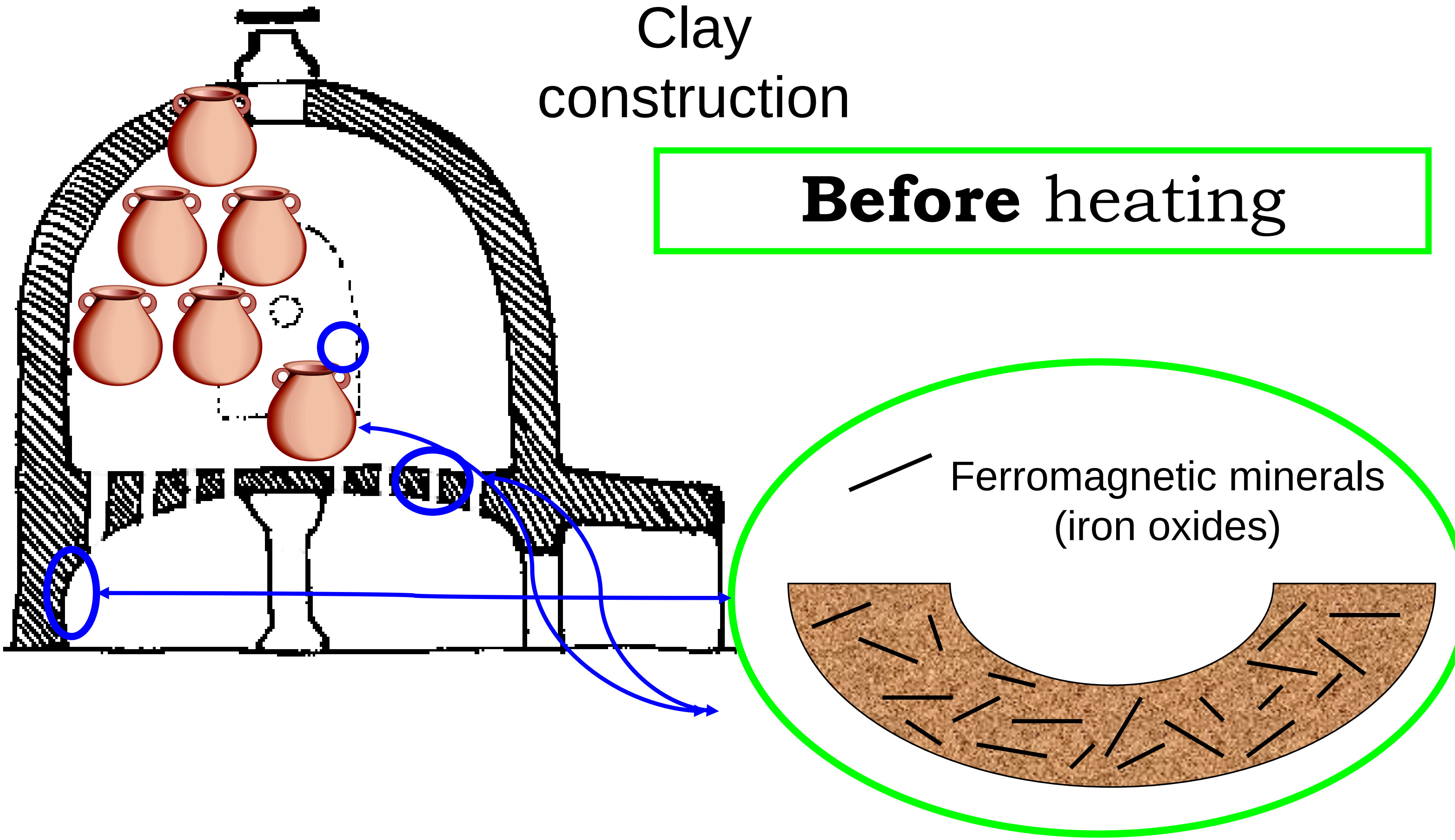


Baked (T>400 ^{0}C)

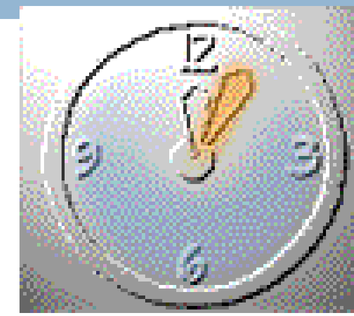


If materials that are rich in iron oxides (e.g., magnetite, Fe3O4, and maghaemite, γ-Fe2O3) are heated above a certain temperature (the so-called *Curie temperature*, which is characteristic for each magnetic mineral), and then cooled down they become easily magnetized in the direction of the ambient geomagnetic field. During cooling below the blocking temperature, this magnetization (TRM) is locked in the material until further heating and, under certain circumstances, is also proportional to the ancient magnetic field. Iron oxides are ubiquitous in most of the clay deposits that were used in the past for the construction of archaeological features (e.g., kilns, furnaces, ovens). In addition, during their heatings, these structures often exceed the Curie temperatures of magnetite (578 ∘ C) and maghaemite (578–675∘C). Even if the original clays were not rich in such iron oxides, the heating and cooling cycles may have produced them due to thermally induced mineralogical transformations.

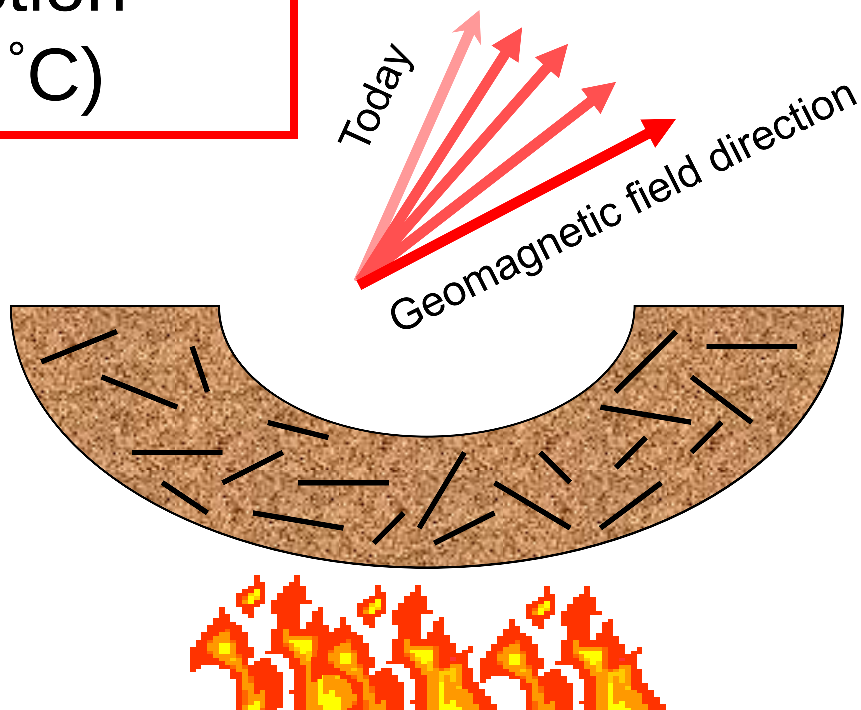
Archaeomagnetism



Archaeomagnetism



Heating of clay construction (T>400 ˚C)



The construction
is not reheated

Archaeomagnetism

Suitable material

Tiles, bricks, pottery and kiln wall fragments are generally very well fired and keep extremely stable magnetisation, so as to be perfectly suited to magnetic experiments in the laboratory.

