Body waves tomography from OBS-recorded earthquakes in the Gulf of Cadiz

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Abstract – *The gulf of Cadiz is a region considered as a complex seismic area, where strong earthquakes occur and where the plate boundary between the African and Eurasian plates is not exactly known. In this paper, we use high resolution seismic data recorded by a network of OBS stations deployed for one year in the Gulf of Cadiz as well as eight permanent Portugal land seismic stations. The OBS network was deployed within an experiment of the NEAREST project. Nearly 600 seismic events are extracted from the recorded data set and their analysis revealed that most of them occur at 20 to 80 km depths, with clusters of seismicity that occur mainly at the Gorringe Bank, within the SW segment of the Horseshoe fault and the Marques de Pombal Plateau and the S. Vicente Fault. A new NW-SE trend of seismicity has been revealed with depths that extend from 35 to 80 km. This seismicity trend is close and nearly parallel to the SWIM (South West Iberian Margin) faults lineament.*
We further present in this paper, the first regional-scale high resolution P- and S-velocity distributions across the Gulf of Cadiz region. These velocity models are obtained using three-dimensional *seismic tomography to invert the OBS data-set. The results show that the patterns of anomalies in the Gulf of Cadiz are in general, oriented in NE-SW and NW-SE directions. They also show the presence of a low velocity zone (LVZ) to the SE of our study area. At shallow depth, this LVZ is interpreted as due to a large accumulation of sediments within the accretionary wedge, while at a greater crustal depth, it may reflect a continental crustal composition rather than an oceanic crust. Moreover, seismic velocity profiles show that under this region of the Cadiz Gulf, the Moho averages a 30-km depth.*
The Gorringe Bank and the Marquise de Pombal plateau are found to be deeply rooted and represent expressions of mantle uplifting. The association of these deep anomalies with active seismicity that occurs at their levels, indicates that the uplifting of these ridges is still an ongoing process.
Furthermore, a NW-SE zone of high velocity is found to the SW of our study area. This zone occurs along and parallel to the SWIM faults zone (SFZ) and appears to support the hypothesis that the SFZ represents the boundary between the Nubia and the Eurasia plates at the Gulf of Cadiz level as previously suggested [1].

***Keywords**: Seismic tomography, Inversion, body wave, Gulf of Cadiz.*

I. Introduction

The gulf of Cadiz region connects the Betic-Rif orogenic arc to the oceanic plate boundary between the Africa and Eurasia plates and the Gloria Fault [1]. The nature and exact location of this plate boundary are still uncertain. It is a large area, with complex deformations and diffuse seismicity that extends over 200 km from north to south [2]-[4].

The 1755 Lisbon earthquake is still considered the most destructive event in the western Mediterranean. This event was followed by a large tsunami that caused several thousand of deaths and many localities were largely destroyed. In particular, all localities on the Atlantic coast of Morocco from Tangier to Agadir, were severely affected by the combined effects of the earthquake and the tsunami that followed [5],[6]. The tsunami flooded about 2 km inland along the coast of El Jadida, Safi and Essaouira [7]. It is worth noting that this event occurred in the Atlantic Ocean, but its precise location is still a matter of debate [8],[9],[1].

Some authors attempted to explain the tectonics and the formation of this zone by suggesting a delamination of the continental lithosphere [10],[11], while others suggested an oceanic subduction [12]-[14] that led to the formation of an accretionary wedge to the west of the Gibraltar arc.

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Some of these studies used data recorded by seismic reflection or refraction surveys. However, such studies usually have a limited depth penetration, which limits their tectonic interpretations, especially that most of the seismic activity in the Gulf of Cadiz occurs at more than 20 km depth as will be shown in this paper. Other studies used data recorded by land stations in Morocco and Iberia to invert for the three-dimensional velocities underneath the Gulf of Cadiz. However, since the used stations are far away from the Gulf of Cadiz, the results are not quite reliable and remain of limited resolution.

