

Ciências
ULisboa

**JOINT ANALYSIS OF ÁGUA DE MADEIROS
AND ANÇOS MAGNETIZATION AGE - REPORT
ON FIELDWORK AND LABORATORY
ANALYSIS**

André Silva
Daniela Bolrão
Miguel João Neves

Master Degree in Geophysical Sciences

Geomagnetism
2014/2015

Professor Dr. Eric Font

June, 21st 2015

Contents

1	Introduction	1
1.1	Some theory about magnetization	2
2	Geological Setting	6
2.1	Água de Madeiros Section	6
2.2	Anços Sill	7
3	Fieldwork - Sampling and Methods	8
4	Laboratory work - Data Processing and Methods	10
4.1	Cutting samples into specimens	10
4.2	Data processing	11
5	Data analysis	14
6	Joint presentation of results and discussion	15
6.1	Água de Madeiros	15
6.2	Anços	18
6.3	Magnetic susceptibility of AM and AN samples	21
7	Conclusions	22
7.1	Difficulties throughout the work	22
	References	23

1 Introduction

The aim of this study is determine the nature of magnetization of the rock samples collected in Água de Madeiros' beach (39.748° , -9.0396°), located 2 km south of São Pedro de Moel, 2 km north of Pedra do Ouro and 12 km west of Marinha Grande (Figure 1). We also analyzed other samples from Anços Sill, located 13 km northeast of Sintra and 13 km southeast of Mafra (Figure 2), to compare results.

We performed this study in Água de Madeiros' beach because it is a Portuguese reference section of the Lusitanian Basin: it is the main stratigraphic reference of the geological period Sinemurian-Pliensbachian, dated at 190 My and provides an excellent record of the Early Jurassic time interval.

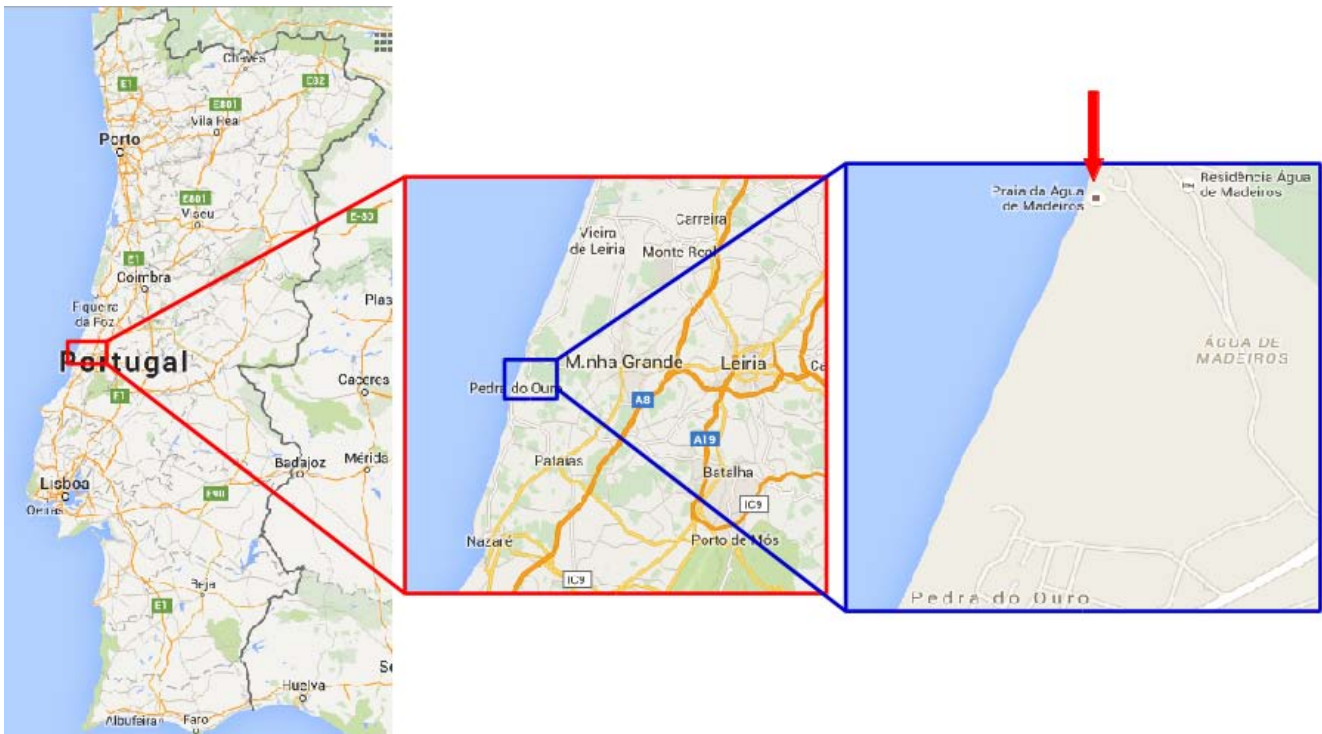


Figure 1: Location of Água de Madeiros' beach.

To study the nature of magnetization we collect several samples in Água de Madeiros' beach (Section 3). These samples were then taken to the laboratory where they were cut into standard paleomagnetic specimens, which then have been treated using alternating field (AF) (Section 4). We also did the same laboratory procedure (apart from cutting) with Anços' samples. We performed a data analysis (Section 5) and then discussed the results (Section 6).

But to understand the laboratory procedure and the results obtained, it is necessary understand some physics involved in it. The next topic explains some of the concepts and the key points to do this work.