- ***Applicable on any type of permanent and undisplaced FIRED STRUCTURES***
  - kilns –pottery, lime, glass, metal
  - ovens & hearths
  - furnaces
  - baths
  - burnt houses, floors and walls
  - as well as on sherds and pottery fragments, tiles, bricks

Advantages of the method

- Low cost
- Applicable for a variety of materials
- For intensity studies the sampled material does not have to be in situ
- High dating accuracy (for qualitative interpretation) can be achieved

Disadvantages of the method

- Laborious procedure (involves much laboratory work)
- The accuracy of the method is affected by the accuracy of the secular variation curve.
- Bureaucratic issues involved (sampling permits etc.)

Error factors that may affect the dating accuracy:

- Differential recording of the magnetic field in different parts of the studied structure
- Displacement or disturbance of the samples material after heating/deposition
- Errors during the sampling procedure and orientation measurements

Sampling techniques

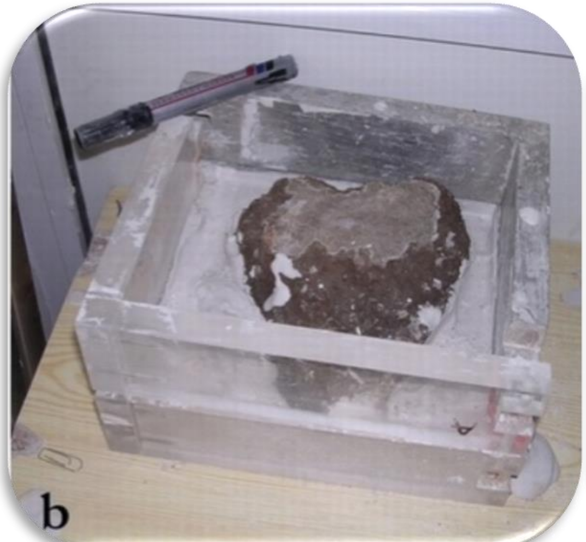
They vary according to :

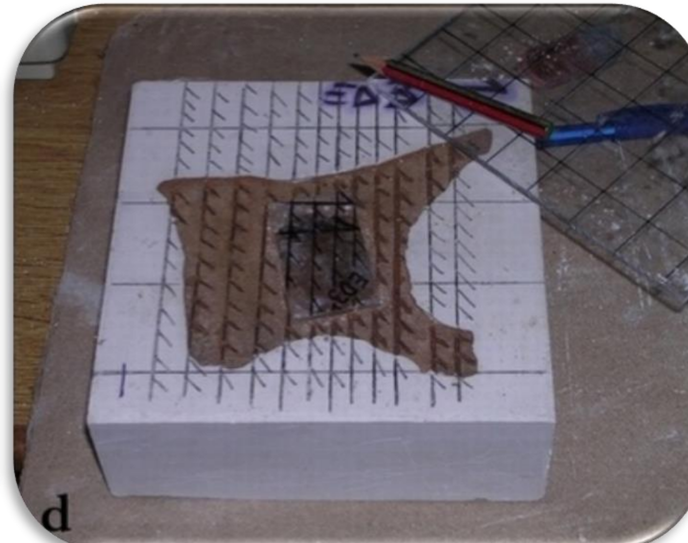
- The size of the structure
- Its conservation or destructibility
- The friability or solidity of the material.

The most common methods are ***the plaster cup,*** the ***plexiglas surface*** and only in few cases, ***drilling***.

Sampling techniques

Laboratory preparation



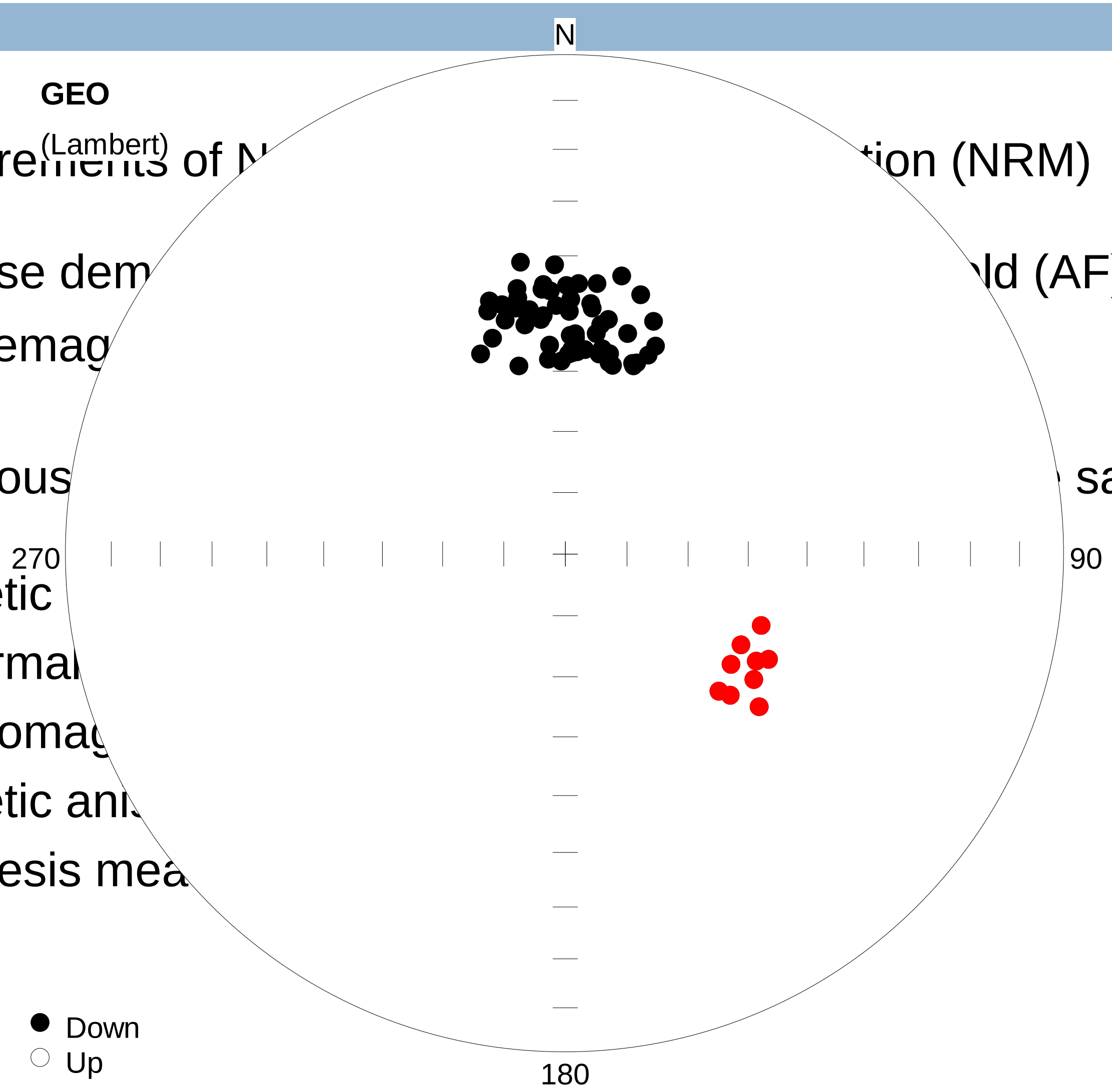


Preparation of cores (2.2x2.5cm)

