

Handbook of instrumental techniques from CCiTUB

Paleomagnetism: principles and applications

Elisabet Beamud

Laboratori de Paleomagnetisme, CCiTUB, Universitat de Barcelona. Institut de Ciències de la Terra “Jaume Almera”, Solé i Sabarés s/n. 08028 Barcelona. Spain.

email: *betbeamud@ccit.ub.edu*

Abstract. This article summarizes the basic principles of Paleomagnetism, with examples of applications in geology that illustrate the capabilities of the technique.

1. Introduction

Paleomagnetism is the study of the record of the Earth's magnetic field in rocks. The Earth's magnetic field has its origin in the convection of the iron rich material of the outer core of the Earth. At any point of the earth surface, the magnetic field (F) can be defined by two angles (Figure 1). Declination (Dec) is the angle between the horizontal component of F and the geographic north, ranging from 0 to 360 ° and defined as positive clockwise; inclination (Inc) is the vertical angle or the angle between F and the horizontal, ranging from -90 to 90 °, positive downwards.

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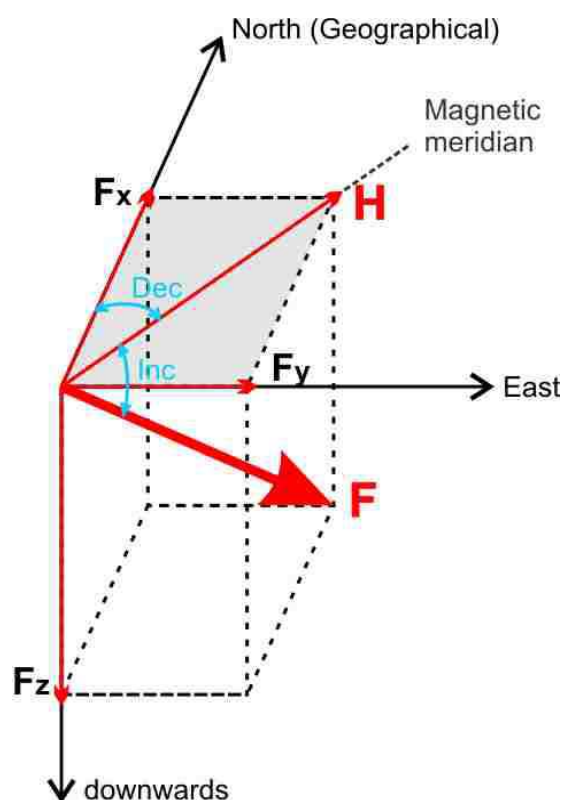


Figure 1 – Description of the direction of the magnetic field (F). Inclination (Inc) is the vertical angle (= dip) between the horizontal and F ; declination (Dec), is the azimuthal angle between the horizontal component of F (H) and the geographic north.

At the Earth's surface, the geomagnetic field can be approximated to the field created by a geocentric axial dipole (GAD), a dipole placed at the center of the earth and aligned with the Earth's rotation axis (Figure 2). The GAD model only accounts for about the 90% of the Earth's surface field, the rest would be the sum of non geocentric dipolar fields, fields of non-dipolar origin and of external origin. In the Earth's surface, magnitude and direction of the geomagnetic field changes with time, ranging from milliseconds, hours, or days (pulsations or short-term fluctuations, daily magnetic variations, or magnetic storms) to centuries, thousands of years, or million of years (secular variations, magnetic excursions, and polarity reversals). Changes with periods between 1 year and 10^5 years constitute which is known as Geomagnetic Secular Variation. Among the longer term variations of the geomagnetic field the polarity reversals, with durations ranging from thousands of years to million years, are the switch of north and south magnetic poles. The present configuration of the dipole field with the north magnetic pole close to the north geographic pole is considered a normal polarity interval, while opposite configuration is considered a reversed polarity interval (Figure 2). Intervals of geological time having a constant geomagnetic field polarity delimited by reversals are defined as polarity chrons. The magnetic reversals are long-period processes (longer than 10^5 years) which do not occur with a simple periodicity but instead appear to occur randomly in time. The duration of a polarity transition is imperfectly known but it is probably in the order of 10^3 to 10^4 years, fast enough to be considered globally synchronous on geologic time scales.

