PTDC/CTA-GEO/2083/2021
Progress Report – Scientific Component

Progress Report nº 2

1. Period:

Starting Date: 01-01-2023
End Date: 31-12-2023

2. Summary of the Activities carried out and deviations to the approved proposal

Figure 1 shows the planned activities by Working Package (WP) for the second year of the GEMMA project, according with the approved proposal.

Tasks	Year 1											
	2022											
	1	2	3	4	5	6	7	8	9	10	11	12
T0 - Management and Dissemination	A1.0		D0.1									D0.2
T1 - GNSS & Gravity Observations & Products									A1.1		D1.1	D1.2
T2 - Flexure Modeling												
T3 - Seismic Anisotropy Tomography and Shear-wave Splitting Analysis												
T4 - Island Tilting Assessed by Magnetic Methods							A4.1					
T5 - Multiscale Seafloor Structural Analysis												D5.1
T6 - Geodynamic Modelling												
T7 - Conciliatory Model												
Milestones									M1			M2

Milestone
M1 - End of main field campaigns
M2 - Progress Report (1st Year)

Activites/Deliverables (Expected Outputs)
A1.0 Kick-off Meeting
D0.1 Web site (http://segal.ubi.pt/GEMMA)
D0.2 Yearly Report

A1.1 First GNSS & gravimetric campaign in Azores
D1.1 First GNSS horizontal and vertical velocity fields for Macaronesia
D1.2 First Strain rate maps at Macaronesia and Archipelagos' Scale

A4.1 Field Campaign in Santa Maria and São Jorge.

D5.1 Compilation of multibeam and seismic reflection database

Figure 1 – Proposed GEMMA Timeline for the second year.

However, due to the unexpected changes already described in the Report for Year 1, particularly for T1 – GNSS & Gravity Observations & Products and T4 - Island Tilting Assessed by Magnetic Methods, a new timeline was developed for Year 2, which is shown in Figure 2.

Tasks	Year 2											
	2023											
	13	14	15	16	17	18	19	20	21	22	23	24
T0 - Management and Dissemination												D0.3
T1 - GNSS & Gravity Observations & Products							A1.1			A1.2	D1.1	
T2 - Flexure Modeling												
T3 - Seismic Anisotropy Tomography and Shear-wave Splitting Analysis												
T4 - Island Tilting Assessed by Magnetic Methods												D4.1
T5 - Multiscale Seafloor Structural Analysis												D5.2
T6 - Geodynamic Modelling												
T7 - Conciliatory Model												
Milestones						M3						M4

Milestone
M1 - End of main field campaigns
M2 - Progress Report (1st Year)
M3 - Halfway through project implementation
M4 - Progress Report (2nd Year)
M5 - AGU/EGU Session
M6 - Final Report

Activites/Deliverables (Expected Outputs)
A1.0 Kick-off Meetings
D0.1 Web site (http://segal.ubi.pt/GEMMA)
D0.2 Yearly Report
D0.3 Yearly Report
A0.4 Final Workshop
D1.5 Final Report
A1.1 First GNSS & gravimetric campaign in Azores
D1.1 First GNSS horizontal and vertical velocity fields for Macaronesia
D1.2 First Strain rate maps at Macaronesia and Archipelagos' Scale
D1.3 Regional gravity fields at archipelagos' Scale
A1.2 Second GNSS & Gravimetric Campaign in Azores
D1.4 Final GNSS horizontal and vertical velocity fields for Macaronesia
D1.5 Final strain rate maps at Macaronesia and archipelagos' Scale

Figure 2 – Updated GEMMA Timeline for the second year.

In this Scientific Report, we discuss the activities carried out based on the updated Timeline.

2.1 Summary of the Activities

WP0 Management and Dissemination

The goals of this WP during the second year were reached, with two project-wide meetings being held online during year two: a first on May 5th and a second on November 22nd. While a brief summary is presented here, the minutes for both meetings can be found as appendixes to the present report.

For the May 5th meeting, 15 researchers were present. During the meeting presentations were carried out by the different WP Leaders regarding the progress of the work done over the previous months. The most important topic discussed concerned the issues raised by the departure of WP2 task leader Machiel Bos from the project, with the consensus among the different members being that another person should be found to lead this task. Other issues discussed included:

a) The start of WP6 – Geodynamic Modelling, with preliminary numerical models being presented by Jaime Almeida.
b) The possible opening of a PhD grant to have someone with full time dedication to WP5.
c) The current and future objectives of the project concerning the publishing of results.

Regarding the meeting held on November 22nd, 17 researchers were present and, as with the previous meetings, presentations were carried out by the different WP Leaders regarding the progress of the work done over the previous months. Specifically, and regarding each WP, the following topics were broached:

a) WP1: there was a lengthy discussion regarding the current state of the GNSS stations in Graciosa, Pico, São Jorge, as well as the results of the previous GNSS campaign.
b) WP2: a new temporary task leader was selected for this task, with Joaquim Luís (UALG) assuming this role.

c) WP3: there was a discussion regarding the anisotropy tests, which according to Graça Silveira have been progressing. Further discussion was conducted regarding temporal variation results for El Hierro and La Palma.
d) WP5: a future publication on bathymetry was discussed, as well as the possibility/difficulty of finding a PhD student to work on this WP.
e) WP6: the current progress of the task was discussed, with Jaime showing the work that had been presented at the GEOMOD2023 conference. One of the issues also discussed at the meeting was the need for more debug due to an update of the used modelling code.

Concerning changes in the research team, as pointed out during the previously detailed meetings, the major negative aspect was the request from Machiel Bos to terminate his participation in the project due to his full dedication to his company. As pointed out in last year's report, his contribution was important in several tasks, namely the coordination of the activities of T1.3 (Gravity Field), and WP2 (Flexure Modeling) but, nevertheless, a new task leader (Joaquim Luís, UALG) has now taken over.