In this paper, we show the results of a body-waves seismic tomography study based on local earthquakes recorded by a network of 24 broadband ocean bottom seismometers (OBS) deployed right on top of the sea floor of the Gulf of Cadiz (Figure 1). The data used were collected within the framework of the European project NEAREST (Integrated observation from NEAR shore sourcES of Tsunamis: towards an early warning system), in which the 24 OBSs were deployed by the German DEPAS instrument pool coordinated by the Alfred Wegener Institute for Polar and Marine Research, Bremerhaven and the GeoForschungsZentrum, Potsdam. The data were collected during 11 months of recording, beginning August 2007 [15] and augmented by seismic data recorded by eight land seismic stations that belong to the Portugal permanent seismic network. The objective of this work is thus, to use these high quality data to help constrain a 3D velocity model of the earth interior beneath the Gulf of Cadiz and to draw implications for the tectonics of the region.

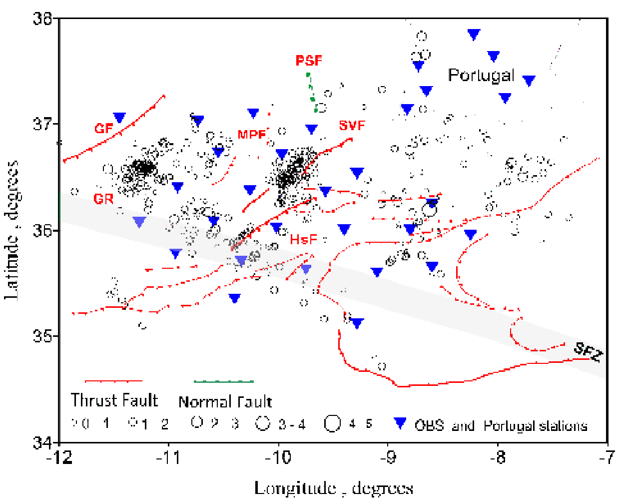


Fig. 1: Seismicity of the Gulf of Cadiz as recorded between august 2007 and July 2008 as shown by the black circles that show the epicentral locations inverted for by the tomography program; GF : Gorringe fault , GR : Gorringe ridge , MPF : Marques de Pombal fault , HsF : horseshoe fault , PSF: Pereira de Sousa fault, SVF: Sâo vicente fault, the inclined gray line represents the SWIM faults zone (SFZ).

II. Tectonic setting

The gulf of Cadiz is located in the Atlantic Ocean and undergoes complex deformations due to plate tectonic interactions between the southern Eurasia and the North Africa plates. In the last decade, several geophysical studies have been undertaken in the Gulf of Cadiz, since this region is a source of many earthquakes and the historical devastating tsunami that followed the great Lisbon earthquake of 1st November 1755th with an estimated M=8.5 to 8.7 magnitude [16].

In this region, scientists have successfully identified some traces of the lithospheric converging plates. In addition, bathymetric and tomography studies suggested the existence of a subduction zone west of the Gibraltar arc [17], and seem to indicate that the tectonic processes leading to the formation of an accretionary prism and the morphology of the southern Gulf of Cadiz are influenced by processes associated with tectomorphic deformation of the accretionary prism of the Gulf of Cadiz [18] as well as a gravitational process [19]. Based on an analysis of seismic data, it was suggested that the base of the accretionary wedge is dipping eastward and has a primarily tectonic origin [13]. The majority of the accretionary wedge was constructed by offscraping of deep sea sediments during Miocene westward motion of the Gibraltar arc [20]. Other geodynamic models suggest however, a delamination of continental lithosphere process [10],[11].

Recent detailed bathymetric mapping in the Gulf of Cadiz shows the existence of major inverse faults that trend NE-SW, mainly perpendicular to the principal stress direction, as well as sub-parallel WNW-ESE strike-slip trending lineaments [21],[1]; the SWIM Faults, that extend from the Hirondelle seamount to the Moroccan continental shelf. Based on this, it was suggested that the SWIM Faults zone (SFZ) constitute the plate boundary between Nubia and Eurasia along a 600 km span between the Gloria Fault and the Rif-Tell plate boundary [1].