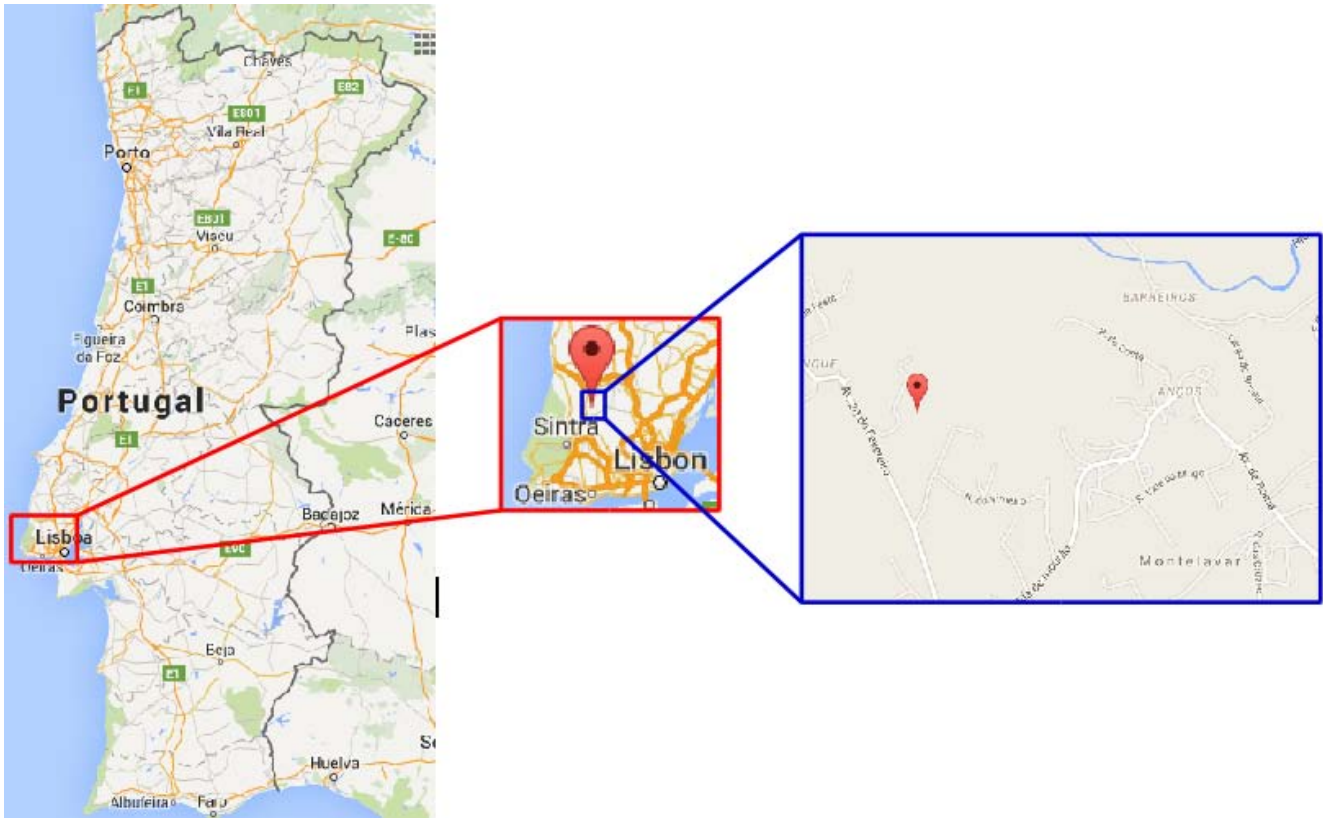


Figure 2: Location of Anços Sill.

1.1 Some theory about magnetization

This work is based on the [1] and [2] works.

Through paleomagnetic studies of rocks it is possible to obtain the past configurations of the geomagnetic field.

The magnetic field of the Earth is approximate to an inclined dipole, with an angle of 11.5° with the rotation axis. The poles of this dipolar component, centered at the Earth's centre, are called Geomagnetic Poles. But actual Magnetic Poles do not correspond to the Geomagnetic ones and some observations confirm nondipolar components, which means that the dipole is not at the centre of the Earth, but placed about 500 km from the geocenter, toward the northwestern portion of the Pacific Basin.

Is important to note that the direction and magnitude of the Geomagnetic field changes with time, and the dipolar component is known to change polarity on long time scales.

The magnetic field at any location of the Earth is represented by the Declination (angle between Magnetic North and Geographic North) and Inclination (angle between the vertical component of magnetic field and horizontal plane) and its intensity. An example is in Figure 3.

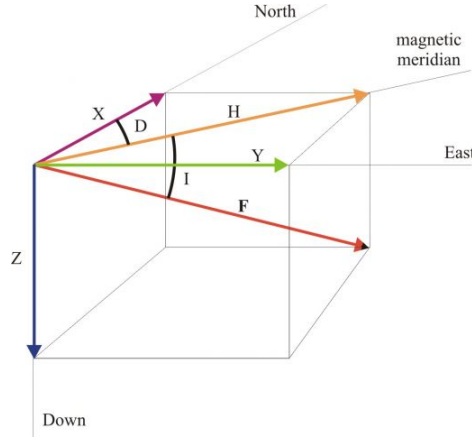


Figure 3: Common coordinate systems used for representing the Earth's magnetic field. Figure from [3].

The magnetic field generated by a geological formation in a point P with coordinates \vec{r} can be determined mathematically by the expression:

$$\vec{F}_a(\vec{r}) = -\frac{\mu_0}{4\pi} \text{grad}_P \int \int \int \vec{M}(\vec{r}') \times \text{grad}_Q \left(\frac{1}{|\vec{r} - \vec{r}'|} \right) dv \quad (1)$$

since we know the value that the magnetization density, \vec{M} , takes for each volume element, dv , of the rock. Q ($\equiv \vec{r}'$) is the current point on the formation.

Magnetization depends of the magnetic history of the rock, which determines the remanent magnetization of the material, \vec{M}^R , and the ambient magnetic field that determines the induced magnetization, $\chi\vec{H}$, as it is shown in Equation 2:

$$\vec{M} = \chi\vec{H} + \vec{M}^R \quad (2)$$

The χ parameter is the magnetic susceptibility, is adimensional (SI), and measures the ability of the rock to magnetize. It could be function of the magnetic field, H , and depends on the amount of ferromagnetic minerals, in particular magnetite.

Sedimentary rocks have the lowest values of average susceptibility and igneous rocks (or basics) the highest. For the same chemical composition, extrusive rocks have remanent magnetization higher and susceptibility lower than intrusive rocks. In sedimentary and metamorphic rocks the values of magnetization are very low.

There are various types of magnetic behaviours of the materials: diamagnetism, paramagnetism, ferromagnetism, ferrimagnetism and antiferromagnetism.

A substance is called diamagnetic when has a negative magnetic susceptibility, so the magnetization induced on the material by field H has an opposite direction to that of the field. The magnetization goes back to zero when the applied field is removed. Although it is present on every materials, it is dominant only in a few because it is weak when compared with the other magnetic behaviours. Graphite, quartz and feldspats, for example, have a diamagnetic behaviour.

When the magnetic susceptibility of the mineral is positive, and the induced magnetization on the substance by field H has the direction of the applied field, the behaviour is named paramagnetic. This type is dominant in substances whose atoms have not completely filled sub-layers and decreases with temperature, like pyroxene, olivine, amphibolite and biotite. When a field

is applied the magnetic moments tend to align, saturating when all are parallel to the field. By removing the field, since the magnetic moments are independent, any small perturbation will make them randomly distributed and the net magnetization will be zero.

The substances that have high magnetization exhibit a behaviour called ferromagnetism, such as iron, nickel and cobalt. In these materials magnetic moments are not independent from each other and interact strongly, giving them the ability of generating a higher magnetization. An interaction where the energy constant (J) is positive is called ferromagnetic and in the case where J is negative is called antiferromagnetic. In antiferromagnetic materials, the antiparallel coupling results in that there is a cancellation between the magnetic moments. There are also ferrimagnetic substances that have an antiparallel coupling but the magnitudes of moments in each direction are unequal resulting in a significant net magnetic moment.

There is a temperature value at which the thermal agitation provides the energy needed to destroy the coupling between the magnetic moments. At this temperature, it is given the name Curie temperature, or Néel temperature for antiferromagnetic materials. For temperatures higher than this the materials assume a paramagnetic behaviour.

There are various types of mechanism for a material to acquire a Natural Remanent Magnetization (NRM), i.e. remanence naturally acquired in the presence of natural ambient fields.