In terms of dissemination, several activities were carried out during the reported period, of which the most noteworthy are:

a) Participation in IDL's Earth Systems Summer School 2023, from 2-7/July 2023, at Angra do Heroísmo, Terceira Island. This summer school, dedicated to the theme "Land-Atmosphere-Ocean Interactions in a Changing Planet: A hands-on approach to Earth Systems observation and modelling", congregated over 30 PhD student participants, and included keynote lectures and research activities, both in the lab and in the field, by a large number of GEMMA's members, namely R. Fernandes, R. Ramalho, J. Duarte, C. Neves, A. Ferreira, and M. Miranda. These activities, chiefly integrated in the sessions "Dynamics of the solid Earth: From the deep mantle to the surface" and "Understanding the Azores: Future Challenges and Opportunities", already incorporated results and lessons arising from GEMMA's research, and encouraged students to creatively think on models and mechanisms to explain the observations, fully involving this international audience in the most timely and relevant discussion points associated with our scientific understanding of the geodynamics of Macaronesia.
b) Participation in the 2nd Edition of the Azores Summer School in Marine Island (Palaeo)Biogepgraphy, taking place at Santa Maria Island from 9-21 July 2023. This summer school integrated ~20 national and internation MSc and PhD student participants, and included lectures and field activities by GEMMA's team members R. Ramalho and R. Quartau. Of note, we highlight a lecture on the evolution of the Azores Triple Junction and the origins of the Azores Archipelago, a lecture on how island shelves are shaped by several factors including tectonic/isostatic movements, and a half-day field trip to explore the evidence of long term uplift of the island, as confirmed by GNSS data arising from GEMMA.

WP1 GNSS & Gravity Observations & Products

The planned activities on this task for the second year were to carry out one dedicated GNSS and gravimetric campaign in the Azores, namely in the Central group of the Azores archipelago. However, due to the annual IDL Summer Course which took place in Terceira Island, the project used that week to also conduct a campaign there, to take advantage of the presence of many of the investigators of the GEMMA project. A second, longer campaign took place in October, with the observation of the Central Group islands, namely São Jorge, Faial, and Pico. Due to the departure of Machiel Bos from the project, the gravimetric campaign was not conducted.

The first campaign took place between July 2nd and July 9th, with 10 stations being observed over this period of time. Of these, four stations (TGIN, TBIS, TSBR, and TPTE) were used for week-long observations, being kept online during the entire campaign. The remaining six stations were observed over two phases of three each (TCAP, TSER, TPVT in the first phase and TPOM, TCCD, TMAC in the second phase). There

was a minimum of 72 hours observation in every station. The members participating in this campaign were Rui Fernandes, Gonçalo Henriques, Jaime Almeida, Pablo González and João Salmim.

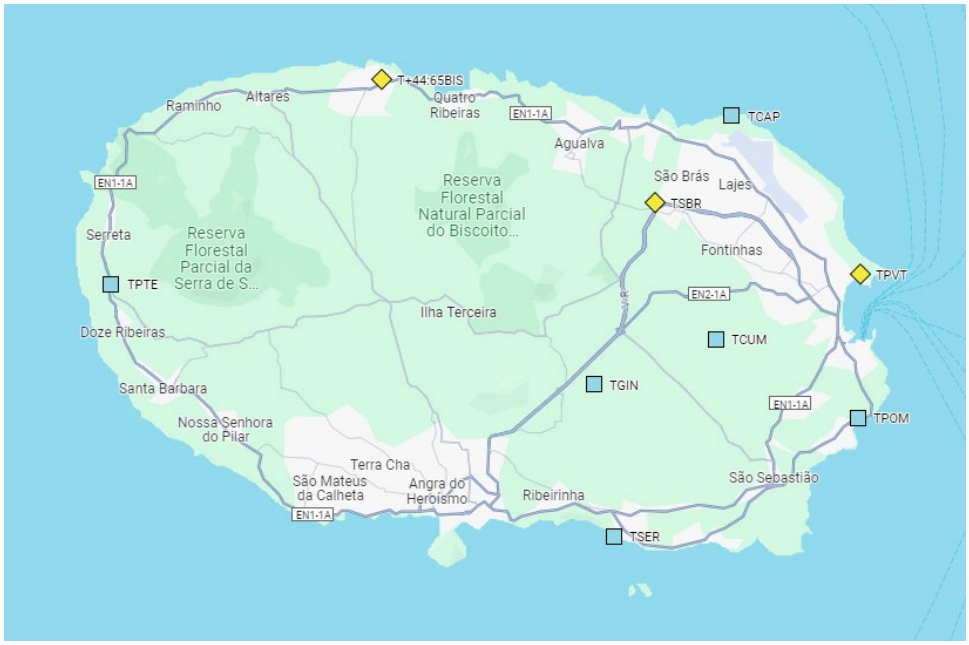

Figure 3 – Distribution of the GNSS stations in Terceira managed by the GEMMA team.

The second campaign took place between October 9th and October 24th, with a total of 25 stations being observed between Pico (8 stations), São Jorge (5 stations), and Faial (12 stations). In Pico, only PRIB was kept online during the entire six days of observation, with the remaining stations (PBJQ, PDRO, PMAD, PMNL, PPRN, and PSMT) being observed for 72 hours each. During the campaign in Pico, the GEMMA team also took updated measurements of the current height of the Pico summit (PPQN) on October 12th. In São Jorge, all stations (JMND, JROS, JTER, JTOP, and JNGR) were observed for 72 hours each. In Faial, two stations (FCGO and FVUL) were observed for six days, while the remaining (FFAR, FCDR, FFAJ, FFLA, FVAR, FPCD, FCBR, FFET, FPNT, and FVUS) being observed for 72 hours each. The members participating in this campaign were Rui Fernandes, Gonçalo Henriques, Jaime Almeida, Pablo González, João Salmim, and Mariana Moreira.

RAEGE-Az volunteered to write a detailed report on both field campaigns, which can be found as an appendix to the present report.

Figure 4 – Distribution of the GNSS stations in São Jorge, Pico and Faial observed by the GEMMA team.

Figure 5 shows the relative velocity with respect to the Nubia plate (using the model published by Fernandes et al., 2010) for all available stations in the Central Group. It is clearly observed that the Terceira

and Graciosa stations show a more eastward movement (close to the Eurasia predicted movement) than Faial and Pico, with the S. Jorge stations having some variation between the western and eastern stations.