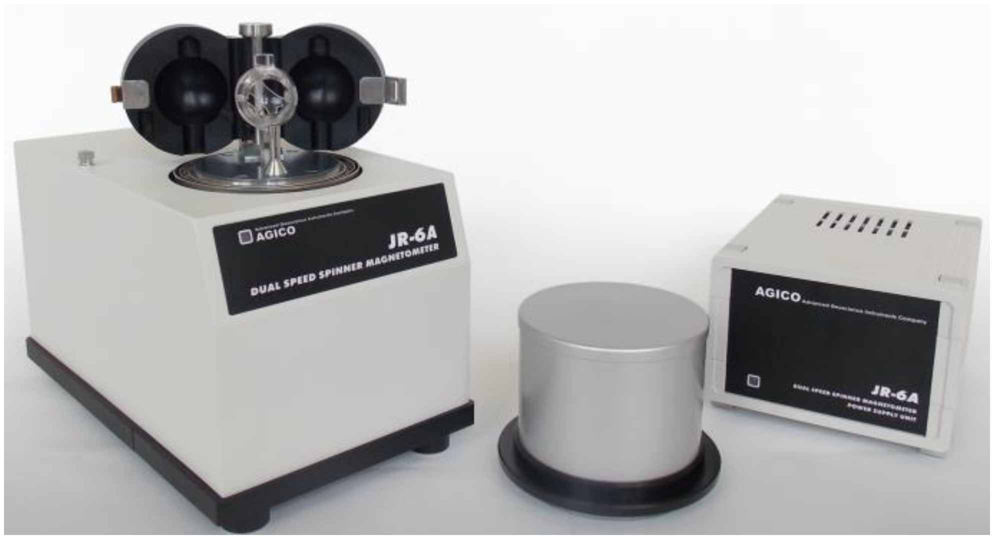
Standard laboratory procedures for directional determination

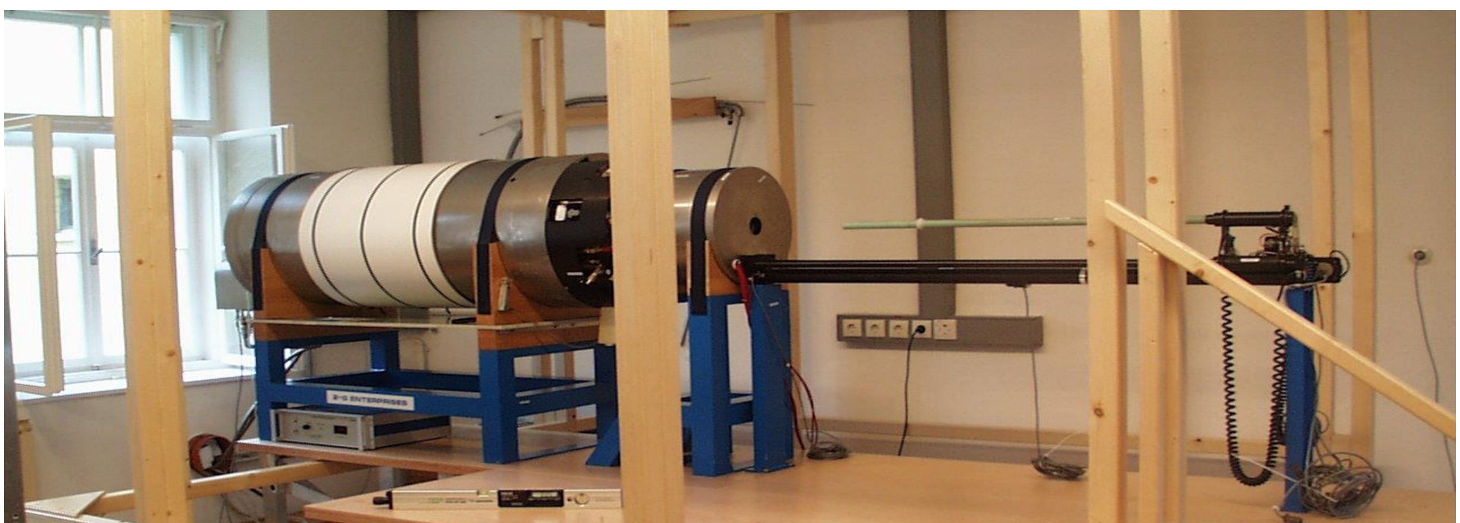
- ❑ Measurements of N... ...tion (NRM)
- ❑ Stepwise dem... ...ld (AF) and thermal (TH) demag...
- ❑ Numerous ... samples:

•Magnetic
•Isothermal
•Thermomag...
•Magnetic ani...
•Hysteresis mea...