The pattern of polarity reversals providing a unique global “bar-code” recorded in Earth’s rock of different ages constitutes the geomagnetic polarity time scale (GPTS) (Figure 2). For the construction of the GPTS geophysicists fundamentally rely on the marine magnetic anomaly record and also on the magnetostratigraphic record, both containing biostratigraphical constraints. Oceanic surveys carried out during the 1950’s and 1960’s and equipped with shipboard magnetometers found linear magnetic anomalies parallel to the mid-oceanic ridges. These anomalies resulted from the remanent magnetization of the oceanic crust, acquired during the process of seafloor spreading. The spreading process results in the magnetization of the crust in alternating normal and reverse polarity. The template of magnetic anomaly patterns from the ocean floor has remained essential for constructing the GPTS from Early Cretaceous onward (ca. 124.5 Ma to 0 Ma). The initial assumption of periodic behavior (Cox et al, 1963) was soon abandoned as new data became available. The first modern GPTS based on marine magnetic anomaly patterns was established by Heirtzler et al. (1968). Subsequent revisions by Labreque et al. (1977), Berggren et al. (1985), Cande and Kent (1992) showed improved age control and increased resolution. A major breakthrough came with the astronomical polarity time scale (APTS) in which every individual reversal is accurately dated (e. g. Hilgen et al., 1997). Because there is an excellent first-order reversal chronology for most of the Mesozoic and all of the Cenozoic and because these reversals occur randomly in time, sequences of reversals can be used for establishing the age of the rocks.

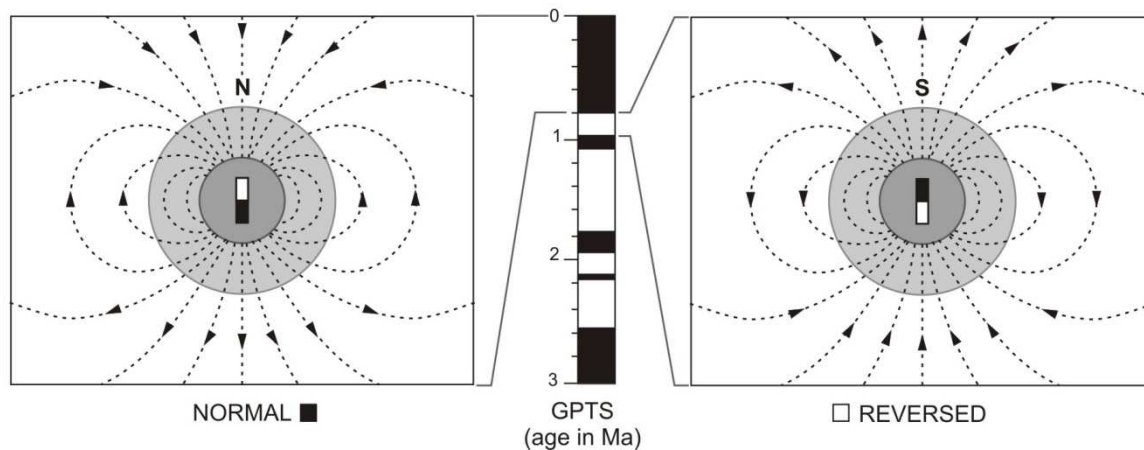


Figure 2 – Schematic representation of the geomagnetic field of a geocentric axial dipole. During normal polarity of the field the average magnetic north pole is at the geographic north pole, and a compass aligns along magnetic field lines. During normal polarity, the inclination is positive (downward directed) in the northern hemisphere and negative (upward directed) in the southern hemisphere. Conversely, during reversed polarity, the compass needle points south, and the inclination is negative in the northern and positive in the southern hemisphere. In the geomagnetic polarity time scale (column in the middle), periods of normal polarity are conventionally represented by black intervals, reversed intervals by white intervals. From Langereis et al (2010)

The study of the ancient Earth’s magnetic field is possible because rocks contain ferromagnetic minerals in their internal structure. During the rock-forming processes these minerals statistically align with the ambient field, and are subsequently “locked in” the rock system, thus preserving the direction of the field as a natural remanent magnetization (NRM). Principal minerals contributing to the NRM are usually iron oxides such as magnetite, hematite, and maghemite, iron hydroxides (goethite), or iron sulphides including pyrrhotite and greigite. Other common minerals such as phyllosilicates (e.g., ilmenite), pyroxenes, and amphiboles can significantly contribute to the induced magnetization. However, they do not have the capability to carry a NRM.