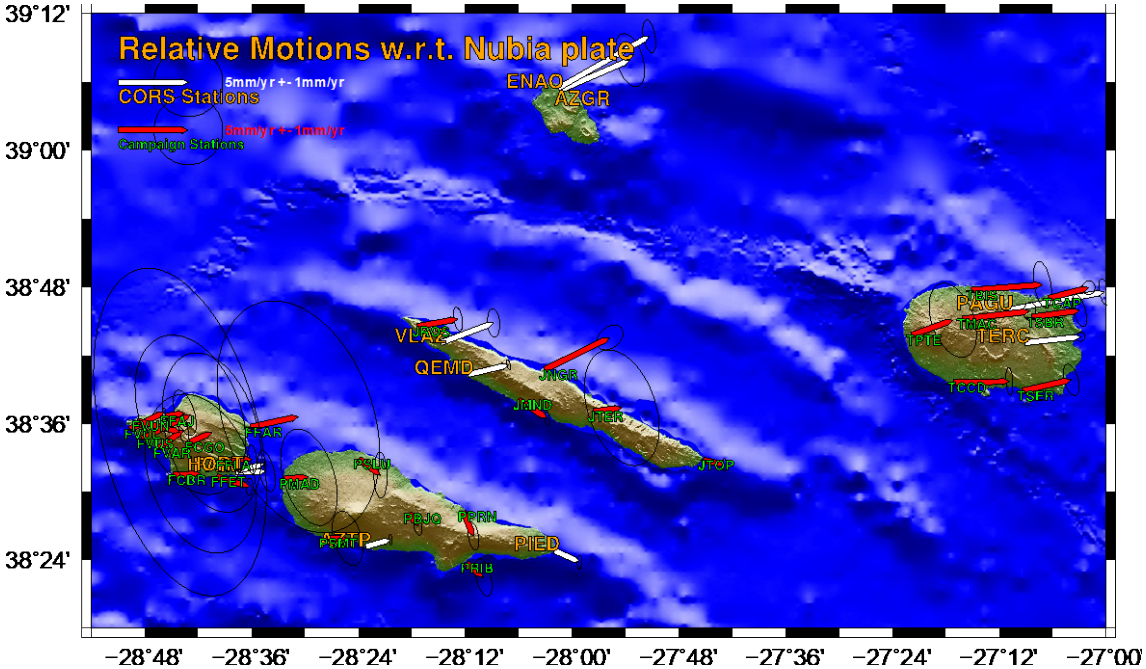

Figure 5 – Relative Motions with respect to Nubia for the stations (campaign and permanent) of the Central Group.

The results concerning the vertical component as shown in Figure 6 show that most of the islands are subsiding except for the stations in S. Jorge. Although the data span covers 20 years, the observed uplift in S. Jorge can be partially related with the seismic crisis in 2022.

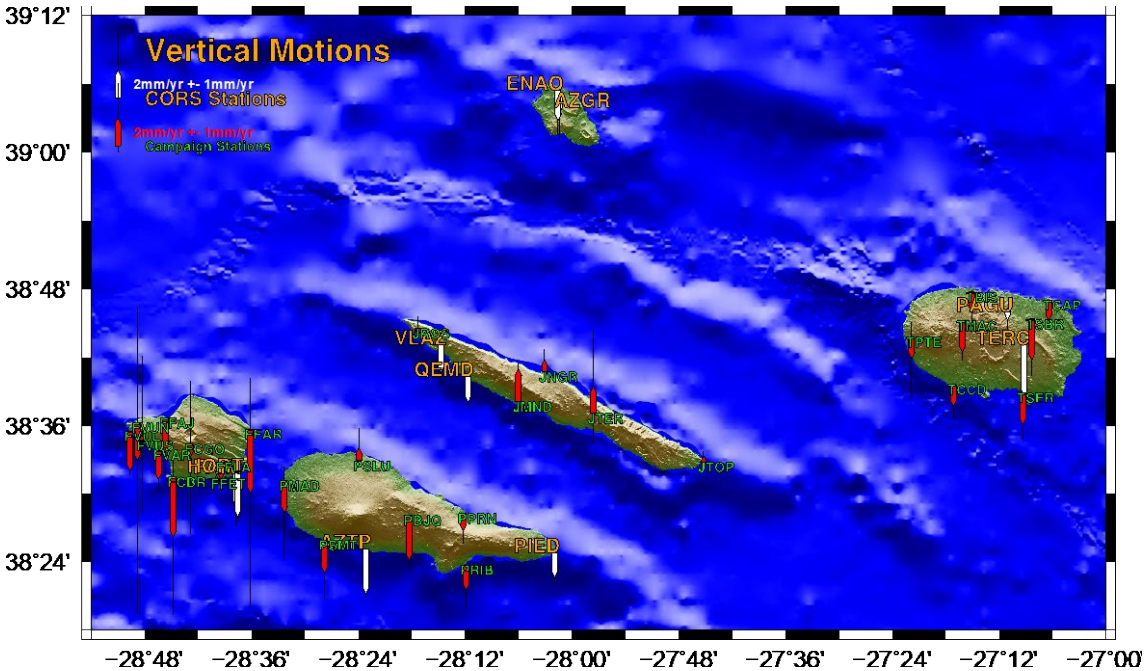

Figure 6 – Vertical Motions for the stations (campaign and permanent) of the Central Group.

Horizontal and Vertical velocity fields were also estimated using only the permanent stations for the entire Azores Archipelago (Figure 7 and Figure 8), Madeira Archipelago (Figure 9 and Figure 10), Canary Archipelago (Figure 11 and Figure 12), and Cape Verde Archipelago (Figure 13 and Figure 14), respectively.