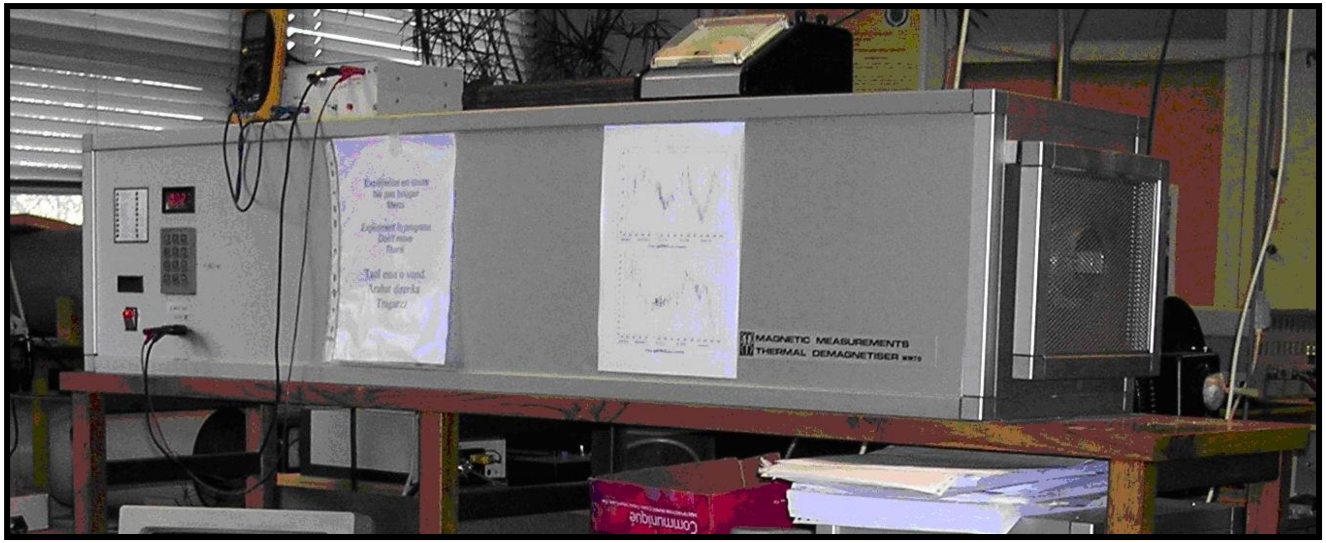


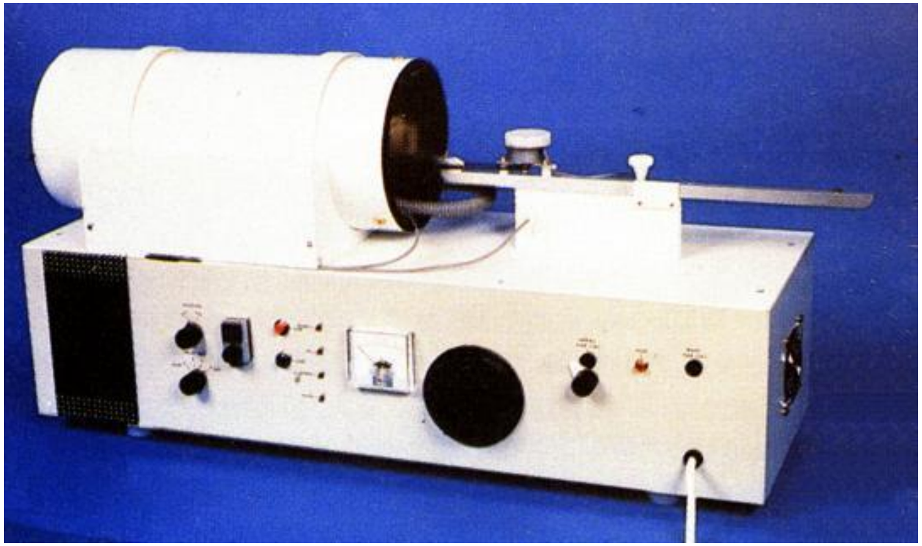
Laboratory equipment



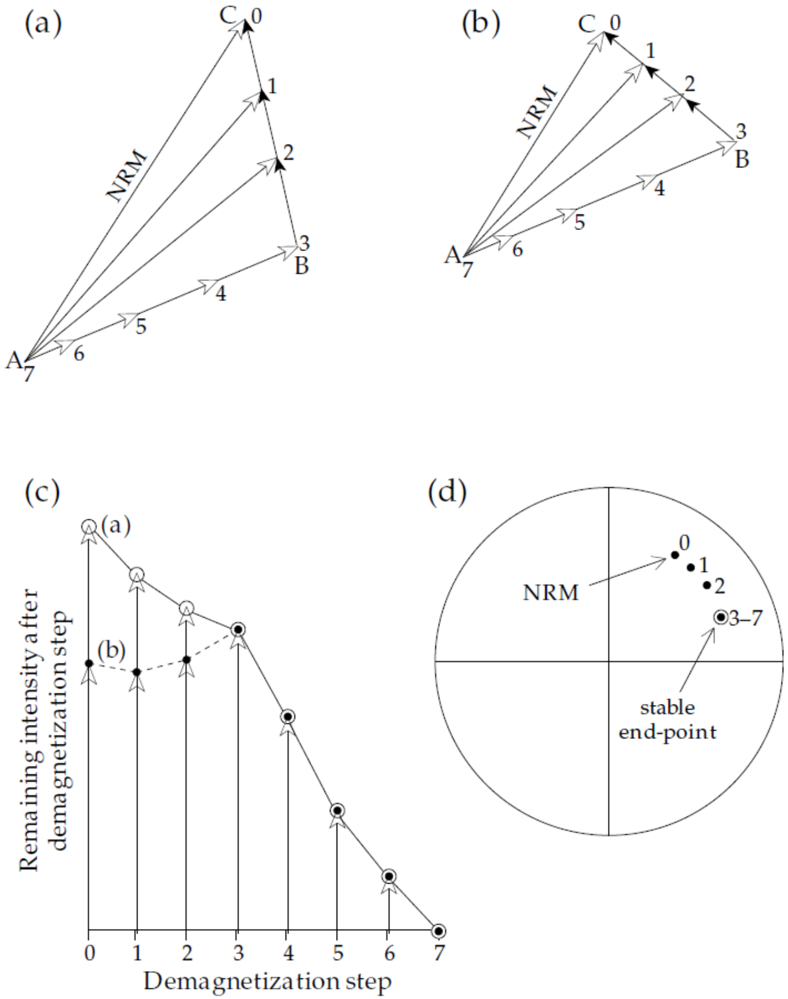


Laboratory equipment



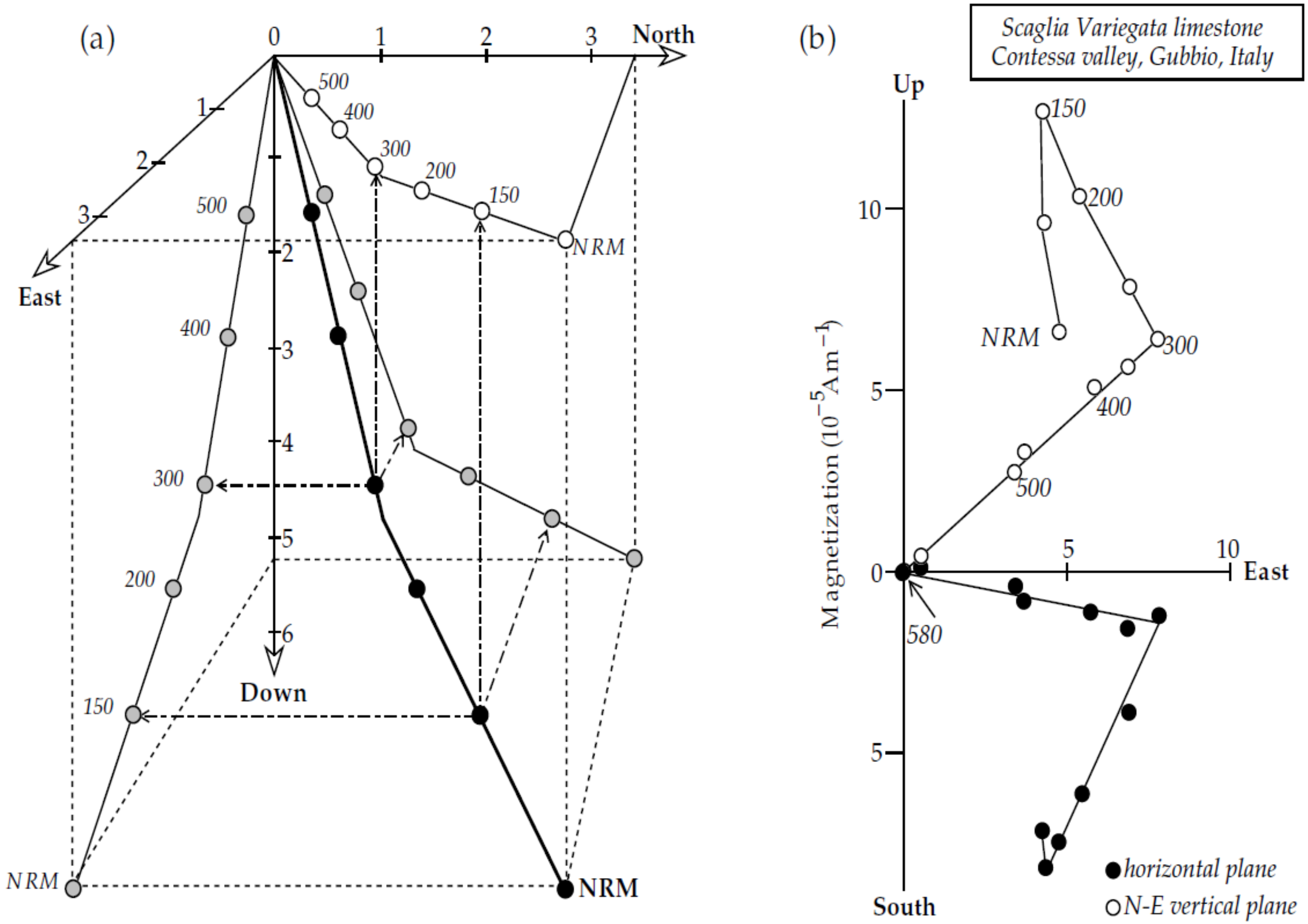


Directional analysis



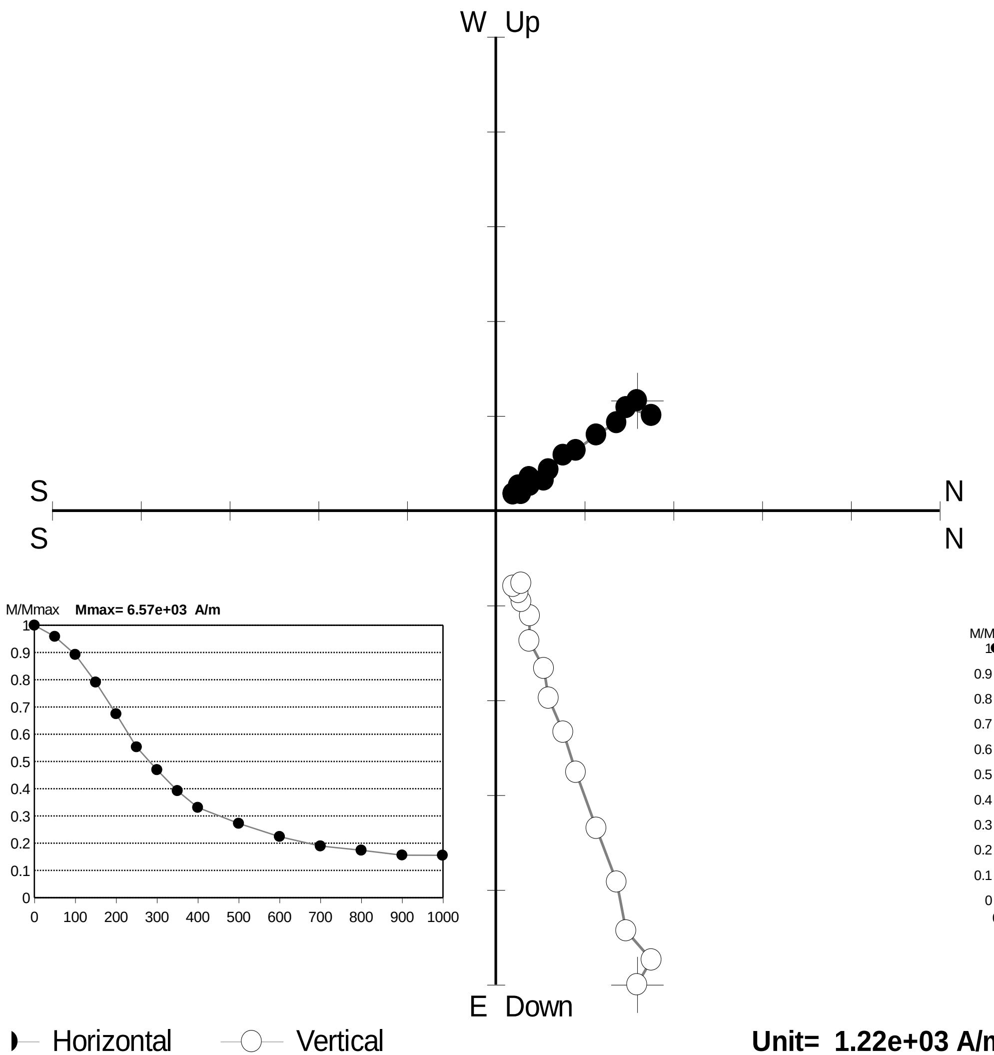
Lowrie, 2007