When a ferromagnetic material with a null net magnetic moment is put under the influence of a field, its magnetization starts to increase (Figure 4). This process is only reversible at low intensities of H , for higher values the curve becomes irreversible and by removing the applied field an Isothermal Remanent Magnetization is acquired (M_r). If all the magnetic moments become aligned by the applied field, magnetization will reach the Saturation Remanent Magnetization (M_{rs}).

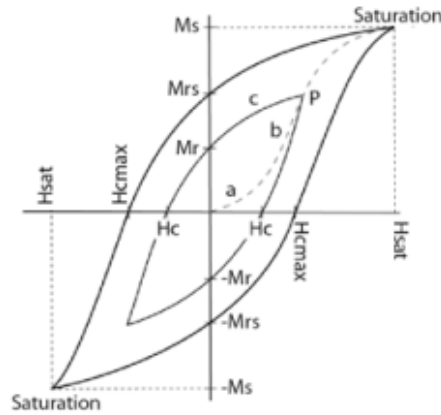


Figure 4: Hysteresis curve. This curve describes the ferromagnetic behavior. Figure from [2].

In single-domain crystals (SD) the NRM is expressed by:

$$J_r(t) = J_{r0}e^{(-t/\tau)} \quad (3)$$

where J_r is the remanent magnetization and τ is the relaxation time. The relaxation time is the time that the magnetization of the mineral takes to be reduced to a factor of $1/e$.

The AF demagnetization consists in exposing the sample to an alternating field . The maximum value of the demagnetization is called HAF and the procedure consists in measure the NRM step-by-step of demagnetization until 100 mT (maximum value reached by the equipment). The response of this magnetization depends on the coercivity (Hc) of the magnetic carriers. According to the Figure 5, the magnetic moments of all grains whose Hc 200 Oe align towards “up” and those with Hc 199 Oe guide towards “down”. Thus, the magnetic moments cancel and the contribution of all grains whose $H_c \leq HAF$ is destroyed. Only NRM carried by grains whose $H_c > HAF$ is preserved [4].

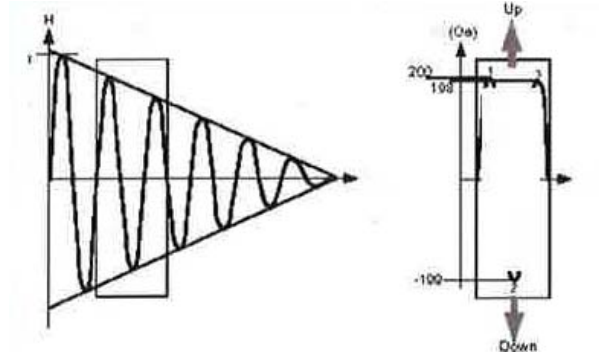


Figure 5: Example of a demagnetization AF in a volcanic rock. Figure from [1].

The anisotropy of magnetic susceptibility can be represented as an ellipsoid, in a simple graphic, where each axis of the ellipsoid equals each major susceptibility values (Figure 6). To do this, we calculate the shape parameter, T :

$$T = \left[\frac{2 \ln(K_2/K_3)}{\ln(K_1/K_3)} \right] - 1 \quad (4)$$

If $T = 0$ the ellipsoid is spherical or neutral, if $0 < T < 1$ the ellipsoid is oblate (flattened), and if $-1 < T < 0$ the ellipsoid is prolate (cigar-shaped).

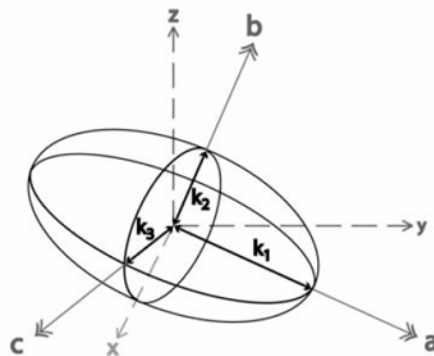


Figure 6: Ellipsoid that represents the anisotropy of magnetic susceptibility. Figure from [5].

The magnitude of this anisotropy depends on the anisotropy of the particles themselves and on their degree of alignment.

2 Geological Setting

This section briefly describes the geological settings of the Água de Madeiros Section and Anços Sill. This work is based on a compilation of [6], [7], [8], [9], [10], [11], [12] and [13] works.

2.1 Água de Madeiros Section

The Água de Madeiros (AM) section stays at about 2 km south of São Pedro de Moel and it is a section with approximately 30 meters in thickness (Figure 7).



Figure 7: Água de Madeiros section. Red dashed line marks the reference of the geological period Sinemurian–Pliensbachian.

AM section is part of the Lusitanian Basin, which is located on the western Iberia passive margin of the Atlantic. It is adjacent to the Iberian Massif in the east and to the Variscan Berlenga Horst in the west. It was formed during the Triassic by an extensional phase that antedated the opening and formation of the Central Atlantic Ocean. After that period there was very important sedimentary infill. It has several phases identified that are bounded by regional unconformities. The interval analysed in this study belongs to the first cycle that goes from the Triassic until the middle Jurassic.

In the Lower Jurassic the Lusitanian Basin intervals generally includes marine carbonate deposits. In the base, probably corresponding to the Hettangian, are found fine-grained, siliciclastic sediments with some dolomitic and evaporitic intercalations (Dagorda Formation). On top of the Dagorda Formation is a succession of dolostone and limestone that form the Coimbra Formation. The limestones indicate a marginal marine palaeoenvironment setting.

An alternating deposition of thin-bedded marl-limestone with common ammonites and black shale characterize the Late Sinemurian interval that belongs to the Água de Madeiros Formation, which is the most continuous succession of the Coimbra Formation. This marks the appearing of open marine conditions in the basin and has two members: Polveira and Praia da Pedra Lisa. In the Lower Pliensbachian–Upper Toarcian interval is also present the fine-grained sedimentation.

In São Pedro de Moel carbonate outcrops from Late Jurassic (from Lower Sinemurian to Middle Toarcian) are restricted to the coastline in an intensely folded and faulted succession. It presents an important Sinemurian record.

The studied section includes an upper part of the Polveira Member of about 14 meters thick at the base, and presents an alternating deposition of marl and limestone, organic rich levels and

wood fragments of decametric sizes. In the lower part of the section belemnites and ammonites are abundant and in the top of the Polveira there is a significant change in the ammonite record.

On top of it is found the Praia da Pedra Lisa Member. It is predominantly calcareous, beginning with approximately 9 meters of microspar limestone, occasionally showing lamination and irregular stratification. Benthic and nektonic macrofauna are scarce [9].

The upper 7 meters show a gradual increase in grey to dark grey marl and there is a thickening of the limestone beds. Some of the intervals with marl correspond to organic rich facies since they show lamination. The Limestone is made of fossiliferous micrite to biomicrite/wackestone with mollusks and ostracods [9]. Is also scarce the presence of Benthic macrofauna.

These levels were attributed to the Upper Sinemurian by [13] and [8], but recently was suggested that they are in fact part of the Lower Pliensbachian by [9]. This last hypothesis was corroborated by [10].