As currently practiced, Paleomagnetism can be applied to age determination, stratigraphy, tectonics, polar wander, magnetic anomaly interpretation, paleoclimatology, as well as studies of the evolution and history of the Earth’s magnetic field.

2. Methodology

2.1. Sampling

Samples are drilled in the field either with an electric or gasoline power drill cooled with water (Fig. 3). As the earth's magnetic field is a vector, samples need to be oriented in situ to get a geographic unambiguous position and orientation in order to provide a reference system to which refer the data obtained during the laboratory analyses. Therefore, samples are oriented in the field by a magnetic compass coupled to an orienting device with inclinometer (Fig. 4). The length of the cores is variable but it is desirable that 2 samples of 10 cm³ can be obtained from each core. Sampling strategy may differ according to the main focus of the study. However, in any case, geological information such as bedding direction, presence of faults or fold axes orientations will be collected during the field work. For magnetostratigraphic purposes, 1 or 2 samples per level will be obtained at a certain stratigraphic spacing (depending on the total thickness of the stratigraphic section to be studied and the number of magnetozones expected to be identified within the section). Sampling focused on tectonic studies, such as identification of vertical-axis rotations within orogenic belts, will consist in the drilling of about 10 cores distributed along the site with an spacing enough to average the geomagnetic secular variation. Several sites distributed all along the study area will be drilled to get a regional pattern of tectonic rotations. In the case of archaeomagnetic studies, about 10-15 samples will be drilled in a random distribution within the archaeological structure and, whenever possible, they will be oriented with a sun compass in order to minimize the perturbation in the magnetic compass caused by the intense magnetization of the archaeological material.



Figure 3 – Paleomagnetic sampling



Figure 4 – *In situ* orientation of drilled cores

2.2. Instrumentation and Measurement in the Laboratory

Paleomagnetism is mainly based on the measurement of the NRM of geological material, which is the fossil magnetism naturally present in a rock. The primary magnetization is the component of the NRM that was acquired when the rock was formed and may represent all, part, or none of the NRM. The primary magnetization may decay through time either partly or completely and additional components, referred to as secondary magnetizations, may be added by several processes. A major task in all paleomagnetic investigations is to identify and separate the magnetic components in the NRM, using a range of demagnetization and analysis procedures.

The main laboratory analysis consists in progressive demagnetization of the samples and the subsequent measurement of the NRM in order to identify and isolate the different paleomagnetic components recorded during the rock-geological history. Progressive demagnetization of the samples can be achieved by two different treatments, thermal (TH) or by alternating fields (AF). During demagnetization experiments, samples are subjected to stepwise increasing values of temperature or alternating field in a zero magnetic field (field-free) space. The residual magnetisation is measured after each demagnetization step and the resulting changes in direction

and intensity are displayed and analysed in order to reconstruct the complete component structure of the NRM. Measurements are made of components (M_x , M_y and M_z) of magnetic moment of the specimen (in sample coordinates). This usually entails multiple measurements of each component, allowing evaluation of homogeneity of NRM in the specimen and a measure of signal-to-noise ratio. Data are then fed into a computer containing orientation data for the sample and calculation of the best-fit direction of NRM in sample, geographic and stratigraphic coordinates is carried out.

2.3. Data analysis

Vector directions are described in terms of declination (D) and inclination (I). After the complete demagnetization of the samples, these directions are displayed with a projection that depicts three-dimension information on a two-dimension environment. Although projections on a sphere are commonly used, the most common representation of results of progressive demagnetization are vector end point or orthogonal projection diagrams, also known as Zijdeveld diagrams (Zijdeveld, 1967). The power of this display is the ability to display directional and intensity information on a single diagram by projecting the vector onto two orthogonal planes (Figure 5). Magnetic components are then extracted from the Zijdeveld diagrams using least-square analysis (Kirschvink 1980), and the most stable and consistent component that can be isolated is referred to as the characteristic remanent magnetisation (ChRM). This ChRM is further investigated to establish if it represents a record of the geomagnetic field at, or close to, the time of rock formation, or a secondary magnetisation acquired later in geologic history by post-depositional processes. With this purpose, several stability tests can be performed on the obtained ChRM, being the most common ones:

- *Consistency test*: a ChRM is considered primary in origin when it defines a sequence of polarity reversals laterally traceable by independent means (e.g., lithostratigraphy) between distant sections from different parts of the basin.
- *Reversal test*: the observation of ChRM directions with different polarity and, in particular, the occurrence of antiparallel (within statistical error) directions is taken as a strong indication for the primary origin of that ChRM.
- *Fold test*: if the ChRM directions from differently tilted beds converge after correction for the dip of the strata, this remanence was acquired before tilting. Strictly speaking, this fold test does not directly prove a primary origin of this component, but only that it dates from before tilting.

