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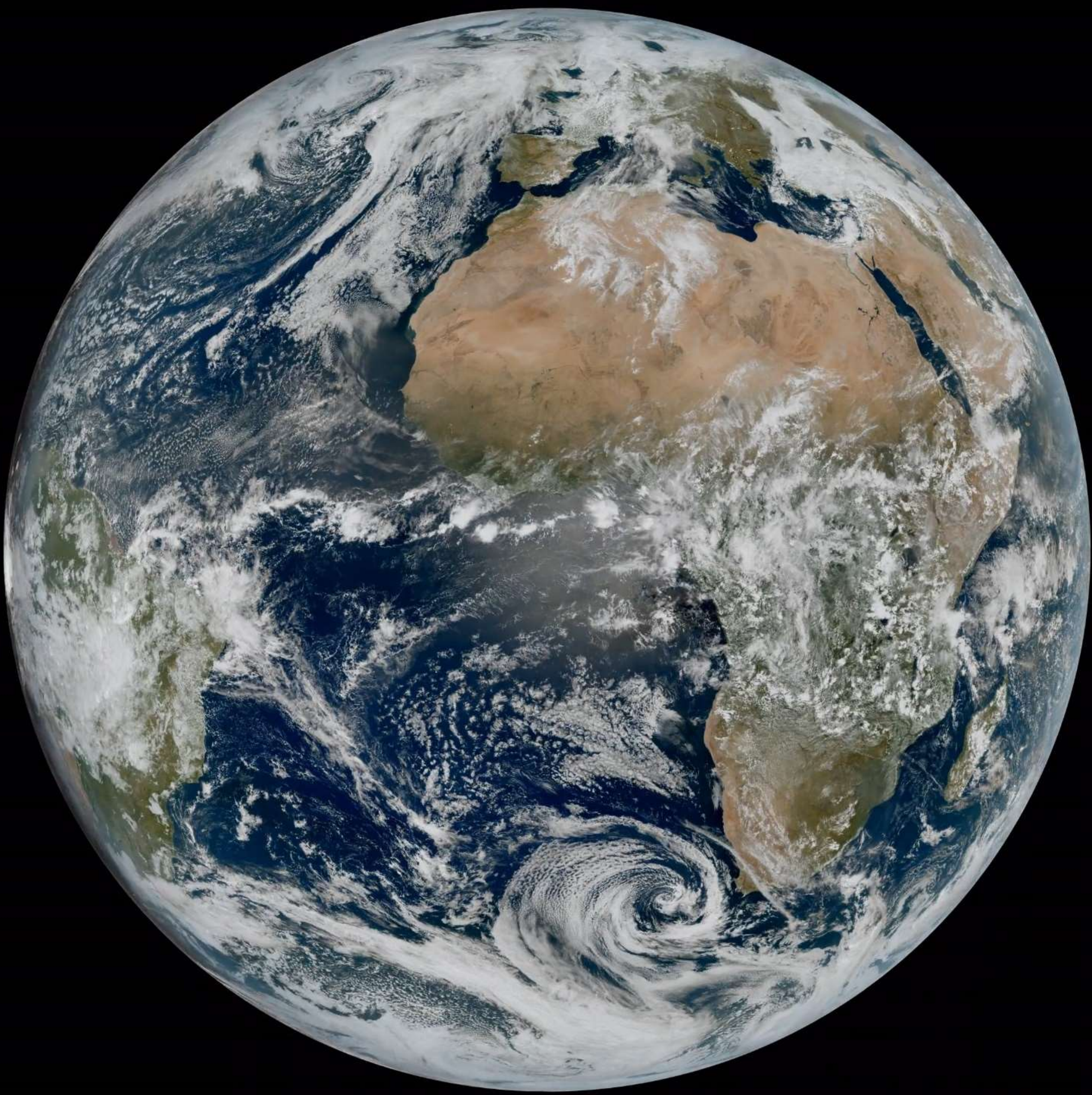

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Density Variations, Thermodynamic Properties and Earthquakes in the Horseshoe Basin

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SUMMARY

This work considers the hypothesis of heating of materials and water in the Region of the Bank of Gorringe and Horseshoe Basin before the earthquake of February 28, 1969. For this purpose, data from the magnetic field obtained in Magnetic Observatories of the Iberian Peninsula were analysed, and anomalies were observed, including strong variations in the magnetic declination. A simple model was used to obtain the effect of heating two different media (peridotite and gabbro) in physical contact, with different thermal and mechanical properties. The results include compression of peridotite by gabbro and shear stresses in the contact of the two materials.