2.2 Anços Sill

The Anços sill (38.8763°N, 9.3181° W) is proposed to be part of the Lisbon Volcanic Complex. This complex was formed by a third pulse of magmatic activity between 72–94 My during the rifting and opening of Atlantic Ocean and opening of the Bay of Biscay. [7] refers that the sill has been dated at 72 My in previous studies.

This pulse is of alkaline nature. Paço de Ilhas and Foz da Fonte sills were also formed during this pulse [14].

The Anços sill intruded marls and limestones from the Albian–Cenomanian period. The Anços sill has a porphyroid texture with plagioclase, feldspar, and colorless clinopyroxene porphyrocrystals in a fine grained matrix composed of plagioclase, clinopyroxene, Fe-Ti oxides and accessory titanite and apatite and sometimes even quartz [7]. The sill can be classified as a monzodiorite.



Figure 8: Anços Sill.

3 Fieldwork - Sampling and Methods

In this section we present the materials and procedure to collect samples in the field. This field work was made by us for the case of the Água de Madeiros section. Samples from Anços sill were collected in previous years by others.

Materials:

- Gasoline-powered rock diamagnetic drill
- Water pump
- Magnetic compass
- Measuring tape
- Acetate pen
- Wire to remove samples

Procedure:

1. Define the geological limit (see Figure 7) and start sampling.
2. Use the water pump and the gasoline-powered rock diamagnetic drill perpendicular to the rock to mark the spot where you want to remove samples. The rock will be marked with a circumference.
3. About at half the circumference cut the rock to get a sample. (Figure 9a)
4. Draw a vertical line on the visible part of the sample with the acetate pen.
5. Remove the sample from the rock. If necessary, use a wire.
6. Use the magnetic compass in the place you removed the sample to orient it: declination and inclination (Figure 9b).
7. Mark the sample to identify the top: on the surface with a vertical line, draw a quarter the circumference to the left, starting from the bottom. From this point, draw a vertical line along the height of the cylinder and make small arrows directed to the top on one side of the line. On the other side of the line draw a diagonal line, starting from the top.
8. Identify the sample: write on it its name at least in three places, along the length of the sample (Figure 9c).
9. Repeat the process to get as many samples as you want, below (identify as AM1) and above (identify as AM2) the limit defined in Point 1. Use the measuring tape to determine the height between the geological limit and the new place where the sample is being collected.



(a) Collecting a sample below the geological limit.



(b) Orientation of the sample: declination and inclination .



(c) Identification of the sample: lines, arrows and its name.

Figure 9: Fieldwork - sampling, orientation and identification of each sample

4 Laboratory work - Data Processing and Methods

In this section we present the materials and procedure to cut Água de Madeiros' samples into standard paleomagnetic specimens. We also present the methods used to analyse the Água de Madeiros' and Anços' specimens.

4.1 Cutting samples into specimens

In this subsection we present the materials and procedure to cut Água de Madeiros' samples into standard paleomagnetic specimens (2.2 cm). Every sample has a cylindrical shape because it has the best approach to the spherical shape, which is considered in theoretical models.

Materials:

- Vernier caliper
- Water
- Electric saw with two discs separated by 2.2 cm

Procedure:

1. Measure samples with standard sizes of paleomagnetic specimens, with vernier caliper.
2. Put water in a container in contact with the two discs of the electric saw so the system does not heat when it is working (Figure 10a).
3. Cut samples with electric saw. This turns on when we press the pedal with a foot (Figure 10b).
4. Repeat the process to cut all the collected samples. Every time you change sample, you need to put the pedal under the table to ensure that the electric saw will not cut your fingers.



(a) Sample about to be cut.



(b) Cutting a sample.

Figure 10: Cutting samples in standard sizes of paleomagnetic specimens.

4.2 Data processing

In this subsection we present the materials and procedure to analyse the specimens. Our group analysed 3 specimens: one from the Água de Madeiros section (AM1-A5) and two from the Anços sill (AN2-N1 and AN2-V1).

Materials:

- Rema6W Software
- Dual Spinner Magnetometer JR-6A
- Calibration cylinder to the magnetometer (7.94 uT, 6.32 A/m, 11.15 ccm)
- AF Demagnetizer LDA-3A
- Cellophane
- Anisoft 42 Software
- Safyr4W Software
- Susceptibility measurer Multi-function Kappabridge MFK1-FA
- Calibration cylinder (89.82E-03 – 22.88E-03) to the susceptibility measurer.

Procedure:

To measure specimens' magnetization:

1. Start Rema6W software and in *Instrument control* choose the options: *GO ONLINE*, *Normal time*.
2. Use the calibration cylinder (Figure 11a) to calibrate the magnetometer (Figure 11b). Choose options: *Run*, *Calibration*.
3. Identify name, declination, inclination and volume (11.15 cm³) of the specimen you are about to use. Choose $P1 = 12$, $P2 = 0$, $P3 = 12$, $P4 = 0$.
4. Measure the Natural Remanent Magnetization (NRM) with the magnetometer, in the four different orientations (see the pictures in Rema6).
5. Wrap the specimen in cellophane. This way, if it breaks within the demagnetizer it is easier to remove it.
6. Use the demagnetizer (Figure 11c) so the specimen can pass through several magnetic states: 2, 4, 6, 8, 12, 15, 20, 25, 30, 40, 50, 60, 80 e 100 mT. Use parameters: *Field*: choose one of the fields above, start from beginning and follow the order; *Time*: 20 s; *Rate dec*: Medium; *Rate inc*: Medium; *Slope*: Linear. Then press *Start/Stop* button.
7. Measure magnetization in the four different orientations. Then save data and select *New State*.
8. Repeat point 6. with a new magnetic state and then repeat point 7. until you complete all the possible states.



(a) Calibration cylinder.



(b) Magnetometer.



(c) Demagnetizer.

Figure 11: Materials used to measure specimens' magnetization.

To measure the magnetic susceptibility:

9. Create a geological file. Use Anisoft 42 and choose options *File, New, Geological file: Site name: AM; Latitude: 39°44.467; Longitude: 9°2.383; P1 = 12, P2 = 0, P3 = 12, P4 = 0*. Save with the name of the specimen and the group.
10. Use the Safyr4W Software to measure susceptibility.
11. Calibrate the susceptibility measurer (Figure 12a) with the calibration cylinder (Figure 12b). Press *Initialize, OK* to remove coil deviations and *Execute, Calibration, Start*. Then save and press *OK*.
12. Make the Holder Correction without the calibration cylinder. Press *Execute, Holder Correction, SAVE*.
13. To determine magnetic susceptibility choose *File, Open data file* and select the file previously created with Anisoft 42 Software.
14. Put the specimen in the susceptibility measurer in the three different orientations to measure the three axis (Figure 13).
15. Calculate total susceptibility in any orientation and press *TOTAL SUSC*.
16. Save the data in the correspondent file.



(a) Susceptibility measurer.



(b) Calibration with the cylinder.

Figure 12: Materials used to measure specimens' magnetic susceptibility.



(a) First position.



(b) Second position.



(c) Third position.