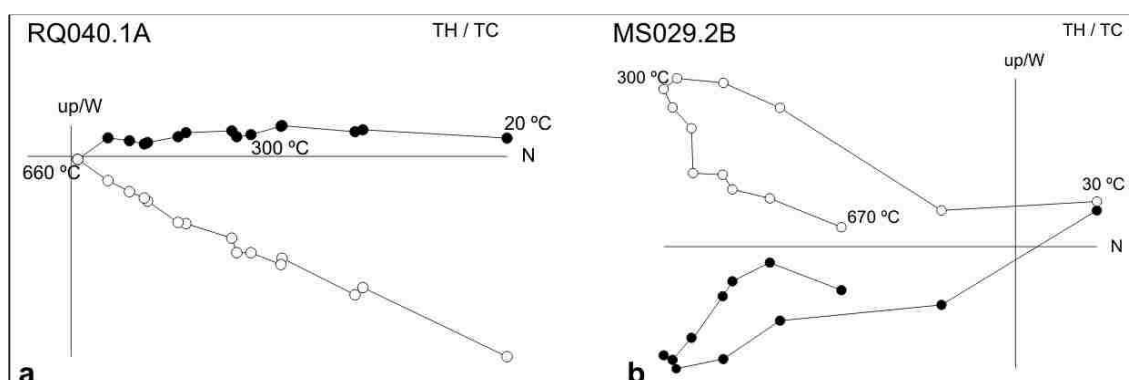


Figure 5 - Examples of Zijdeveld diagrams. Solid (open) circles correspond to projection onto the horizontal (vertical) planes. a: sample of normal polarity (northward declination and positive inclination); b: sample with a low temperature normal polarity component, defined between 30° and 300°, parallel to the present-day magnetic field and a ChRM of reversed polarity, defined from 300° to 670° (southward declination and negative inclination)

3. Examples of applications

3.1. Magnetostratigraphy of Can Mata (Hostalets de Pierola, Vallès-Penedès Basin, NE Spain)

As mentioned above, magnetostratigraphy is based on the fact that the earth's magnetic field polarity changes through time at a non-constant frequency and on the fact that sediments have the capability to record and retain the magnetic field present at the moment of their formation. Therefore, if we study a sedimentary succession long and continuous enough we will be able to identify a reversals characteristic pattern which will allow us to establish a correlation to the Geomagnetic Polarity Time Scale (GPTS). The example presented corresponds to the magnetostratigraphic dating of the Middle Miocene sediments of Can Mata in the Hostalets de Pierola area, a sedimentary succession containing many fossil remains, being the main one among them the remnants of *Pierolapithecus catalanicus* and the hominoid *Dryopithecus fontani*. The magnetostratigraphic study was carried out in order to provide the mammal bearing sediments of Can Mata a robust absolute chronology. This paleomagnetic study was based on the analysis of 369 samples uniformly distributed along 460 m composite section. The correlation of the local magnetostratigraphy to the GPTS (Gradstein et al, 2004) (Figure 6) establishes the age of the sedimentary succession in Upper Aragonian-Vallesian (13 to around 10.5 Ma), and the estimated age of *Dryopithecus fontani* is established in 11.8 Ma (Moyà-Solà, et al, 2009).