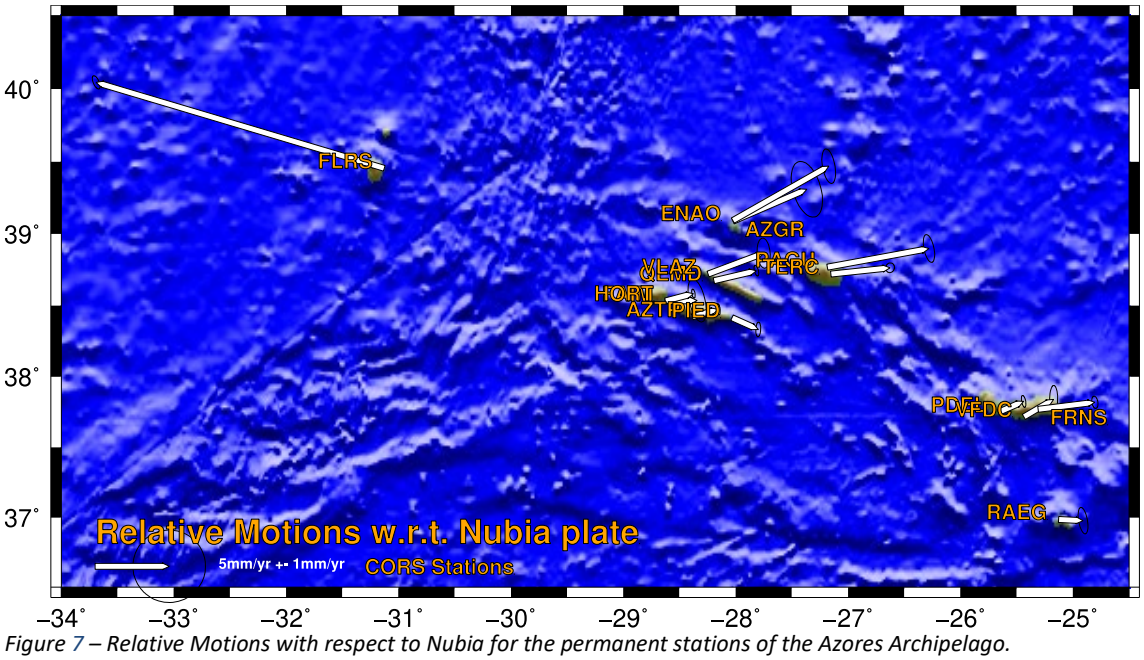

Figure 7 – Relative Motions with respect to Nubia for the permanent stations of the Azores Archipelago.

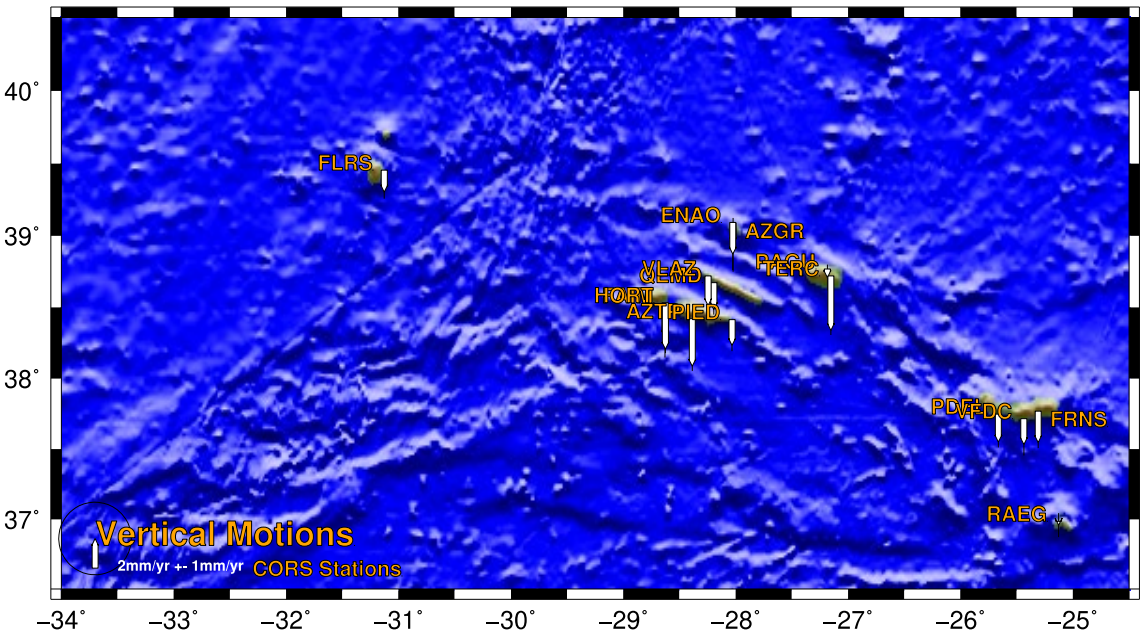

Figure 8 – Vertical Motions for the permanent stations of the Azores Archipelago.

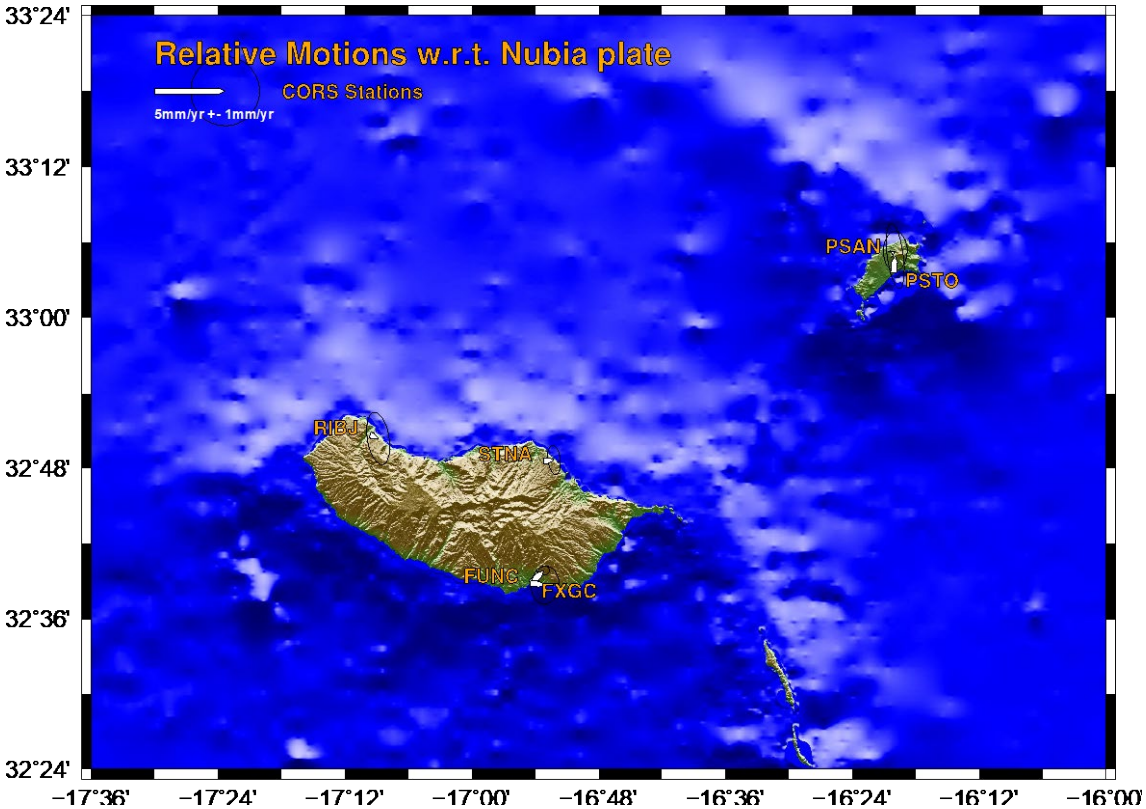

Figure 9 – Relative Motions with respect to Nubia for the permanent stations of the Madeira Archipelago.