Figure 13: Three different orientations to measure the susceptibility in the three axis.

5 Data analysis

In this section we present the methods used to analyse the data obtained in the laboratory.

Materials:

- Remasoft 3.0 Software
- Super IAPD 2000 Software
- GMAP2012

Procedure:

To calculate mean poles:

1. Start Remasoft to find vectors to poles.
2. Choose the best data points, the ones which are logical and minimized MAD, to get the vectors. Choose options *include ORIGIN* and *Anchor to last point*.
3. Save *C1* component with *APPEND TO FILE* option.
4. Analyse *C1* component in *Group Statistics*.
5. Insert field coordinates.
6. Get results from two types of coordinates: Geographical and Tilted. Each time you switch the coordinates, you need to click on *RECALCULATE* button.
7. Repeat the procedure with the Anços (AN) samples.

To compare AM and AN poles with known poles

8. Start Super IAPD to compare our pole with known poles. Add information of AM mean pole and the known poles in the rows.
9. Repeat the procedure with the AN samples.

To compare AN pole with the Iberia Apparent Polar Wander Path (APWP)

10. Start GMAP2012.
11. In VGP open the file *Iberian mean poles.vgp* that contains the medium poles for Iberian Plate for eight time periods.
12. In table add the coordinates of the obtained pole for comparison.
13. Click *Draw* and choose the best projection.

6 Joint presentation of results and discussion

6.1 Água de Madeiros

We started our analysis of the 28 specimens from the Água de Madeiros section with Remasoft aiming to find a mean pole. This software uses principal component analysis and Fisher statistics.

We tried to find vectors for each $C1$ principal component of each specimen (one example can be seen in Figure 14, for AM2D3). We dismissed 10 specimens since they were very difficult to analyse or did not present stable demagnetization patterns (one example is in Figure 15). So only 18 specimens were considered.

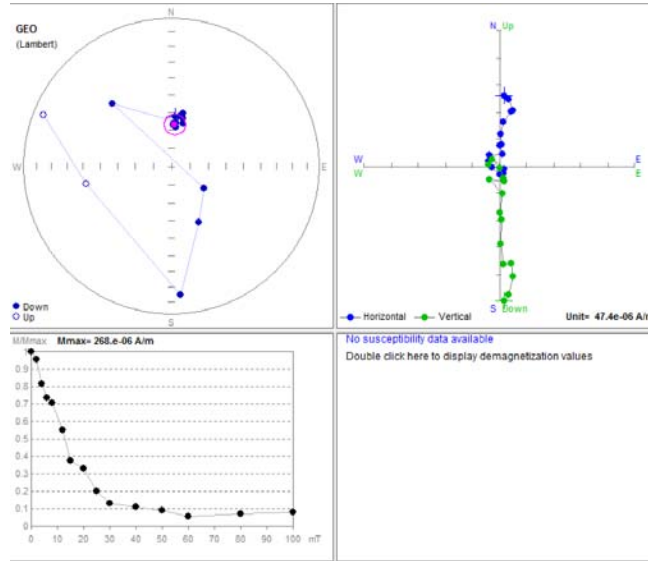


Figure 14: AM2D3 specimen. This present a stable magnetization pattern.

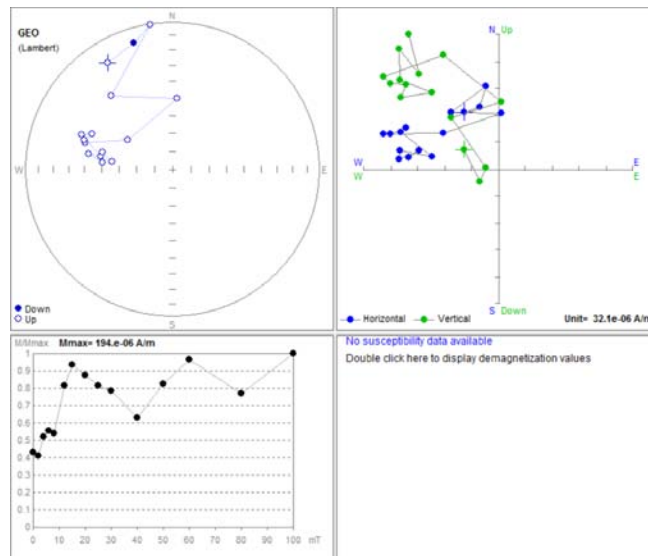


Figure 15: AM1K3 specimen. This do not present a stable demagnetization pattern.

Coordinates	Number of points	D (°)	I (°)	Pole Lat (°)	Pole Long (°)	R	k	A95 (°)
In situ	18	14.8	56.4	78.1	89.7	16.93	15.94	8.9
Tilted	18	341.7	51.2	73.3	-121.3	16.93	15.94	8.9

Table 1: Água de Madeiros Mean Poles: differences between geographical and tilted coordinates. D, I, Pole Lat and Pole Long stands for Declination, Inclination, Pole Latitude and Pole Longitude, respectively.

By analysing our demagnetization curves we observed that our samples have a remanent coercivity (H_{cr}) that goes from 5 mT to values inferior to 20 mT. This indicates that our samples have a very low coercivity thus they have a very low relaxation time and are easily remagnetized.

When we analysed the $C1$ component in *Group Statistics* we got two results with different types of coordinates: Geographical (or in situ – Figure 16a) and Tilted (Figure 16b). The results are in Table 1.

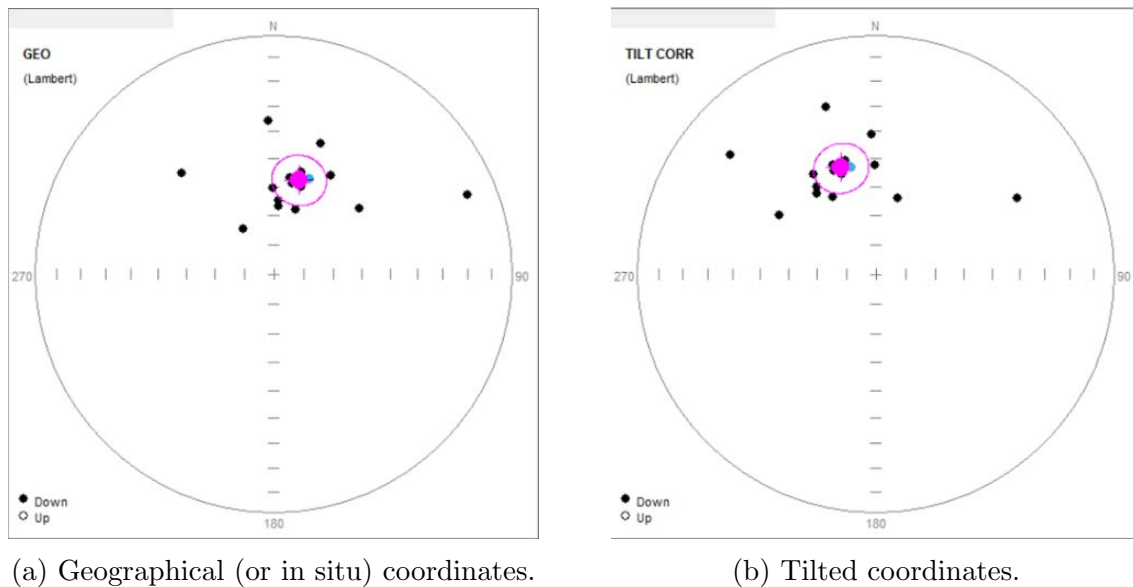


Figure 16: Mean pole for AM - geographical (or in situ) and tilted coordinates. Value in blue is the one that our group obtained in laboratory.