Reference [1] further suggests the existence of active thrust structures in the Gulf of Cadiz to explain the main clusters of seismicity. While some authors [22] support that subduction is still active and poses significant seismic hazard to the region, others based on the low level of seismicity in the accretionary wedge and the undeformed package of deposited sediments, find that the subduction zone is not active at present time or is rather dying out and confirm the existence of an oblique collision between the Nubia and the Iberia plates [1].

Recently, based on focal mechanisms of seismic events recorded by the network of OBS instruments deployed in the Gulf of Cadiz and used in this study, it has been shown that compression acts in the northern part of the Horseshoe fault [15], while a strike-slip regime acts in its southern part, trending parallel to the plate boundary.

III. Seismic data and seismicity

Within the NEAREST project, 24 Ocean Bottom Seismometers (OBS) were deployed in the Gulf of Cadiz to collect seismic data during this project experiment. They were equipped each with a Güralp CMG-40T broadband seismometer incorporated in titanium pressure housing, a hydrophone, and a GEOLON MCS (Marine Compact Seismocorder). The electric power supply for the recorder and the seismometer is driven by 132 lithium power cells. Each sensor channel is sampled with 100 Hz, preamplifier gain of the hydrophone channel is 4 and 1 for the three seismometer components [15]. The OBS recorded seismic data are collected in SEED format; then all events recorded by the OBSs and eight Portugal land-stations were extracted for processing and analysis, in order to determine their hypocenters and local magnitudes.

The initial hypocentral locations were performed using the Seisan software package, [23]. Reliable locations depend on many factors. So, locating earthquakes using unreliable models contributes in part to the uncertainties on results especially for complex areas. For this reason, we start with the model proposed in the 2008 NEAREST-cruise and was improved subsequently [14]. Afterwards, all recorded events are localized with the resulting appropriate initial velocity model obtained using the Velest inversion algorithm [24]. The data set thus collected, consists of more than 600 local events (Figure 1). The quality of the initial earthquake locations is rather high, with an RMS travel time residual less than 0.8 s. These events allowed us to obtain a total of 9194 arrival times, consisting of 2968 P-wave and 6226-S wave arrival times.

Thus, in the period of observation [August 2007 to July 2008], the OBS network revealed that the seismicity in the study area is characterized by a nearly-continuous activity of low magnitude events. The ML=4.8 January 1st, 2008 earthquake is the largest event recorded by the OBS network and the Portugal seismic stations used in this observation period. The large number of earthquakes recorded in this one-year time period shows that the Gulf of Cadiz is a quite active area and testifies of the great sensitivity of the deployed OBS network.

The determined local magnitudes showed that approximately 61 % of the events have local magnitudes less than 2, and 22 % have magnitudes between 2 and 3. The relocated events show that the majority of the recorded events are between 20 and 80 Km depth (Figure 2), with only few events with depths shallower than 20 km. Figure 1 shows that the seismic activity concentrates in three main blocs; namely along the Gorringe ridge, SW of the Horseshoe fault, and near and along the Marques de Pombal plateau and the Sâo Vicente Fault. Few earthquakes occurred in the accretionary wedge zone while dispersed seismicity is found south of Portugal (Figure 1).