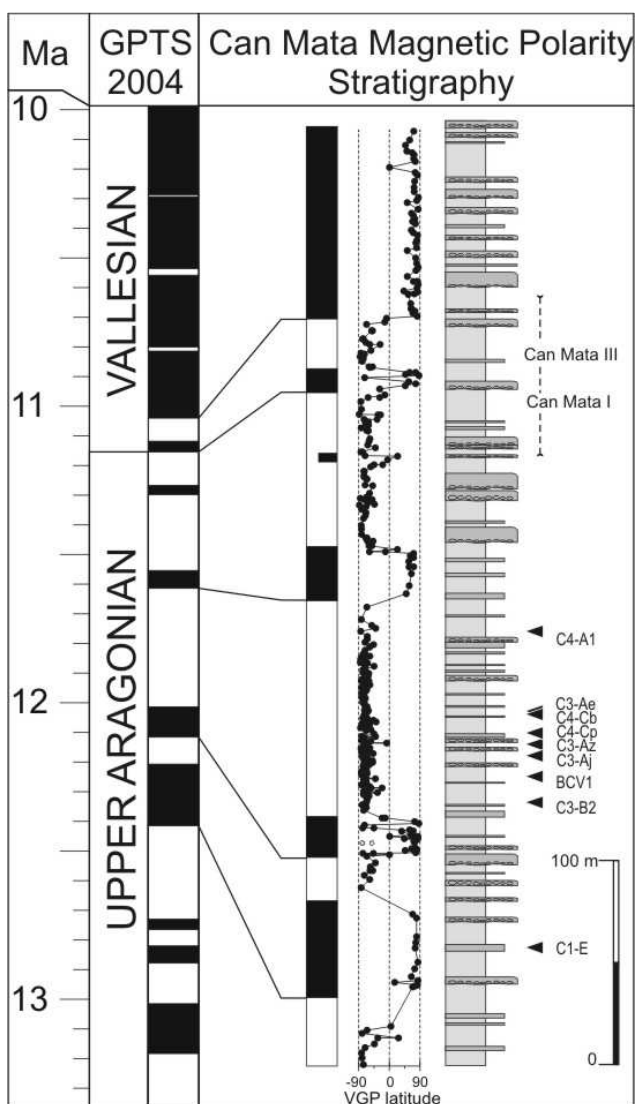


Figure 6 - Composite magnetic polarity stratigraphy of Can Mata and correlation with GPTS2004 (Gradstein et al, 2004).

3.2. Archaeomagnetic dating of combustion structures

Archaeomagnetic studies in Spain have undergone a significant progress during the last few years and a reference curve of the directional variation of the geomagnetic field over the past two millennia is now available for the Iberian Peninsula (Gómez-Paccard et al, 2006). These recent developments have made archaeomagnetism a straightforward dating tool for Spain and Portugal. In this example, we illustrate how this secular variation curve (SVC) can be used to date the last use of burnt structures from Spain. A kiln of the archaeological site of Can Xammar (Figure 7) (Mataró) of Mediaeval times has been studied and archaeomagnetically dated (Gómez-Paccard and Beamud, 2008). The directions of the characteristic remanent magnetization of the structure have been obtained from classical thermal and alternating field (AF) demagnetization procedures on the collected samples, and a mean direction for the combustion structure has been obtained (Figure 8). These directional results have been compared with the new reference curve for Iberia, providing archaeomagnetic dates for the last use of the kiln between 1492 and 1609, consistent with the archaeological evidences available (Figure 9).



Figure 7 - Combustion structure of the Can Xammar archaeological site and location of the samples. Modified from Gómez-Paccard and Beamud (2008)

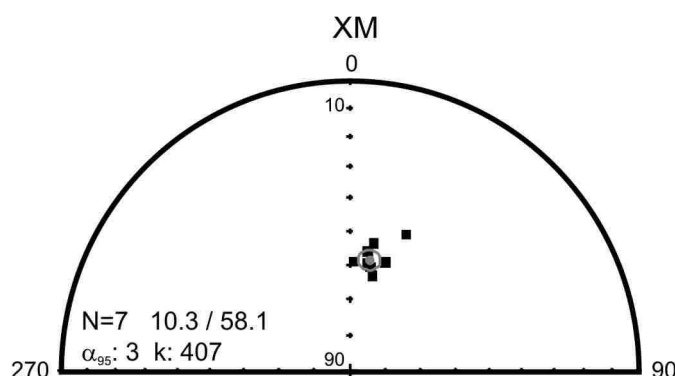


Figure 8 - Mean direction for the Can Xammar kiln. Modified from Gómez-Paccard and Beamud (2008)