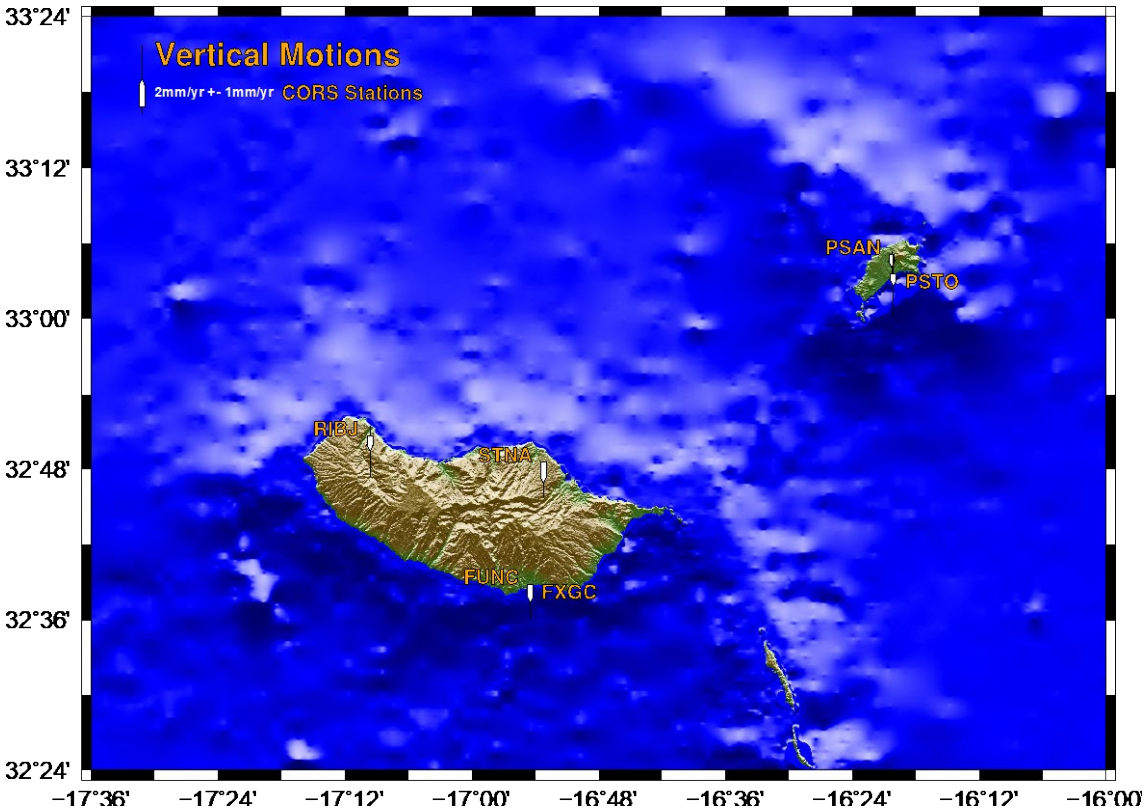

Figure 10 – Vertical Motions for the permanent stations of the Madeira Archipelago.

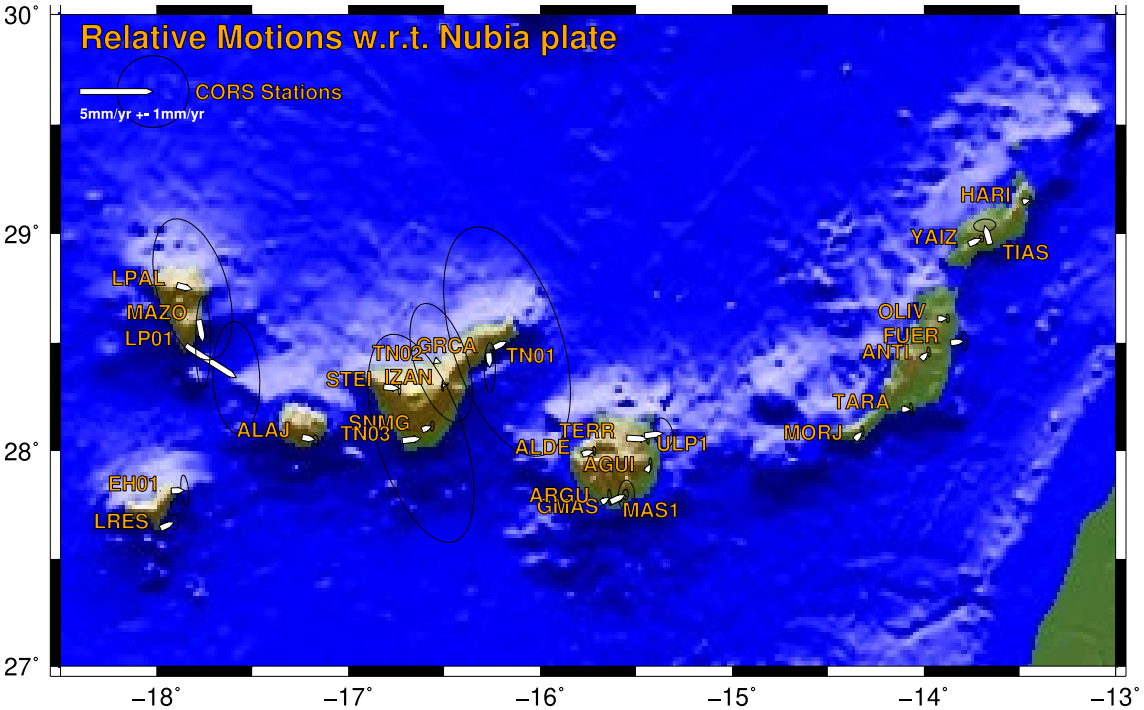

Figure 11 – Relative Motions with respect to Nubia for the permanent stations of the Canary Archipelago.