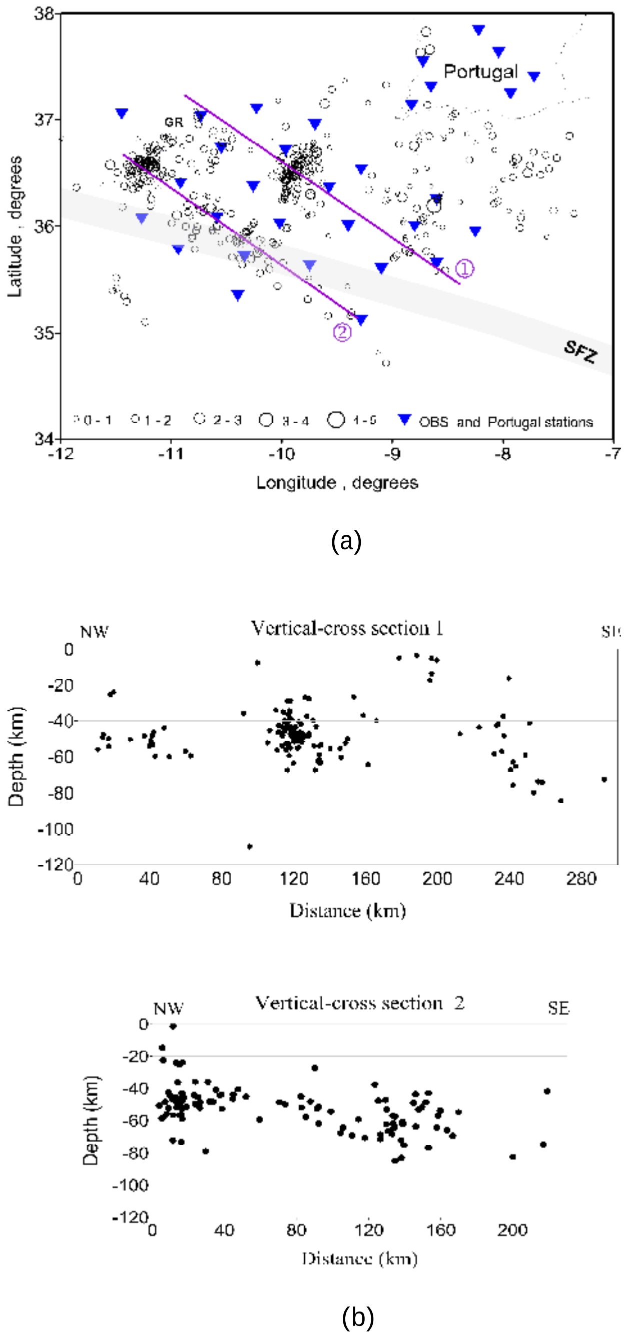


Fig. 2: (a) Location of seismic profiles, (b) Seismic profiles shown in figure 2a, showing events that occurred within 40 km distance from the profile. Note that profile 1 shows three separate clusters of seismicity while profile 2 indicates a more continuous pattern of seismicity.

Also, a NW-SE trend of seismicity that crosses the horseshoe fault can be observed to the south of our study area (Figure 1 and seismic profile 2 on Figure 2a). This seismic alignment seems to occur rather in segments of seismicity, with depths that vary between 35 and 80 km. This trend of seismicity is nearly along and parallel to the SFZ and may thus, be correlated to the SWIM faults, which were mapped on the surface, mainly based on bathymetric scanning.

IV. Inversion Method and procedure

The 3-D tomography inversion is performed using the LOTOS-09 code, which is described in detail by Koulakov [25]. Here, we very briefly present the main steps of the algorithm [26]. Input files for our calculations include a list of the stations with coordinates and elevations, and a catalog of the arrival times from local earthquakes. The algorithm does not require any information about coordinates and origin times of the sources.

Seismic tomography typically requires multiple solutions of inverse problems and adjustment of model parameters to satisfy data observations. Since achieving good results depends on carefully choosing the initial model and user-defined free parameters such as amplitude damping and smoothing, in this work, confidence in the obtained results is checked through a series of synthetic tests.

Calculations begin with preliminary earthquake locations in a 1-D velocity model. We used a starting 1-D velocity model obtained when the database was relocated using the Velest inversion algorithm [24], we further tested several other initial velocity models (cf. to section V below). At this stage, the source coordinates and origin times are determined using a grid search method [27]. We perform preliminary locations and optimization for the 1-D model then the sources are relocated in the 3-D velocity model and the rays are traced using the bending method as described by Koulakov [25].