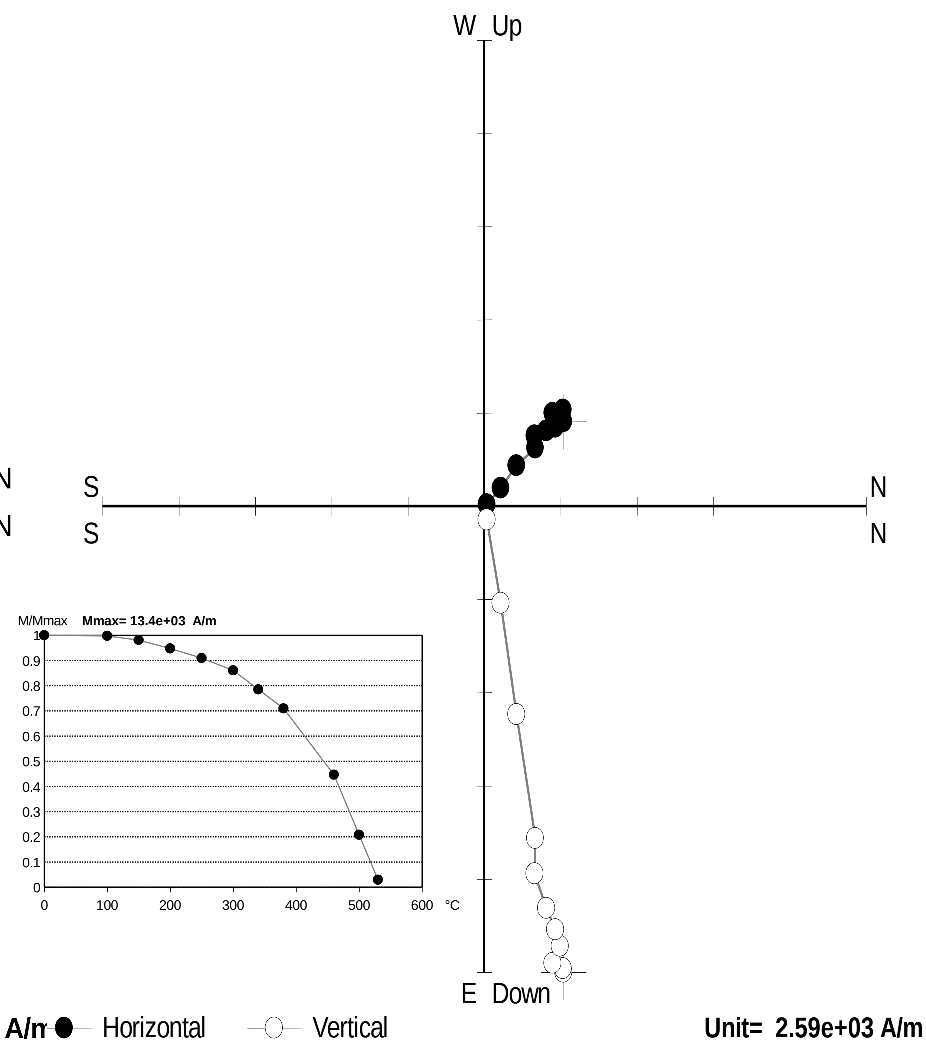
Directional analysis



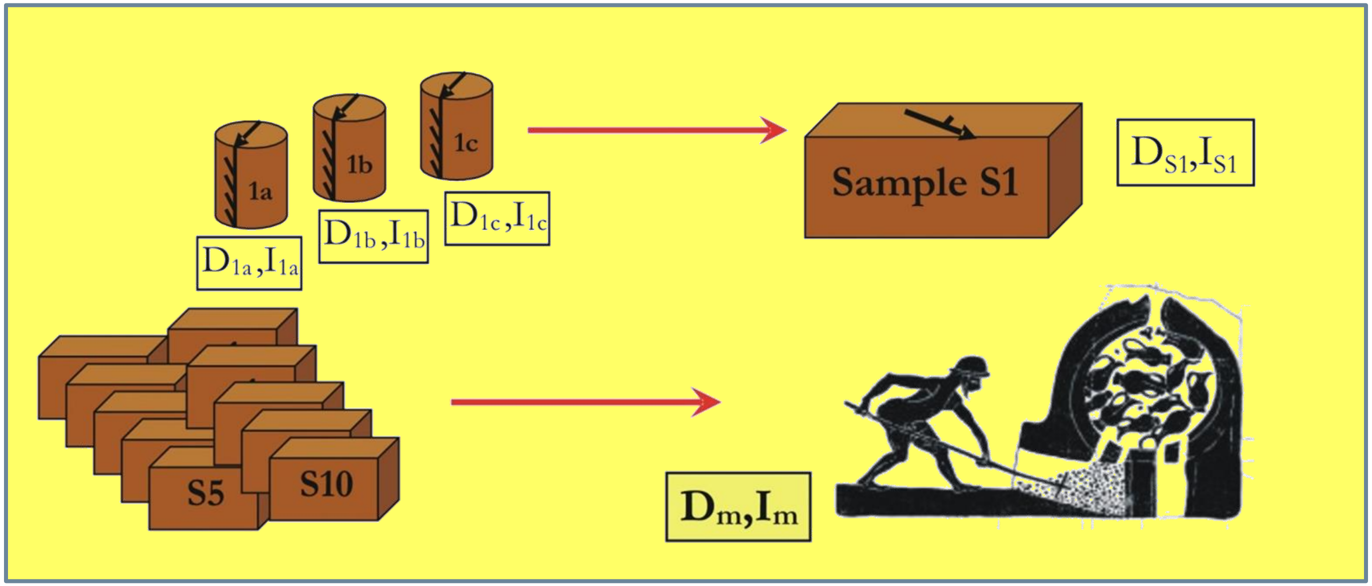
Lowrie, 2007

Directional analysis



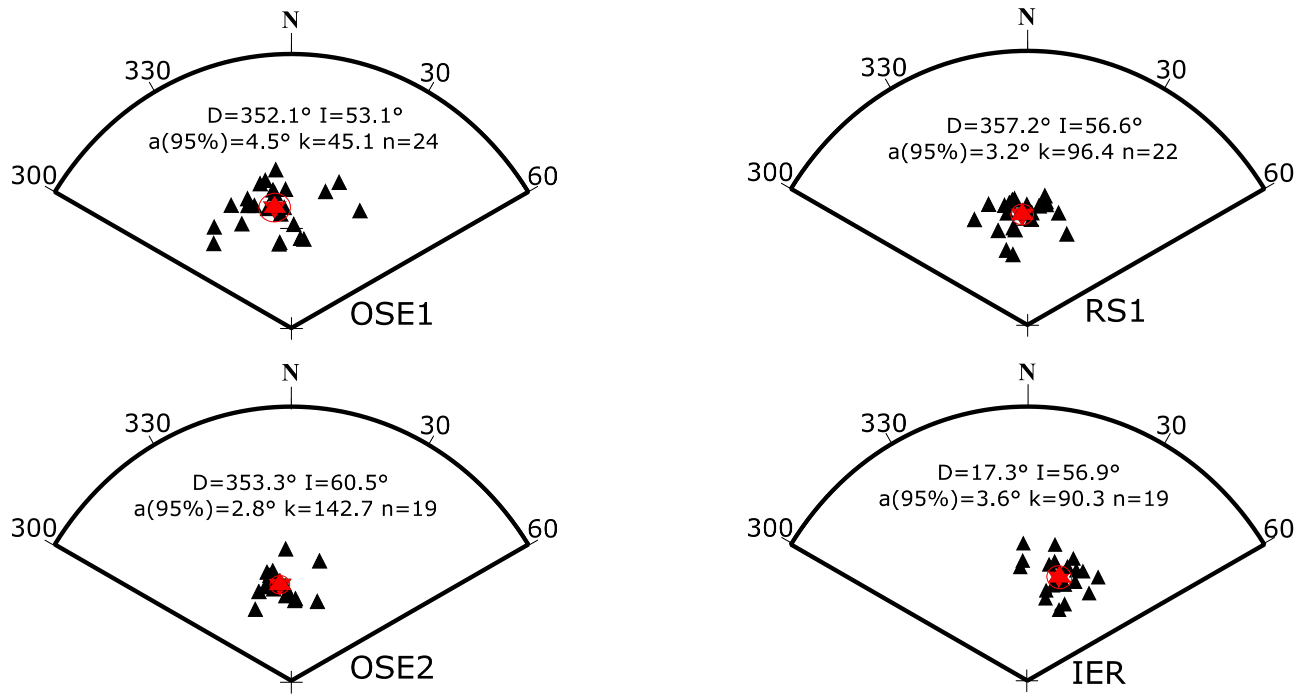


Archaeodirectional results



Mean archaeomagnetic Direction (D_m, I_m)

Mean Archaeodirectional results



Archaeointensity determination