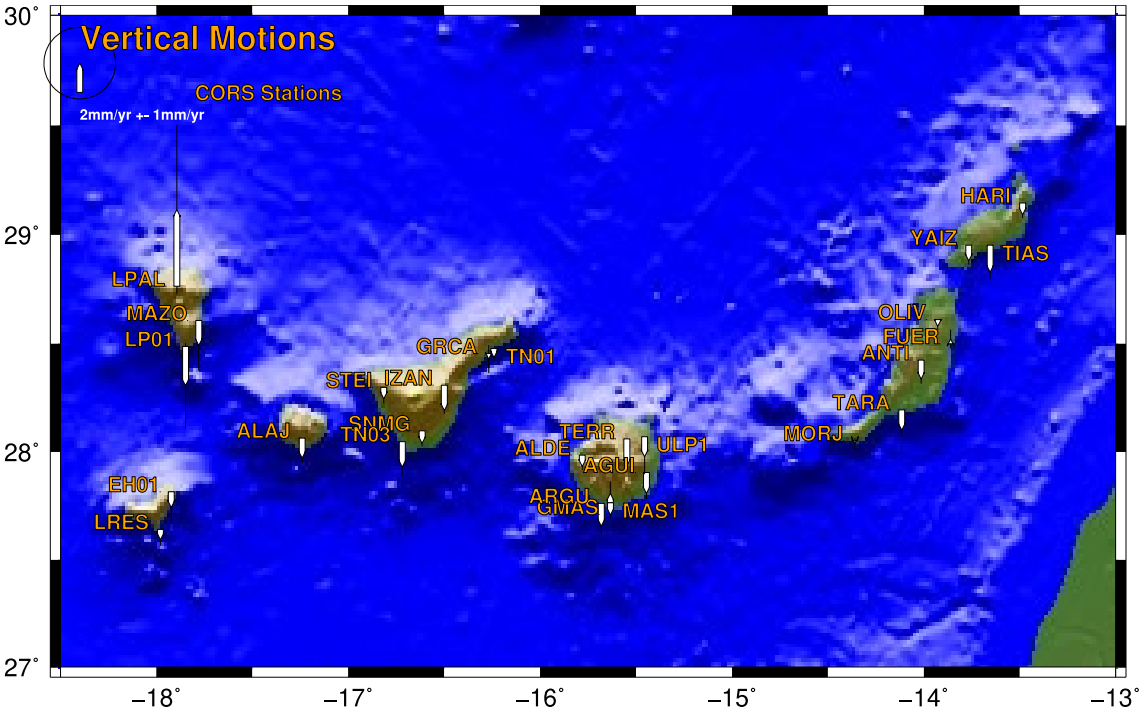

Figure 12 – Vertical Motions for the permanent stations of the Canary Archipelago.

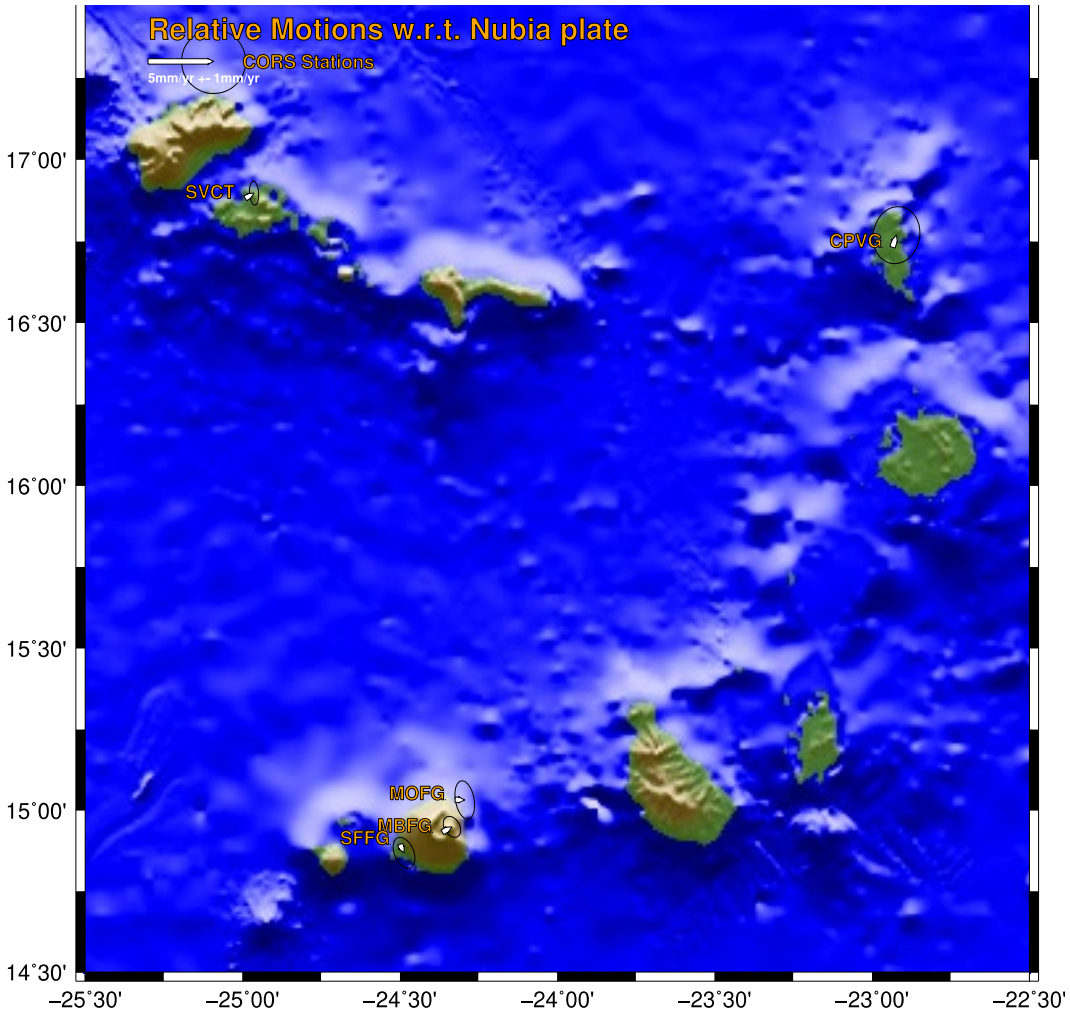

Figure 13 – Relative Motions with respect to Nubia for the permanent stations of the Cape Verde Archipelago.