The method allows the optimization of a Goal Function (GF) that reflects the probability of the source location in the 3-Dimensional space. Model travel-times are computed using tabulated values calculated in the 1-D velocity model at a preliminary stage, and matrix inversion for P and S velocities and source parameters are performed using a least-squares method [28],[29].

The LOTOS tomography codes are used in this study to invert for the three-dimensional Vp and Vs velocity structures. The inversion process is performed in five iterations considered as the optimal number of iterations to reduce nonlinear effects [26]. Resolution and evaluating the optimal values of the free parameters used in the inversion are assessed using checkerboard tests constructed from synthetic models which is a succession of positive and negative blocs anomalies with ±7% amplitudes for P and S waves respectively.

V. One dimensional initial velocity model optimization.

The inversion process requires an initial 1-D velocity model; we used different starting velocity models in order to select one which gives optimal locations. Thus, we tested seven initial velocity models, including the one yielded by the Velest algorithm [24], in addition to several variants of these initial models (Figure 3).

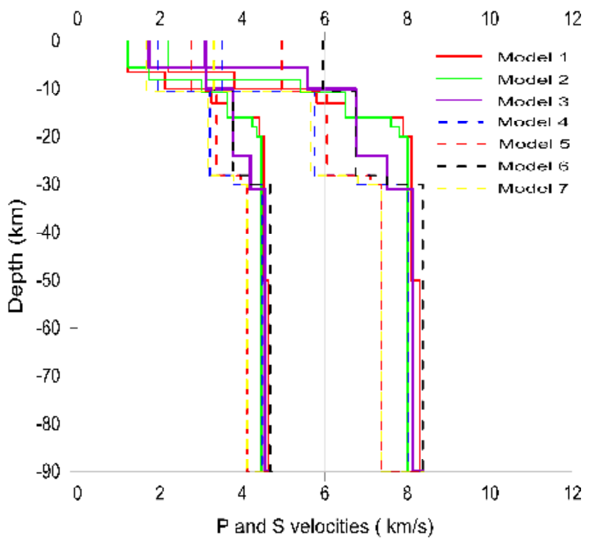


Fig. 3 : Different starting P-velocity models used for optimization of the initial velocity model; model 1 is the velocity model proposed in the NEAREST-2008 cruise report, model 3 is the model derived using Velest, while models 2,4,5,6 and 7 are initial-velocity models with slight modifications of the previous ones.

Based on the analysis of the resulting velocity distributions and the RMS of residuals, we find that the 1-D velocity model which gives the least RMS residuals in the Gulf of Cadiz region corresponds to model 3 presented and Figure 3, which is the model found using the Velest inversion algorithm. This model consists of a crust with three layers with an interface at ~6 km depth, and the Moho at 30 km depth. Using the LOTOS software, Model 3 was then optimized and yielded the model given in Table I.

TABLE I
P AND S VELOCITIES IN THE REFERENCE 1-D MODEL AFTER OPTIMIZATION BY THE LOTOS SOFTWARE.

Depth (Km)	Vp (Km/s)	Vs (Km/s)
0	2.713239	0.919177
10	6.093362	3.755473
20	6.839791	3.845567
30	7.766315	4.629175
40	8.243161	4.554774
50	7.922880	4.675756
60	7.808963	4.645917
70	7.722842	4.563402
80	7.685386	4.518101
90	7.939282	4.506800
100	8.103004	4.549830

VI. Three-dimensional tomographic inversion

Using the relocated hypocenters in the optimized initial model, the inversion scheme described above allowed us to invert for the three-dimensional structures beneath the Gulf of Cadiz. Thus, Figure 4 shows the obtained P-velocity tomograms at selected depths; namely at 10 km, 15 km, 25 km, 35 km and 50 km depths, while Figure 5 shows the S-velocity tomograms at the same depths. These depths were selected for their importance in terms of velocity distribution and also because the tomograms have higher resolution at these depths. For shallower depths and for depths greater than 50 km, the checkerboard tests show that the results are not reliable.