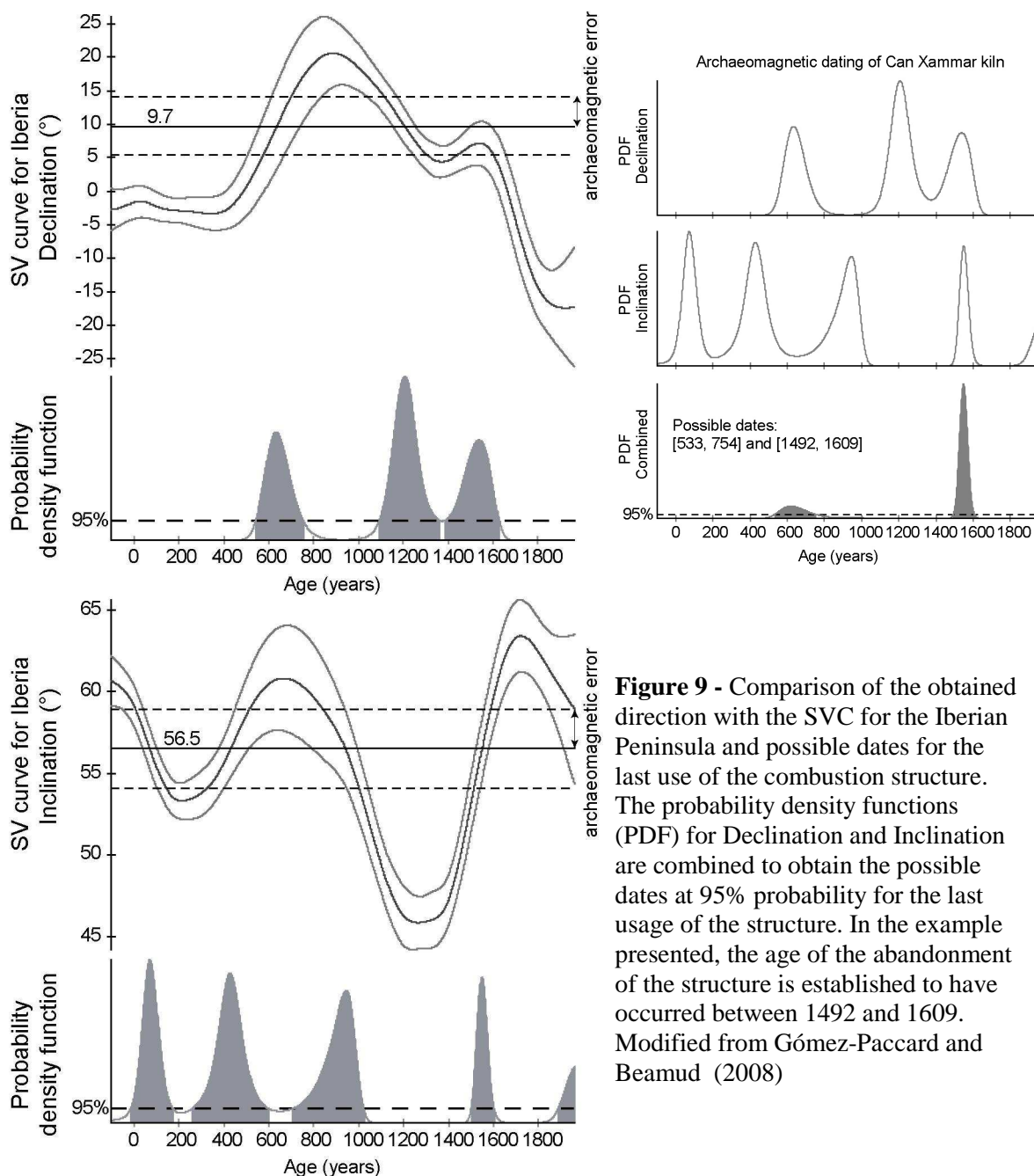


Figure 9 - Comparison of the obtained direction with the SVC for the Iberian Peninsula and possible dates for the last use of the combustion structure. The probability density functions (PDF) for Declination and Inclination are combined to obtain the possible dates at 95% probability for the last usage of the structure. In the example presented, the age of the abandonment of the structure is established to have occurred between 1492 and 1609. Modified from Gómez-Paccard and Beamud (2008)

3.3. Tectonic rotations in the south-central Pyrenees during the Tertiary

The ability of rocks to record the direction of the ancient magnetic field provides the key quantitative information for unravelling tectonic deformation in orogenic belts. The orogenic environment, however, causes specific problems to the analysis of the magnetism in rocks due to the effects of strong deformation and temperature increase. Rocks in this environment are more likely to have their primary magnetism partially or completely overprinted by magnetizations linked to the deformation. Partially set against this disadvantage, the deformed nature of the rocks means that the paleomagnetic fold test is more readily applied to constrain the geological ages of the magnetizations than would be possible in less deformed settings. Paleomagnetic analysis assumes that the mean direction of magnetization recovered from the rock-unit is a record of the time averaged dipole field source at the time of magnetization. The cumulative deformation can then be resolved by comparing this direction with the predicted direction at the study location at the time of magnetization. Usually, the difference is the resultant of more than one episode of

deformation and in favourable circumstances it can be decomposed using geological evidence or from studying the paleomagnetism of rocks of different ages. The angular deformation is usually considered in terms of differences of declination and inclination with respect to the reference direction from the stable plate. The difference between the observed and expected directions is described in terms of rotation and flattening. A difference in declination implies rotation (R) of a crustal block about a quasi-vertical axis.