The big question now is: what is the age of magnetization of the sediments? Is it contemporary to the deposition of the sediments or was it remagnetized throughout its history?

To try answer this question we compared our results with some of the known and well dated poles of the Iberian plate (see Table 2) with the software Super IAPD.

For the comparison between known poles and AM pole, we took in account that if the magnetization was prior to the inclination of the section we need to consider the pole obtained with tilt correction, but if the sediments were remagnetized after the inclination we need to consider the non-corrected pole. Since we do not know this we analysed both cases.

Formation	Age (My)	Declination (°)	Inclination (°)	A95 (°)
Present Day Field (2015 – WMM model)	-	-2.7224	54.1358	-
Present Day Field (2011 – IGRF model)	-	-3.3864	53.1775	-
Sintra Granites	80	359.0	43.5	5
Paço de Ilhas sill	88	350.0	42.2	1.4
Foz da Fonte sill	94	346.0	44.3	3.1
Organya Basin - Col d’Abella	108	356.0	48.1	2.7
Algarve Limestones	145	328.0	45.9	3.9
Messejana Plasencia Dyke	200	341.0	46.3	3.3

Table 2: Information of known poles: present day field (2015 for AM and 2011 for AN), Sintra Granites, Paço de Ilhas sill, Foz da Fonte sill, Organya Basin - Col d’Abella, Algarve Limestones and Messejana Plasencia Dyke.

When there is no overlap of the alpha95, the distributions are statistically different, thus, the poles do not have the same age. If there is overlap it means that the poles could share the same age.

Água de Madeiros comprises the Sinemurian–Pliensbachian limit, which has about 190 My. So we started by comparing our obtained pole with poles dated around this age. We plotted our mean pole and compared it with Messejana Plasencia Dyke Pole (see Table 2), dated at 200 My [15]. For this comparison we consider the pole with tilt correction (Figure 16b).

Since there is an overlap of the alpha95 between this two poles, i.e., the Messejana pole is inside AM A95 interval and vice versa, we can assume that our magnetization is primary. But this overlap can be fortuitous, because we did not find magnetic reversions in Água de Madeiros’ samples, above and under the geological limit (AM1 and AM2), opposite to what should be expected in this limit. Thus, the rocks were probably remagnetized.

Therefore we went to try to understand what could possibly have remagnetized the rocks. It could be due to cretaceous hydrothermal fluids or the current field.

To evaluate this hypothesis we compared our pole with Paços de Ilhas (88 My) and Foz da Fonte (94 My) poles (see Table 2), obtained by [14], and with the Present Day Field obtained from NOAA [16]. We also test it with other ages: we plotted the Organya Basin – Col d’Abella pole (108 My) and Algarve Limestones pole (145 My), taken from a compilation found in [14].

Observing the Figure 17b, where we consider that the magnetization was prior to the deformation of the sediments, we see that AM pole A95 interval overlaps all the poles we plotted, for the exception of the Paço de Ilhas sill pole. Therefore we cannot draw any conclusion from this analysis. By considering that the sediments were remagnetized after the deformation (Figure 17a) we see that AM pole A95 interval overlaps the Present Day Field (2015). So we can assume that the Água de Madeiros section was probably remagnetized by the current magnetic field. This a plausible explanation when taking into account the very low coercivity of the samples.

The obtained pole does not even have a quality factor, Q , of 1 since it was most probably remagnetized by the Present Day Field and does not fulfil the criteria of presumption that the magnetization has the same age as the rock.

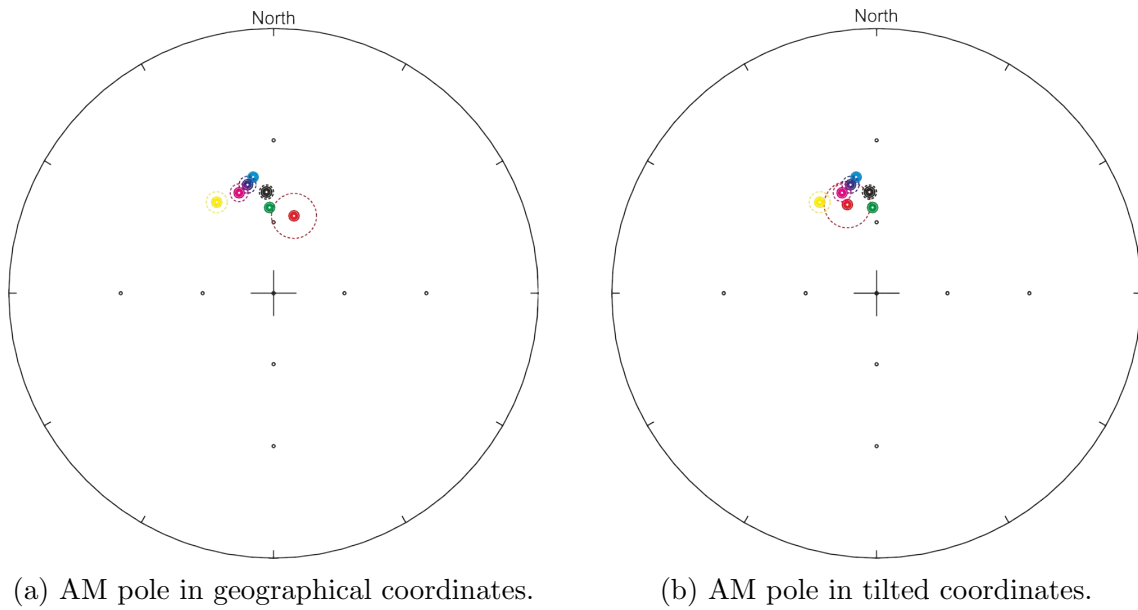


Figure 17: Comparison between mean pole for AM (Red) in geographical (left) and tilted coordinates (right), and known poles: Light Blue - Paço de Ilhas, 88 My; Dark Blue - Foz da Fonte, 94 My; Green - Present Day pole (2015); Pink - Messejana Plasencia Dyke, 200 My; Black - Col d'Abella, 108 My; Yellow - Algarve Limestones, 145 My.

6.2 Anços

We analysed 7 specimens from the Anços sill with Remasoft aiming to find a mean pole. We considered all the specimens since all presented stable demagnetization patterns and we were able to find the principal component. One example can be seen in Figure 18.