Archaeointensity determination is more complex compared to the directional studies.

- Much more laboratory work!
- Application of strict criteria for a successful determination
- Low success rate

Several proposed methods:

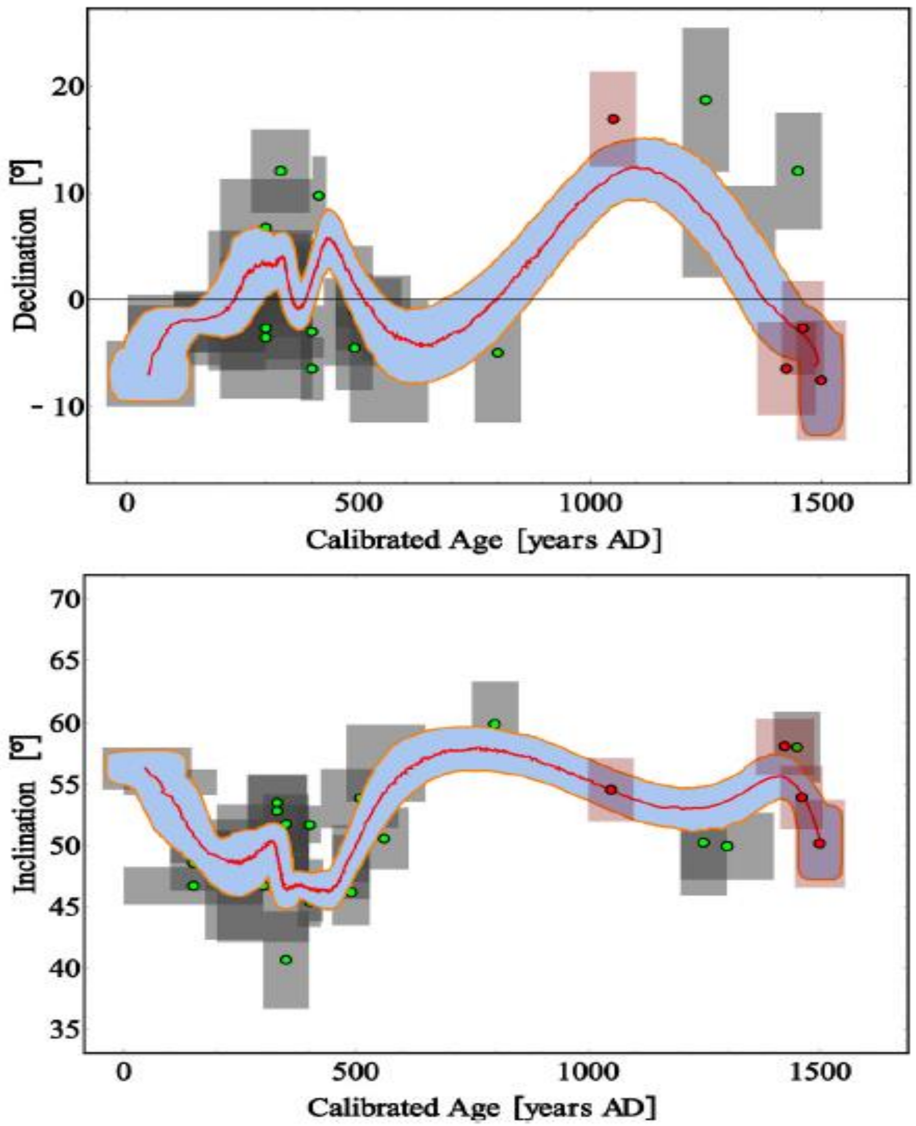
- Thellier and Thellier
- Microwave
- Triaxe
- Multispecimen