Keywords: Geoid height; magnetic anomalies; thermal properties; mechanical properties, thermal stresses.

1. Introduction

In the early morning of February 28 in 1969, a seismic crisis began with epicentres located in the SW of Cabo de São Vicente (Portugal). In a time interval of less than three hours, five earthquakes of magnitude 8, 5.6, 3.9, 4.4 and 3.8 were registered by seismic stations. The events mentioned caused 13 deaths and considerable damage. On that day, a total of 32 seismic events occurring in the region were registered by seismic observatories (Pena et al, 2014).

Some answers to surveys carried out after the earthquake of February 28 include descriptions of phenomena that may be associated with changes in the terrestrial magnetic field. This work analyses data registered 54 years ago. Geoid height data with models from 1984, 1996 and 2008 are also used.

2. Geoid Height values

Geoid height values for the region were obtained using EGM models 1984, 1996 and 2008. The results obtained for latitude values 36.00°N and 36.36°N can be seen in **Figure 1a** and **Figure 1b**.

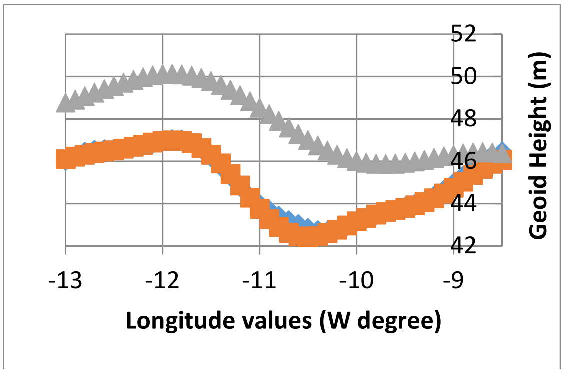

Figure 1a. Geoid height values were obtained for latitude 36°N- green-1984, red-1996 and blue-2008.

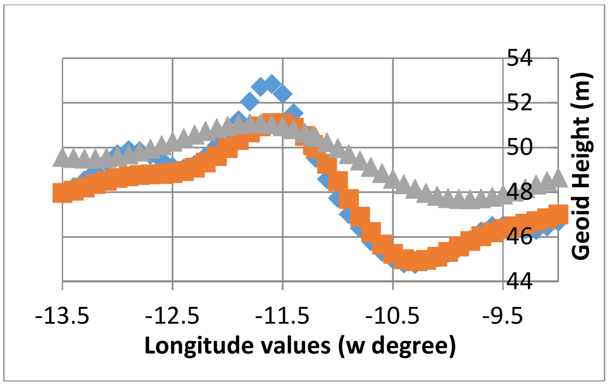

Figure 1b. Geoid height values were obtained for latitude 36.36°N- green-1984, red-1996 and blue-2008.

Figure 1a shows clearly that values decrease in all longitude values from 1984 to 1996 but the values change with longitude. An increase is visible in longitude values from -10.4° to -11.0° in 2008 (blue points).
An increase in geoid height values is seen in **Figure 1b** for longitude values from -11.3° to -12.0° in 2008 (blue points). It is possible to see also that values decrease in all longitude values from 1984 to 1996. The decreasing value changes with longitude in both latitudes. The greatest values are obtained in **Figure 1a** (≈5 m) between longitude values -10.5° and -11.0°.
The changes found in geoid height values at latitude 36.00°N are difficult to explain, particularly the blue points between -10.4° and -11.0°. A possible explanation for density alteration is temperature changes in the region.