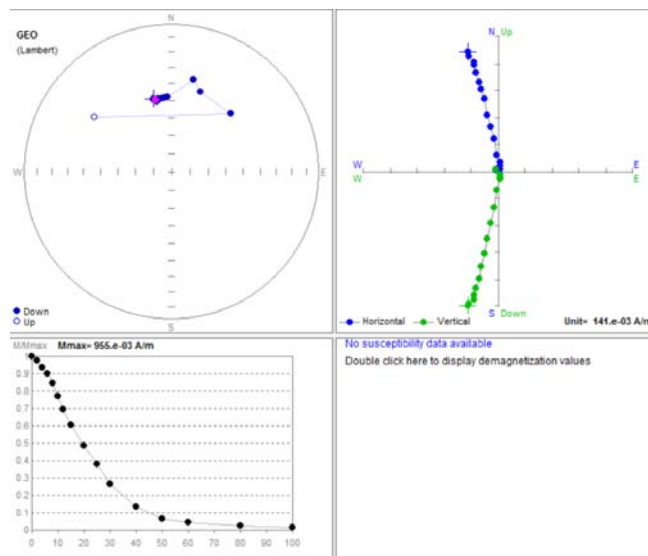


Figure 18: AN2M3 specimen. This present a stable demagnetization pattern.

By analysing our demagnetization curves we observed that our samples have a remanent coercivity (H_{cr}) around 20 mT. This indicates that our samples have a low coercivity.

Then we tried to find vectors for each *C1* principal component, and analysed this in *Group Statistics*. The mean pole (Figure 19) has a high value of A95 probably due to the low number of specimens that we analysed. The result is in Table 3.

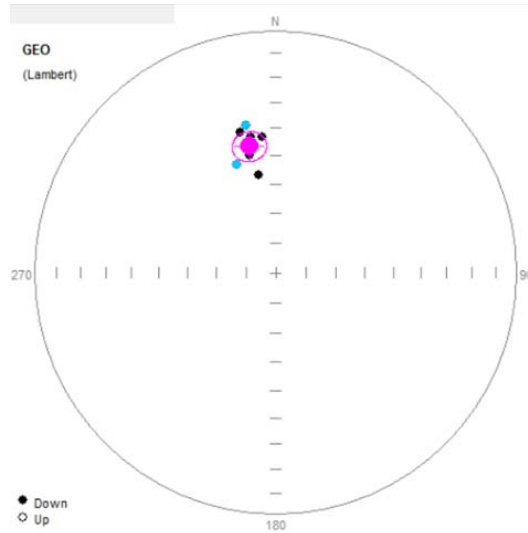


Figure 19: AN mean pole. Values in blue are the ones that our group obtained in laboratory.

Number of points	D (°)	I (°)	Pole Lat (°)	Pole Long (°)	R	k	A95
7	348.0	45.6	74.5	-145.6	6.95	125.63	5.4

Table 3: Anços Mean Pole. D, I, Pole Lat and Pole Long stands for Declination, Inclination, Pole Latitude and Pole Longitude, respectively.

Again we compared our result with some known and well dated poles of the Iberian plate with the software Super IAPD, to try to find the age of the magnetization. Since the sill has been dated at 72 My [7], we started by compare it with the poles of the and Present Day Field - 2011, Sintra Granites, Paço de Ilhas sill, Foz da Fonte sill and Col d’Abella (see Table 2 for informations). The result can be seen in Figure 20.

The pole we obtained does not contain the Present Day Field - 2011 in the A95 interval, so we can conclude that our samples were not remagnetized by the present geomagnetic field (2011). The pole contains the Paço de Ilhas sill (PI) and Foz da Fonte sill (FF) poles and these poles also contain in their A95 intervals the AN pole. So according to the statistic the AN pole shares the same direction as PI and FF poles at 95%.

We also compared the pole with the Sintra Granites pole (80 My) and the Organya Basin – Col d’Abella pole (108 My). The AN A95 interval contains the Cola d’Abella pole and there are also an overlap with the A95 interval of the Sintra Granites pole.

So from our analysis we can conclude that the pole we obtained is in the 80 - 108 My period with a strong statistical evidence that is in the period of 88 - 94 My, different from the 72 My of its own formation.

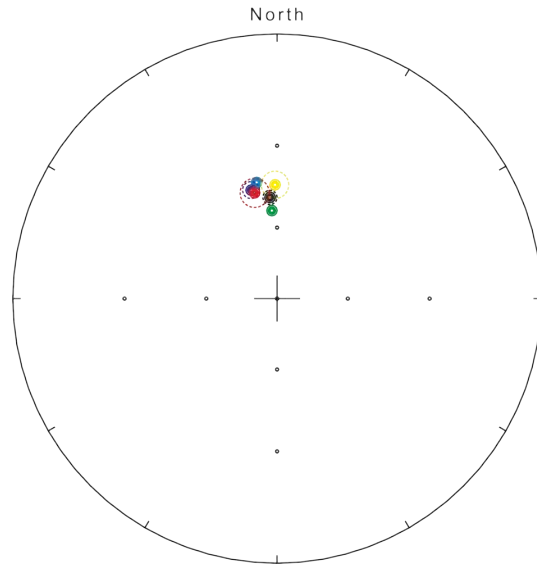


Figure 20: AN mean pole (Red) and comparison with known poles: Green - Present Day pole - 2011; Yellow - Sintra Granites, 80 My Light Blue - Paço de Ilhas, 88 My; Dark Blue - Foz da Fonte, 94 My; Black - Col d'Abella 108 My.

Further analysis of more samples would be necessary to elucidate this possibilities. The pole obtained could only obtain a quality factor $Q = 1$ if its age is confirmed to be contemporary of the sill formation and to achieve more criterias more samples are needed.

By using GMAP we compared our pole with the APWP for the 203 - 70 My time period (Figure 21).

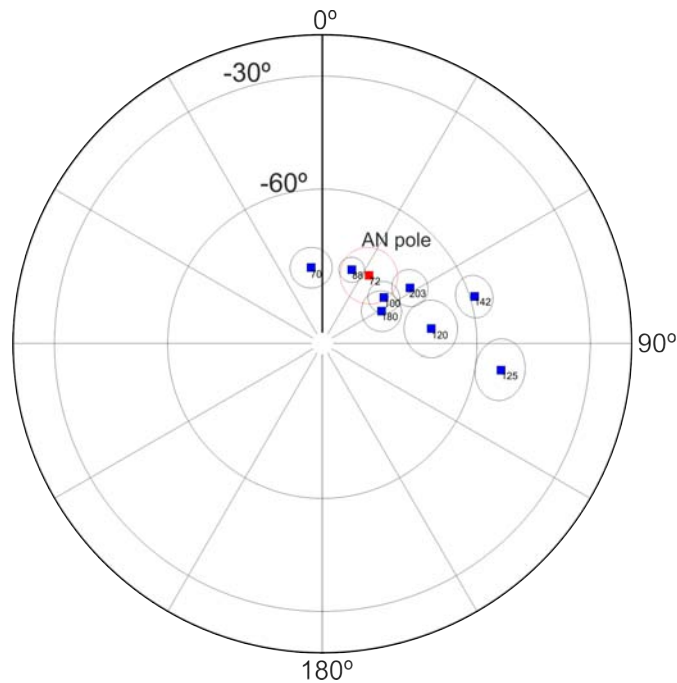


Figure 21: Comparison between AN (Red) pole and APWP (Blue) for the 203 - 70 My time period. Orthogonal Projection. It should be noted that GMAP plots the poles in the South Hemisphere.