A general observation from the tomograms of Figures 4 and 5 is that the limits between the different positive and negative anomalies in this study area strike either in a NE-SW or in NW-SE directions. We further notice that the tomograms of both Figures 4 and 5 show more or less similar velocity distributions and features. We further notice that the S-waves tomograms show a better resolution as indicated by the synthetic tests of the Appendix. This can be explained by the fact that there are about twice as many S-arrivals than P-arrivals in our earthquake hypocentral phases.

At depths 35 km and shallower, the tomograms of Figures 4 and 5 show a large negative anomaly to the SE of the study area, approximately between latitudes 35.1°N and 37°N and between 8°W and 10°W longitude. This anomaly coincides with the inverted part of the accretionary wedge and extends all the way to the continental margin of Portugal. At shallow depths, this anomaly can be attributed to the existence of an area with a large concentration of sediments (the accretionary wedge), while at greater depths, this anomaly could be interpreted as reflecting that this part of the Gulf of Cadiz is rather made out of continental crust and thus, its northern part delineates more or less the limit between continental crust and oceanic crust. However, the many alternances between positive and negative anomalies in these tomograms do not seem to clearly delineate a continent-ocean boundary such as previously reported [21].

To the NW of the study area, a positive anomaly extends indeed from 10 km to 35 km depth and approximately coincides with the uplifted Gorringe Bank (Figures 4 and 5). Below these depths, these positive and negative anomalies continue but appear rather attenuated. To the South of the study area, a NW-SE positive anomaly shows up. This anomaly approximately follows and coincides with the SWIM lineaments (SFZ) [1], which is suggested as the boundary between the Nubia and the Eurasia plates. Our results thus, seem to support this suggestion, although our results do not extend far enough to the south to definitely confirm this observation.

In order to help understand the tomographic images of Figures 4 and 5, we made vertical projections of these tomograms along the profiles shown on Figure 6a. These projections (Figures 6b) represent true-velocity seismic vertical section, rather than velocity perturbations. Thus, vertical section 1 and 2 are oriented in a NW-SE direction. Vertical section 1 crosses the seismic cluster along the Sâo Vicente fault (SVF), while vertical section 2 crosses the seismicity cluster along the Gorringe Bank. Both of these cross-sections (1 & 2) show that the Moho underneath the Gulf of Cadiz is rather deep, with an average depth of 30 km below sea surface.