3. The geomagnetic field

Magnetic field data used in this work were obtained from Geomagnetic Observatories located in the Iberian Peninsula and the Canary Islands. The data consist of average time values of the horizontal and vertical components of the magnetic field and the magnetic declination, recorded at the Observatories and inserted in Annales of the years 1969 and 1968.

3.1. The year 1969

Figure 2a shows the average monthly values of the horizontal component of the geomagnetic field measured in the Coimbra Geomagnetic Observatory during the year 1969 (blue points). Orange points show the values obtained using the IGRF model for Coimbra in the year 1969.

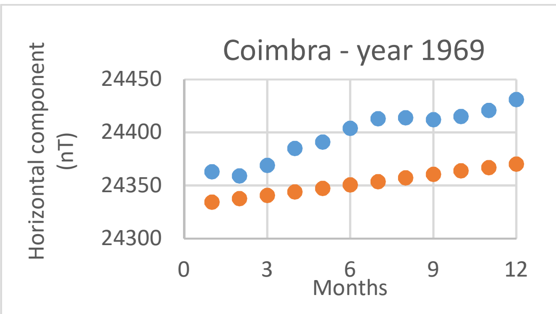

Figure 2a. Average monthly values of the horizontal component measured in Coimbra Observatory (blue points) and values obtained with the IGRF Model (red points).

It is possible to see that the values measured are higher than the values obtained with the model IGRF. February is the month with a value near that obtained with the model.
Figure 2b shows identical anomalies to those observed in Coimbra. In this case, the data were obtained in Toledo Observatory from July 1968 to June 1969. The anomalies of the horizontal component of the geomagnetic field are present in all data presented. November 1968 is the month with a value close to the value obtained with the IGRF model. February 1969 is also a value close to that obtained with the IGRF model.

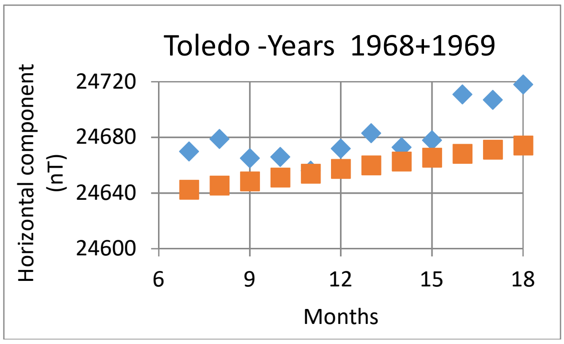

Figure 2b. Average monthly values of the horizontal component measured in Toledo Observatory from July 1968 to June 1969 (blue points) and values obtained with the IGRF Model (red points).

Table I shows the values of the horizontal component of the geomagnetic field measured in February 1969 in different observatories and the values obtained with the IGRF model. Only in one station (Tenerife), the value measured is lower than the value obtained with the IGRF model.

Table I. Values of the horizontal component of the geomagnetic field in May 1969. Dif is the difference between the values measured and modelled by the IGRF model.

Observatory	Measured	IGRF	Dif
Coimbra	24391	24352	39
Toledo	24707	24655	52
San Fer.	26406	26205	201
Almeria	26289	26249	40
Tenerife	28762	29160	-398

The analysis of the values measured in February 1969 shows that the lower value of the horizontal component of the geomagnetic field is associated with three strong anomalies that occurred in that month. In November 1968 a strong anomaly occurred at the end of October and the first days of November.

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3.2. February and May 1969

Seismic records show the occurrence of earthquakes of high magnitude on 28 February (M=7.9) and 5 May (M=5.4) in 1969. **Figure 3a** shows hourly average values of the horizontal component of the geomagnetic field in a time interval from February 25 to February 27 (blue points). Red points are average values obtained on quiet days registered by the Observatory. It is possible to identify some hours with increased values (blue points) of the geomagnetic data. **Figure 3b** shows the same type of data obtained for the time interval from May 3 to May 5. In this case, the positive anomalies are present in the three days studied but the increase is lower than in February. The negative anomaly found on February 27 is not visible in May.