All these methods are based on the progressive replacement of the natural remanent magnetization of the samples (acquired in the past) by an artificial TRM acquired in a known field.

Paleosecular Variation Curves (PVC)

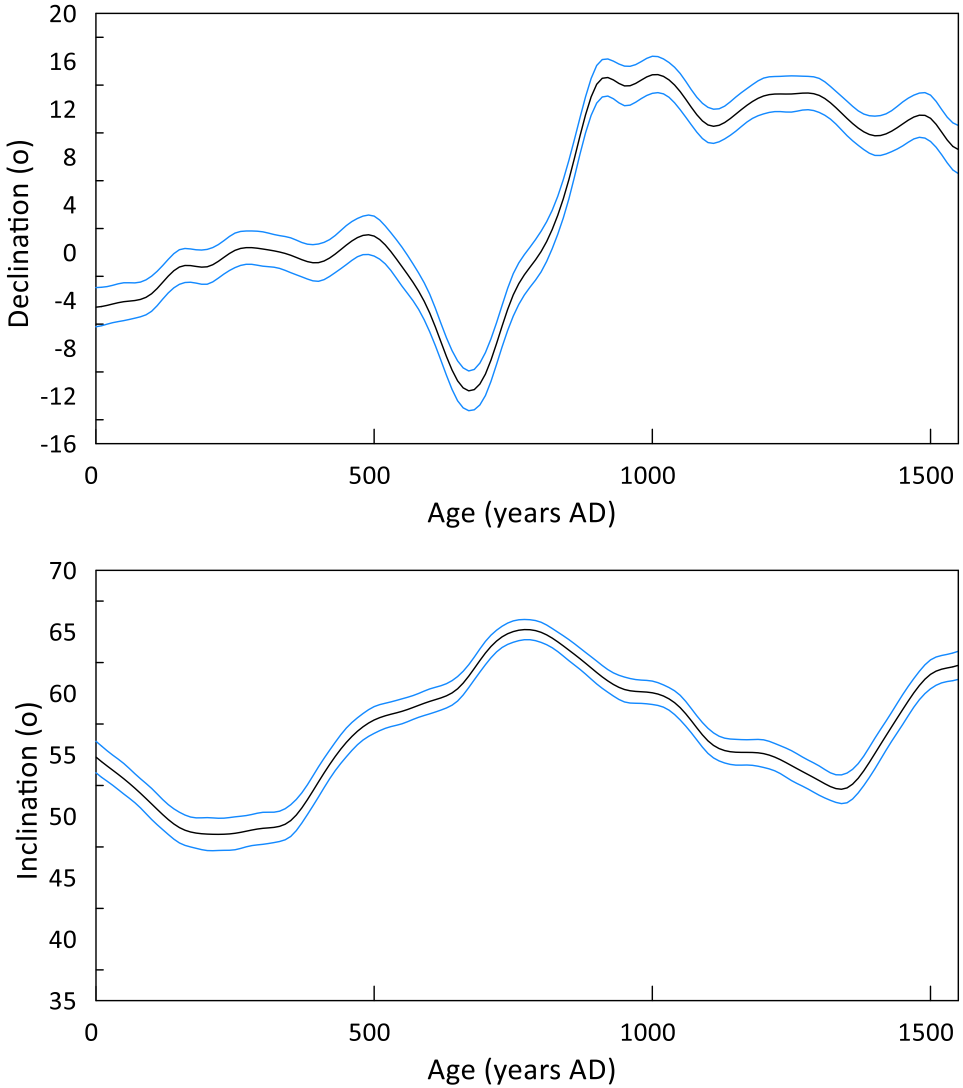
- The compilation of archaeomagnetic data from a particular region allows the construction of time-continuous paleosecular variation (PSV) curves.
- The reference curve can be depicted either as changes in inclination (I), declination (D), and intensity through time.
- Archaeomagnetic data included in these datasets must be dated independently through other techniques, such as dendrochronology or radiocarbon dating, and precision criteria often require these data to have independent date ranges of 200 years or less.
- Due to the spatial and temporal variability of the geomagnetic field, the PSV curves may vary significantly from one continent to another, and therefore for dating purposes the curves need to be defined for each particular region.
- Different statistical techniques such as moving-average running windows, Bayesian statistics, bootstrap algorithms, or the Markov chain Monte Carlo method are applied to obtain these PSV curves.
- Furthermore, these curves can be calculated from either a regional dataset or directly from a global model.

Secular Variation Curves for Greece



Aidona et al., 2021

SCHA.DIF14k Secular Variation Curves



Pavón-Carrasco et al., 2014

Archaeomagnetic dating

A basic application of archaeomagnetism and the most interesting for the archaeologists is DATING

For a successful dating we need:

- a. Archaeomagnetic data of high quality
- b. Well-constrained *reference curves*