The Graus-Tremp piggy-back basin is an elongated trough formed during the emplacement of the allochthonous units of the South Central Pyrenean Units. Previous studies in both the Mesozoic basement and the Paleocene sediments of the Graus-Tremp basin have evidenced significant vertical axis clockwise rotations (Figure 10). These rock units are unconformably overlain by the syntectonic continental conglomerates of the Sierra de Sis and La Pobla de Segur, which were recently dated as Bartonian to Priabonian on basis of magnetostratigraphic correlation (Beamud et al, 2003). More recently, the syntectonic conglomerates of the Senterada basin have been dated as Oligocene also based on magnetostratigraphy (Beamud et al, 2011). Paleomagnetic data from these units provide constraints on the timing and spatial distribution of the tectonic rotations in the Graus-Tremp Basin. No significant rotations during the Tertiary are observed near the Noguera Pallaresa River. Further west, between the Esera and the Ribagorçana rivers, the lower Eocene materials record up to 30° of clockwise rotation. The lack of significant rotation in the overlying Bartonian sediments of the Sierra de Sis constrains this rotation to the Ypresian-Lutetian. In the Ainsa basin, about 30° of clockwise rotation is still recorded by Bartonian sediments. These data suggest an east-west trending of the vertical axis rotations magnitude and timing.

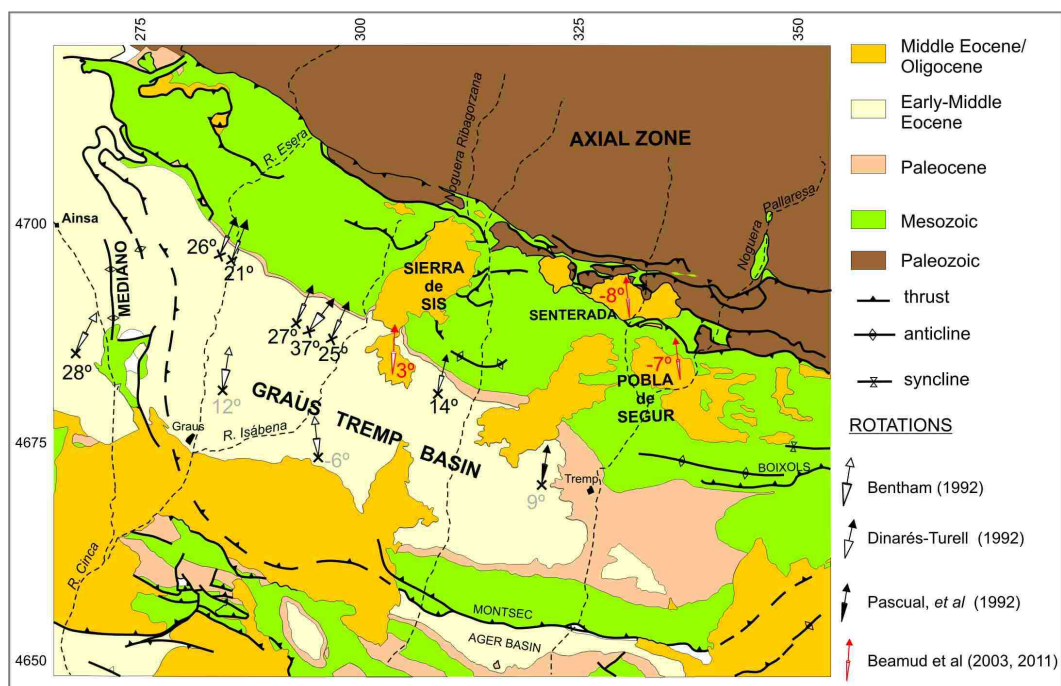


Figure 10 - Distribution of the vertical-axis rotations within the Graus-Tremp piggy-back basin during the Tertiary. Modified from Beamud et al (2004).

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