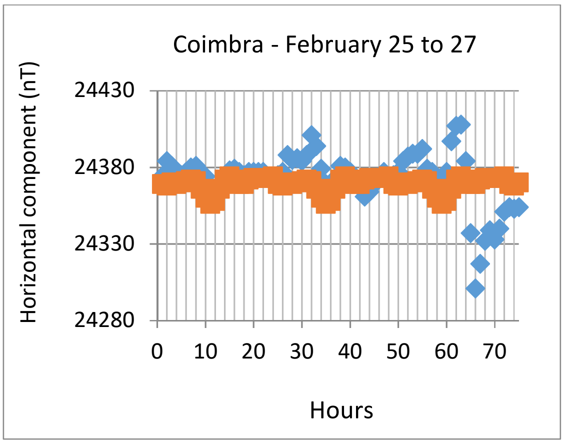

Figure 3a. Average hourly values of the horizontal component o the geomagnetic field (blue points). Average values for quiet days (red points).

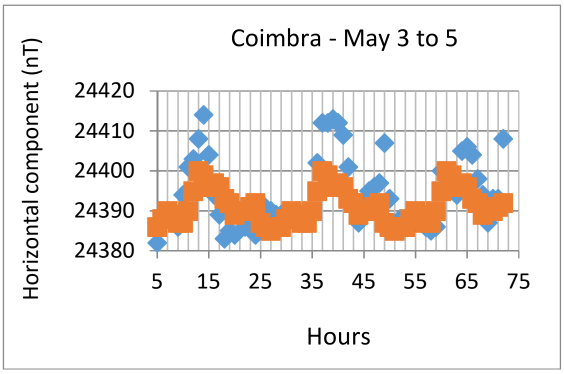

Figure 3b. Average hourly values of the horizontal component of the geomagnetic field (blue points). Average values for quiet days (red points).

The vertical component of the geomagnetic field shows lower values than those obtained on quiet days on February 25, 26 and in the morning of 27. A strong positive anomaly appears only on February 27 (**Figure 4a**) with the maximum values at hour 18. Small anomalies occurring in small time intervals may be seen in **Figure 4b**.

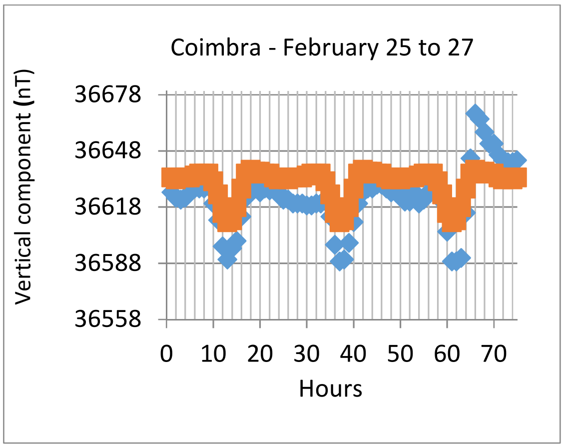

Figure 4a. Average hourly values of the vertical component of the geomagnetic field (blue points). Average values for quiet days (red points).

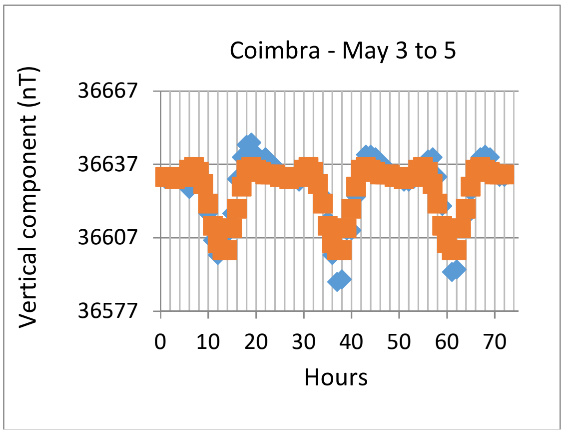

Figure 4b. Average hourly values of the vertical component of the geomagnetic field (blue points). Average values for quiet days (red points).