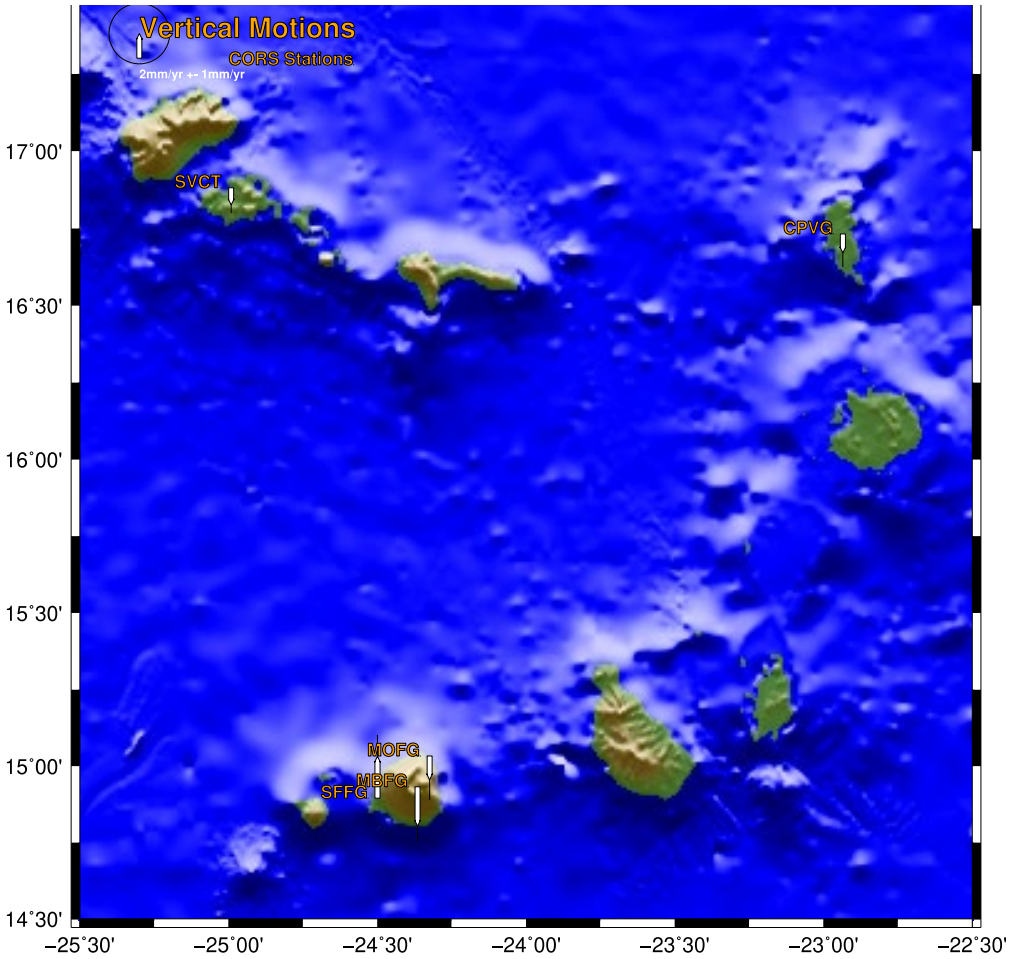

Figure 14 – Vertical Motions for the permanent stations of the Cape Verde Archipelago.

WP2 Flexure Modeling

Joaquim Luis has taken the responsibility for this task. Conceição Neves was invited to be part of the GEMMA research team to collaborate in this task.

WP3 Seismic Anisotropy Tomography and Shear-wave Splitting Analysis

The aim of this work page (WP) is to obtain a 3D model of the isotropic and anisotropic shear-wave lithospheric structure in the GEMMA study region.

Katrina Harris, an UPFLOW PhD student, employed the PWI method, conducting nonlinear waveform fitting of surface waves filtered between T~ 16 s and T~ 300 s. Initially, we extracted the surface wave fundamental mode to derive path average perturbations in shear radial anisotropy and isotropic shear wave velocity. These perturbations established a new initial model, enabling estimation of the path-averaged radial anisotropy model. Subsequently, an iterative, regularized least squares inversion inferred 3-D radially anisotropic mantle structure, with uncertainties aiding interpretation. Preliminary results compared to previous tomographic models validated our findings.

Hotspot volcanism reflects dynamic subsurface changes, influencing stress patterns and seismic anisotropy. Studying seismicity around El Hierro and La Palma post-eruption reveals variations in location, depth, and polarization direction, indicating ongoing subsurface dynamics. Increased seismicity since 2018 in El Hierro suggests renewed activity in deeper plumbing systems, impacting overall seismicity without affecting vertical island movement.

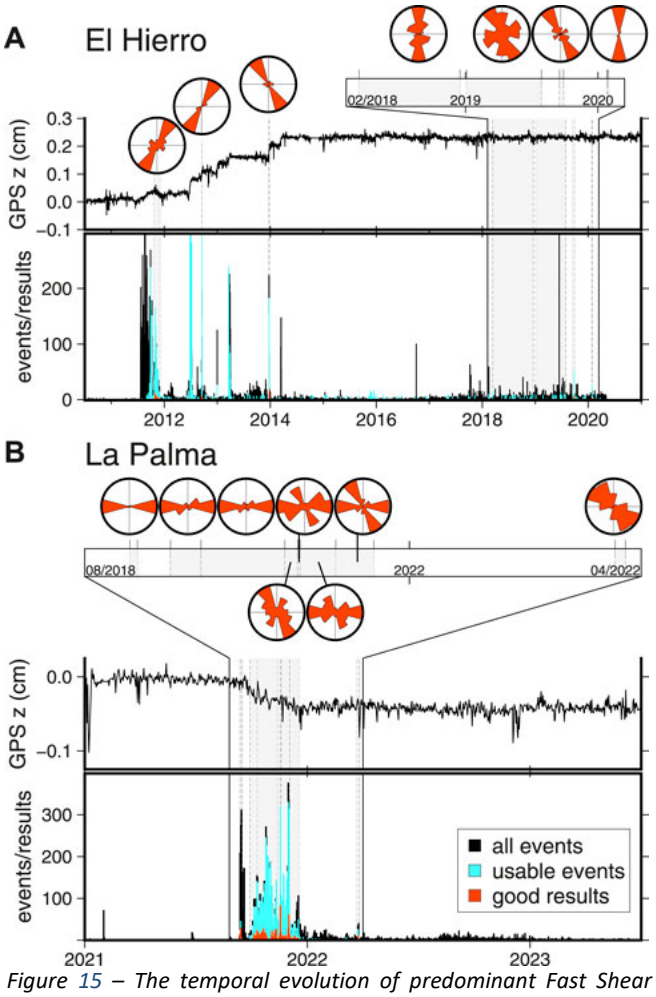

Figure 15 – The temporal evolution of predominant Fast Shear Wave Polarization Direction (FPD), vertical GPS variations, and seismicity is depicted for El Hierro (A) and La Palma (B). Histograms display three colors representing all available events, usable events within the 35° shear-wave window, and good results used in this study. Rose diagrams for La Palma differentiate between events from shallow (grey) and deep swarms (black).