Archaeomagnetic dating

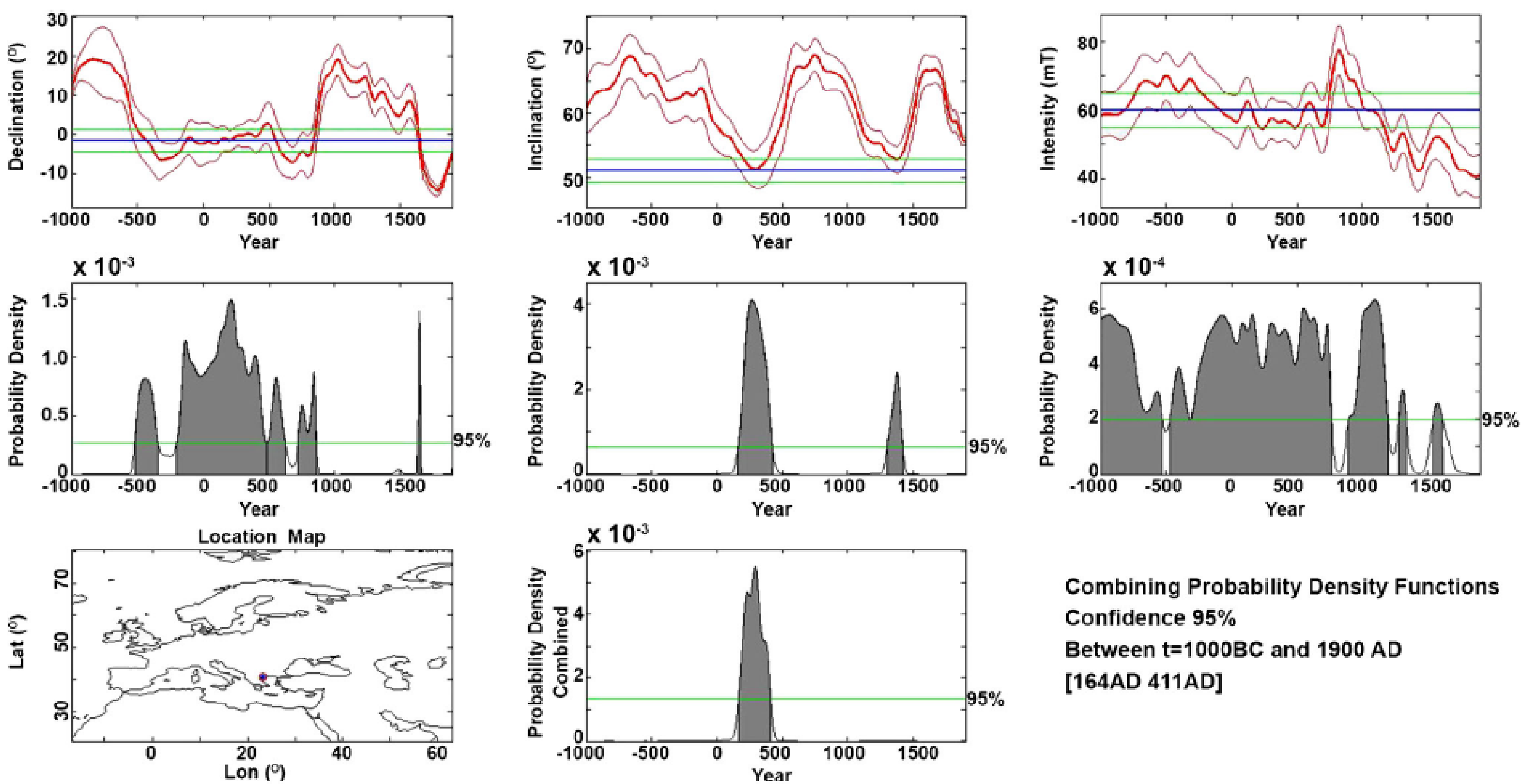
- Archaeomagnetic dating consists of the statistical comparison of the archaeomagnetic field information obtained from an undated archaeological structure with the corresponding PSV curve.

- The precision of archaeomagnetic dating depends on several factors and varies from case to case. The most significant are:
  - the rate of variation of the geomagnetic field,
  - the envelope errors of the master curve,
  - the error in the archaeomagnetic data derived from the undated archaeological material.

  It is worth pointing out that the accuracy of the PSV curves depends on the temporal and measurement uncertainties of the archaeomagnetic data on which the curves are based, and on the number of structures available for each period. This indicates not only the need to obtain additional data, but also the importance of studying well-dated materials in order to better constrain the PSV reference curves.

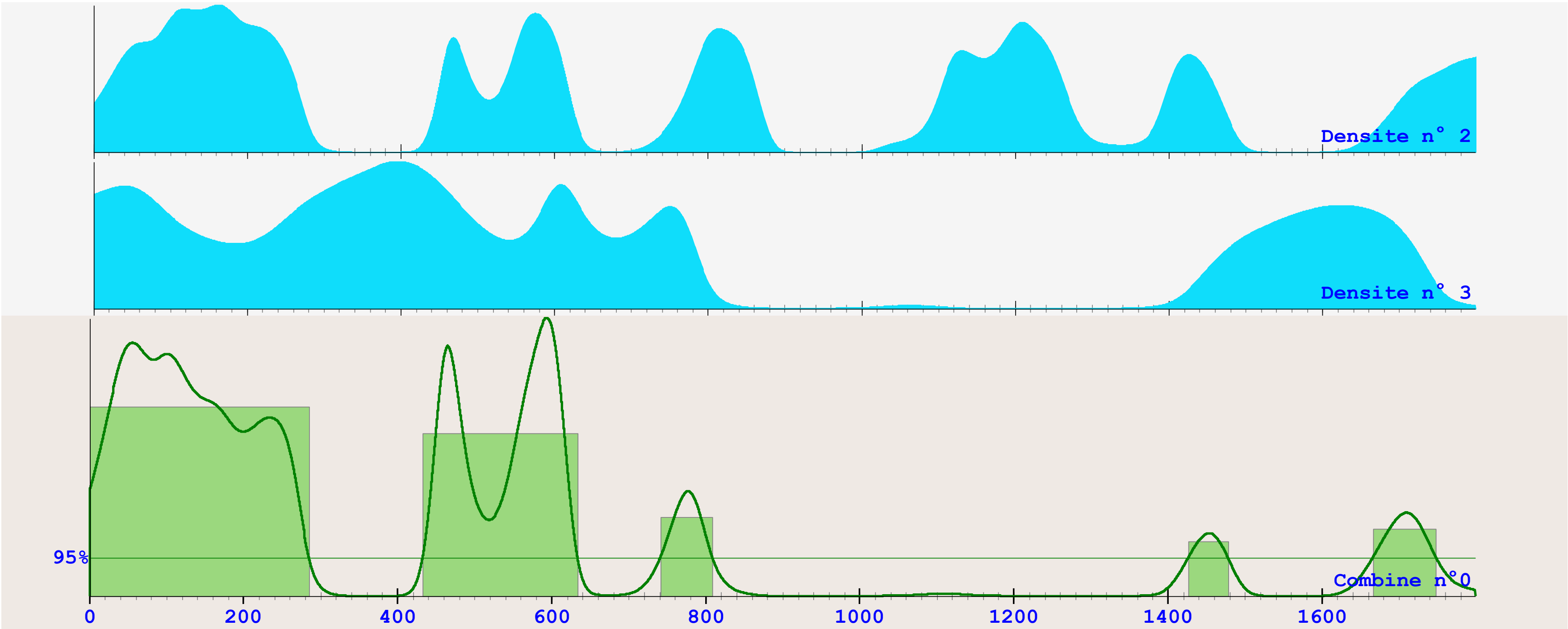
Archaeomagnetic dating

Archaeomagnetic dating tool (Pavón-Carrasco et al., 2011)



Archaeomagnetic dating

Rendate software (Lanos and Dufresne 2008)



Between t=0 and 1799

[0 ; 285] with :51.3%

[433 ; 633] with :31%

[742 ; 808] with :5%

[1427 ; 1478] with :2.7%

[1667 ; 1747] with :5.1%

Summarizing…

- The technique of *archaeomagnetic dating* is a low cost (compared to other techniques) and quite effective method for dating archaeological structures.
- Even if the archaeomagnetic technique cannot always provide very accurate datings (due to bad quality of material used or not precise reference curves) it can give other very useful information to the archaeologists (e.g. narrow the archaeological age estimations).
- The *contribution of other methods*, e.g. mineralogy, in archaeomagnetic research may lead to more detailed conclusions about the relative dating and history of archaeological structures and artefacts.
- The attempt to fill the gaps in the SVC should be continued in order to obtain more accurate datings.
- The study of *magnetic properties of baked clays and soils* can offer valuable information for an archaeological excavation and retrieved materials.