The inclination of the magnetic field in **Figure 5a** (25 to 27 February) is lower than the average values found on quiet days. An exception is found on day 27 with a strong positive anomaly. In the last days of February 1969, the horizontal component of the geomagnetic field was higher than the values measured in quiet days, but the vertical component and the inclination of the geomagnetic field are lower than the values obtained in quiet days. On the afternoon of day 27, a positive anomaly occurred in the vertical component and the inclination of the field. This type of anomaly was not observed on May 3 to 5 (**Figure 5b**).

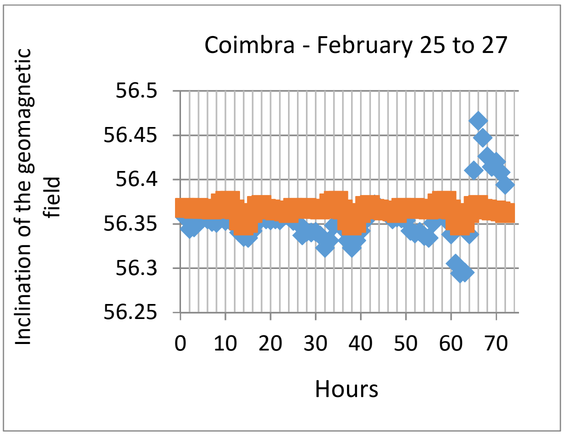

Figure 5a. Average hourly values of inclination of the geomagnetic field (blue points). Average values for quiet days (red points).

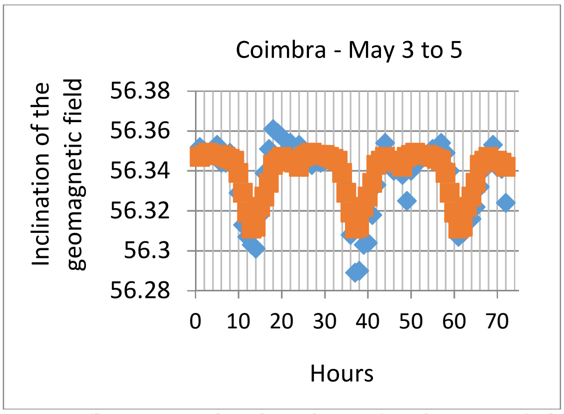

Figure 5b. Average hourly values of inclination of the geomagnetic field (blue points). Average values for quiet days (red points).

4. Thermodynamic properties

The variations found in geoid height values in the Horseshoe Bain and the Gorringe Bank suggest heating episodes separated from time intervals with decreasing temperatures.

It is thought that in the region referred the main type of formations are peridotites with intercalations of gabbros. These types of rocks show different thermal and mechanical properties when subjected to the same heat source.

A study considering a body formed by two different materials with the same volume but with different thermal properties heated by the same heat source was made (Duque, 2023). **Table II** presents the main properties of the constituent materials of the body.

In the initial state, the temperature of the two materials is equal. T_0=10°C. The two materials will be heated simultaneously. Because they have different densities and specific heat capacity values, the temperature increase will be different in both materials. T_{1A}=45°C, T_{1B}=89.7°C≈90°C.

Table II. Some properties of the structure studied.

	Material A	Material B
Density	3200 kg m^{-3}	3000 kg m^{-3}
Specific heat	1.26 $KJ.kg^{-1}.K^{-1}$	0.59 KJ kg^{-1} K^{-1}
Thermal expansion coefficient	3.5×10^{-5} K^{-1}	4.8×10^{-5} K^{-1}

The temperature difference between the two materials originates temperature gradients and heat flow by conduction in the horizontal direction. The horizontal flow of heat near the border between the two materials must be equal. Using the Fourier law, we will have

$$\text{Grad } T_A.K_A = \text{Grad } T_B.K_B \qquad (1)$$

Using as thermal conductivity values, K_A =4.0 W.K^{-1}.m^{-1} (peridotite rock) and K_B = 2.3 W.K^{-1}.m^{-1} (gabbro rock) it is possible to obtain the temperature value in the contact zone of the two materials, T_{in}=61.4°C. **Table III** contains temperature values obtained in materials A and B and the contact zone after different intervals of heating, considering constant values of C_p, mass, and thermal conductivity.