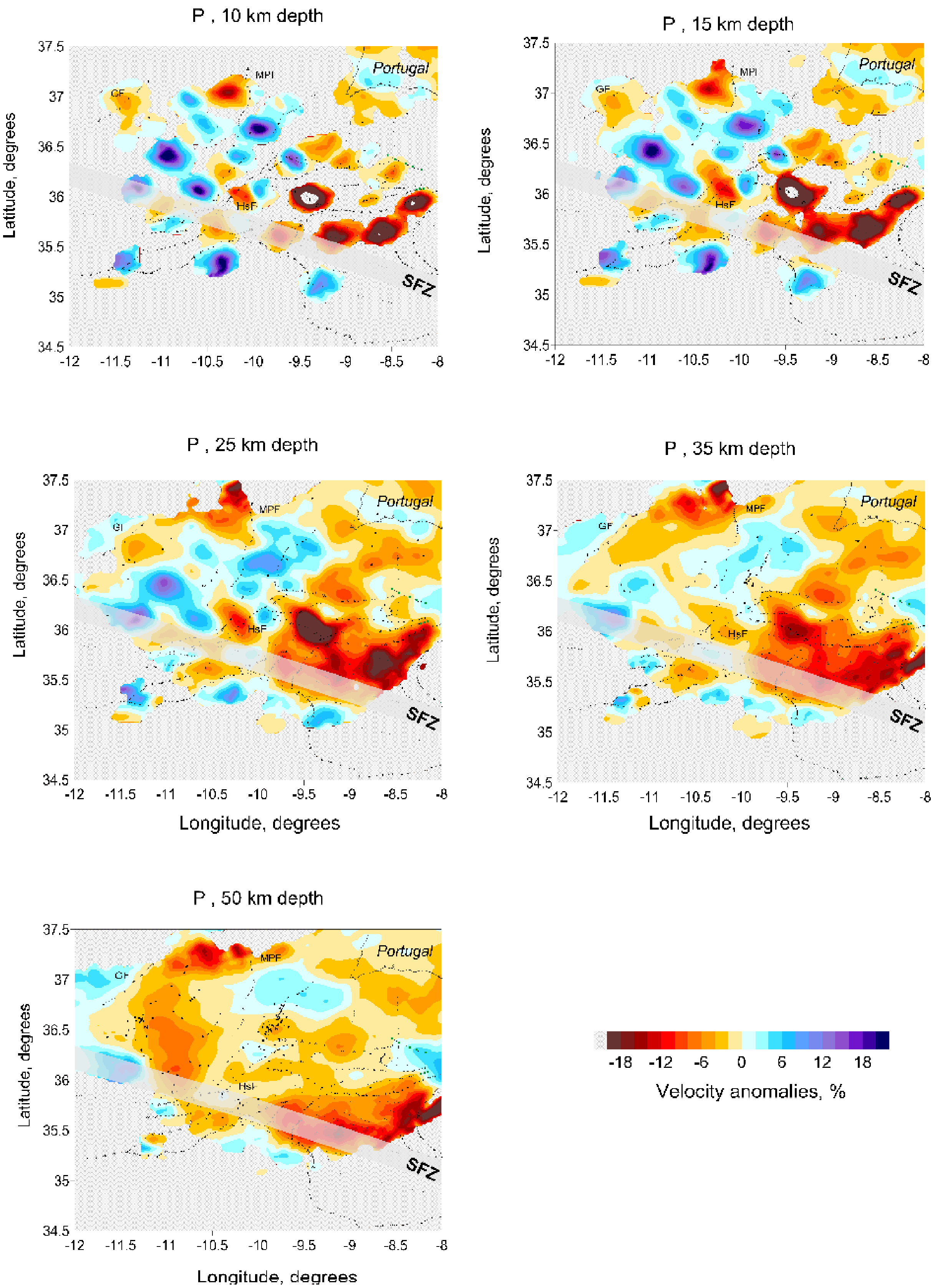


Fig. 4: Horizontal P-velocity distribution at different depths. Solid lines show the existing faults and dotted lines show possible strike-slip faults, and black dots show the epicenters location given by tomography program and inclined gray line represent the SWIM fault zone (SFZ).