The pole obtained for the Anços sill is between and contains the mean poles of 88 and 100 My. This further confirms our conclusion that the pole is in the 80 - 108 My time period. The pole is also seen to be far from the 70 My mean pole and does not even contain its A95 interval: this may indicate that the magnetization is prior to the datation of the sill. So there might have been a problem with our samples or the datation of the sill is not correct, since samples cannot be remagnetized by a Geomagnetic Field prior to their own formation, or the samples were remagnetized by a Geomagnetic Field similar to the field of the 80 - 108 My period.

6.3 Magnetic susceptibility of AM and AN samples

In the laboratory work we also measured the susceptibility of the rocks. The results are shown in Table 4.

Specimen	χ	Error (%)	T	Ellipsoid
AM1A5	-1.89E-07	7.6514	0.474	Oblate
AM2F1	-5.80E-06	0.5526	-0.337	Prolate
AM2F1	-6.006E-06	0.8281	0.007	Oblate
AM2D4	-2.84E-06	8.1345	0.054	Oblate
AM2I3	-1.60E-06	2.3813	0.130	Oblate
AN2N1	1.89E-02	0.0023	0.376	Oblate
AN2V1	2.41E-02	0.0137	0.502	Oblate
AN2U2	2.22E-02	0.0047	0.645	Oblate
AN2X2	2.64E-02	0.0017	0.428	Oblate
AN2M3	1.30E-02	0.0005	0.439	Oblate
AN2M1	1.25E-02	0.0115	0.918	Oblate
AN2R3	2.23E-02	0.0043	0.531	Oblate

Table 4: Magnetic susceptibility, χ , and shape parameter, T , of AM and AN specimens.

As we can see, magnetic susceptibility of the AM samples is very low, which is expected for sediments, that are nearly transparent to magnetism. This fact corroborates the idea that AM section was remagnetized.

AN samples present positive and higher values of magnetic susceptibility, which means it is easier to these rocks maintain the magnetization acquired during sill cooling. This idea indicates that the magnetization can be primary, but more tests are needed to understand the problem around datation and magnetization of the sill.

7 Conclusions

With this work we obtained a mean paleomagnetic pole for Água de Madeiros Section (Table 1). The Section was probably remagnetized after its formation with the Present Day Field, but it also overlaps with several other poles. For this reason, the pole does not even obtain a quality of $Q = 1$. Besides, these rocks present low values of magnetic susceptibility and a diamagnetic behavior, which corroborates the idea of remagnetization.

We also obtain a mean paleomagnetic pole for the Anços sill (Table 3). The pole corresponds to the time period of 80 - 108 My. It is necessary an analysis of more samples to improve the obtained values. With the analysis in GMAP we can also put the possibility that could have been a problem with our samples on laboratory analysis, that the datation of the sill is not correct or even that the samples were remagnetized by a Geomagnetic Field similar to the field of a period prior to the sill cooling, e.g. an artificial magnetic field acquired during sampling or data processing.

7.1 Difficulties throughout the work

We had some difficulties in the laboratory work during the data processing because the magnetizer had a small breakdown in the middle of measurements, but this problem was solved fastly.

References

- [1] R. Butler, *Paleomagnetism: Magnetic Domains to Geologic Terranes*. Blackwell Scientific Publications, 1992.
- [2] J. M. Miranda, *Introdução ao Geomagnetismo*. Aulas de Geomagnetismo do Departamento de Engenharia Geográfica, Geofísica e Energia da Faculdade de Ciências da Universidade de Lisboa, 2009.
- [3] “Elements of the geomagnetic field – istituto nazionale di geofisica e vulcanologia - roma2 department.” http://roma2.rm.ingv.it/en/research_areas/1/earth-s_magnetic_field/8/elements_of_the_geomagnetic_field, 2015.
- [4] “Trabalhos práticos em magnetismo de rocha – disciplina de geomagnetismo.” Laboratório de Paleomagnetismo e Magnetismo de Rocha, Prof. Eric Font.
- [5] “Aula de geomagnetismo – cap 2. campo magnético crustal.” DEGGE–FCUL, Prof. Eric Font, 2015.
- [6] R. Dias, A. Araújo, P. Terrinha, and J. C. e. Kullberg, *Geologia de Portugal. Vol. II: Geologia Meso-cenozóica de Portugal*. Lisboa: Escolar Editora, p. 798 p., 2013.
- [7] R. Miranda, “Petrogenesis and geochronology of the late cretaceous alkaline magmatism in the west iberian margin,” *Ph.D. thesis, Universidade de Lisboa*, 2010.
- [8] M. Antunes, R. Rocha, and S. Wenz, “Faunule ichtyologique du lias inférieur de são pedro de moel, portugal,” *Ciências da Terra 6*, 101-116, 1981.
- [9] L. V. Duarte, M. José Comas-Rengifo, R. L. Silva, R. Paredes, and A. Goy, “Carbon stable isotopes and ammonite biochronostratigraphy across the sinemurian-pliensbachian boundary in the lusitanian basin, portugal,” *EGU General Assembly 2014, held 27 April - 2 May, 2014 in Vienna, Austria, id.2011*, 05/2014.
- [10] C. Meister, J. Dommergues, and R. Rocha, “Ammonites from the apoderoceras beds (early pliensbachian) in são pedro de muel (lusitanian basin, portugal),” *Bulletin of Geosciences 87(3)*, 407-430, 2012.
- [11] M. Neres, “Magnetic studies of the late cretaceous magmatism in portugal: from iberian plate kinematics to magnetic fabrics,” *Ph.D. thesis, Universidade de Lisboa and Université de Toulouse*, 2013.
- [12] A. C. Azerêdo, R. L. Silva, L. V. Duarte, and M. C. Cabral, “Subtidal stromatolites from the sinemurian of the lusitanian basin (portugal),” *Springer*, 2009.
- [13] R. Mouterde, “Le lias moyen de s. pedro de muel (portugal),” *Comunicações dos Serviços Geológicos de Portugal 52*, 185–208, 1967.
- [14] M. Neres, E. Font, J. M. Miranda, P. Camps, P. Terrinha, and J. Mirão, “Reconciling cretaceous paleomagnetic and marine magnetic data for iberia: New iberian paleomagnetic poles,” *J. Geophys. Res.*, 117, B06102, doi:10.1029/2011JB009067., 2012.

- [15] J. M. Cebriá, J. López-Ruiz, M. Doblas, L. T. Martins, and J. Munha, “Geochemistry of the early jurassic messejana–plasencia dyke (portugal–spain); implications on the origin of the central atlantic magmatic province,” *J. Petrology* (2003) 44 (3): 547-568 doi:10.1093/petrology/44.3.547, 2003.
- [16] “Magnetic field calculators – noaa - national oceanic and atmospheric administration.” <http://www.ngdc.noaa.gov/geomag-web/#igrfwmm>, 2015.