Table III. Temperature values in materials A and B and the contact zone of the two materials.

T_A (°C)	T_B (°C)	T_{in} (°C)
45	90	61
80	170	113
106	231	152
200	443	289
316	707	459

The values of this Table show that the difference between the temperature values of materials A and B increases with the increase in temperature values. The thermal gradient near the contact zone of the two materials is higher in material B than in material A.

Due to the increase in temperature, the materials will tend to expand. If they are confined, they will suffer an increase in pressure. Because they are subjected to different temperature variations and because they have different expansion coefficients, the volume variations will be different.

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If the materials are confined, they will not be able to expand and pressure variations will happen. The results obtained will depend on the value of the volumetric elasticity/ compressibility modulus of the materials (**Table IV**). The effect of the temperature increase was not considered, and the values presented are considered constant values.

Table IV. Values of mechanical properties used in the work.

Property	Material A	Material B
Bulk modulus (Pa)	75.3×10^{9}	44.4×10^{9}
Young modulus (Pa)	1.1×10^{11}	$0.8\ 10^{11}$
Torsion modulus (Pa)	0.44×10^{11}	0.30×10^{11}
Poisson coefficient -υ	0.25	0.20

The pressure will increase in the two materials but near the border between them, the pressure is higher in material A than in material B.
Due to the increase of temperature in material A (decrease in material B) near the contact zone of the two materials, σ_3 (the thermal stress in the vertical direction) presents a gradient value with a positive signal in material A (the stress increases near the contact zone) and negative signal (the stress decreases near the contact zone B).

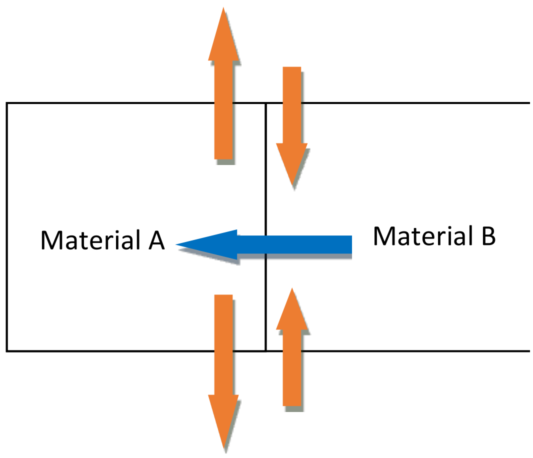

Figure 6. Thermal stresses originated from the contrast of thermal properties of the materials subjected to heating.

It is observed a horizontal compression is exerted by material B on material A. Its value increase with temperature increase.
Shear stresses appear near the boundary between the two materials (**Figure 6**).
Table V shows that stresses due to heating are higher in material B than in material A but in the region near the contact zone of the two materials thermal stresses are higher in material A than in material B.

Table V. Thermal stresses.

σ_A(MPa)	σ_B(MPa)	σ_{bA}(MPa)	σ_{bB}(MPa)
60	28	87	82
120	256	176	165
164	354	241	226
465	693	478	446
524	1115	772	722

At the boundary between the two materials, there is a decrease in the thermal stress in the vertical direction in material B relative to material A. The decrease increases with the heating process (temperature values used).

5. Some final comments

The variation of mechanical properties with temperature was not considered in this work. Water was not introduced in the model. The introduction of water into the model will decrease the temperatures and also pressure increases and thermal stresses.
As the degree of fracture and the transmissivity between them may be different in both materials, the amount of water introduced may also be different on the two sides, originating changes in the results obtained.

6. Future work

Thermal episodes of heating in the region could give rise to compression and deformation phenomena and may eventually reach the rupture of materials.
Anomalies of the geomagnetic field seem to be present sometime before the occurrence of some earthquakes in the region before and after February 28 A great increase of the vertical component and in the declination and inclination of the geomagnetic field were detected on the afternoon of February 27.
The velocity at which the increase took place was very high and alterations in the electric field are expected but that is a work to be done in the future.

7. Acknowledgements

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