The seismic crisis on São Jorge Island in 2022 triggered 12,000 earthquakes; PMAN station showed waveform-similarity variations, indicating seismic structural changes during the crisis. In the Canary Islands (cf. Figure 15), the ambient noise correlation analyzed post-eruption in La Palma revealed decorrelation, suggesting medium changes. Correlations computed using phase cross-correlation, stacked over 3 days, detected decorrelation before and after the eruption, indicating structural alterations. Phase-shifts and waveform distortion inferred structural changes, occurring at depths localized around 8 km.

WP4 Island Tilting Assessed by Magnetic Methods

No activities have been carried out in this first year related to this Working Package due to personal issues related to the members responsible for this Working Package. It is expected to be done during the next year.

WP5 Multiscale Seafloor Structural Analysis

The aim of this WP was to compile all the available high-resolution bathymetry and seismic reflection data. This had a delay in the first year but was already completed during the second year.

During this second year, we analyzed all the compiled data and decided to focus on a case-study, the Terceira Rift, linking São Miguel Island to Gloria fault in the Azores.

WP6 Geodynamic Modelling

The goal of this work package (WP) is to develop advanced numerical geodynamic models that incorporate new observational data and test different conceptual hypotheses that arise from the previous work packages and tasks. The planned activities for this WP over the second year included the development of stable baseline models using the code LaMEM. At present, a set of stable models exists which approaches the establishment of the entire triple-junction, the Azores plateau, the West Gloria Fault and mid-Atlantic ridge by exploring the contribution of the individual geological factors in the region (example shown in Figure 16), namely: (1) the length of the transform faults; (2) the rheology of the Azores plat eau (i.e., more oceanic vs more "continental" signature); and (3) the Azores hotspot (i.e., the impact of the plume head under the plateau). The preliminary results from this WP have been presented at GEOMOD2023, in Paris, having received positive feedback during discussion.

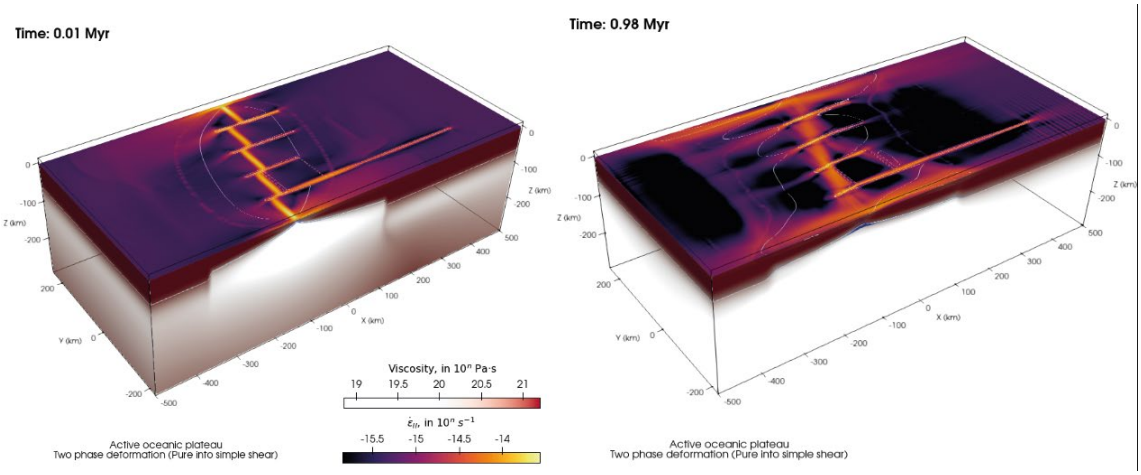

Figure 16 – Stable model of the formation of the Terceira Ridge as the consequence of a shift in tectonic forcing. Results to be presented at EGU24.

WP7 Conciliatory Model

Although this task is set to start in the second semester of the second year, it has not been started. As stated in the previous report a minimum of integration of the results from the WPs 2 to 5 was necessary to start developing the geodynamic numerical models (WP6). The development of these models is currently underway, with encouraging results, however it is yet premature to develop a conciliatory model that will feed from results of all WPs.

2.2 Desvios à Proposta Aprovada

The deviations to the proposal were already described in the description of the activities carried out by the different work packages.

3 Publicações

Conferences Abstract/Papers (International)

Carvalho, J., Silveira, G., Bento, V., Schimmel, M., and Antón, R.: Insights into the fluid migration dynamics of Tajogaite eruption, La Palma, EGU General Assembly 2023, Vienna, Austria, 23–28 Apr 2023, EGU23-9245, https://doi.org/10.5194/egusphere-egu23-9245, 2023.

Almeida, J., J. Duarte, F. Rosas, R. Fernandes, H. Mohammadigheymasi, F. Geraldes, L. Carvalho, R. Ramalho, A new geodynamic model of the Azores archipelago: preliminary results (2023). GEOMOD2023, Paris, France

Fernandes, R.M.S., Almeida, J., Duarte, J., Rosas, F.M., Ramalho, R., Mohammadigheymasi, H., Geraldes, F., Carvalho, L. and Henriques, G., 2023. New insights on geodynamic modelling of the Central Group of the Azores archipelago. *AGU23*.

4. Indicadores de Realização Física

Indicadores	Quantidade realizada
A - Publicações	
Livros	0
Artigos em revistas internacionais	1
Artigos em revistas nacionais	0
B - Comunicações	
Comunicações em encontros científicos internacionais	1
Comunicações em encontros científicos nacionais	0
C - Relatórios	1
D - Organização de seminários e conferências	0
E - Formação avançada	
Teses de Doutoramento	0
Teses de Mestrado	0
Outras	2
F - Modelos	0
G - Aplicações computacionais	0
H - Instalações piloto	0
I - Protótipos laboratoriais	0
J - Patentes	0
L - Outros	0