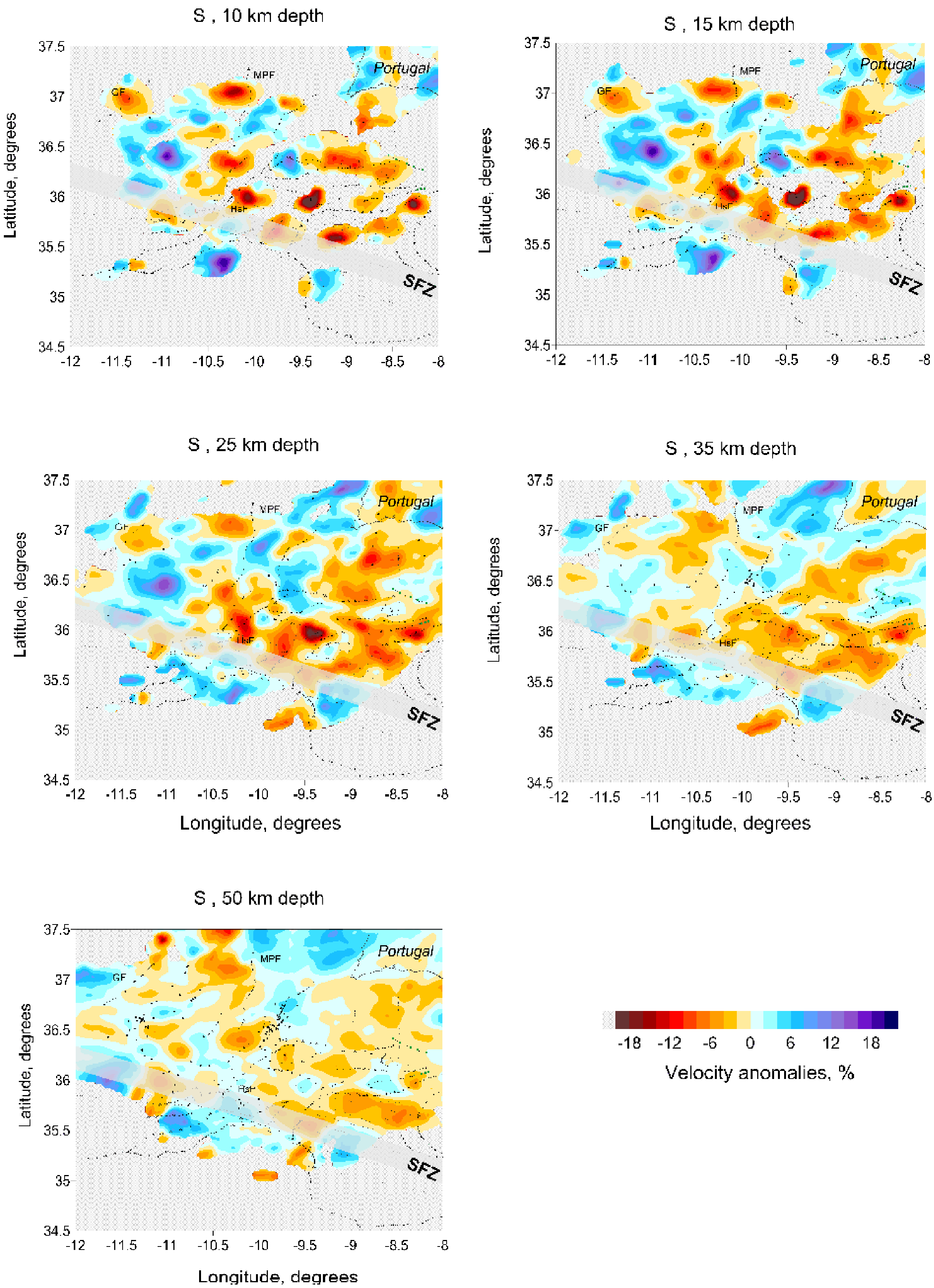
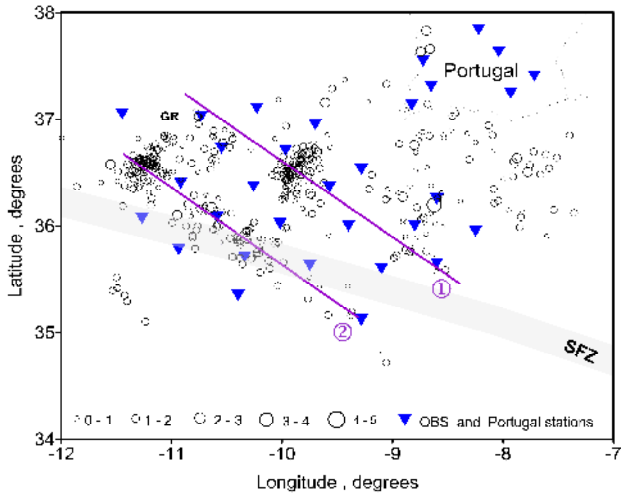


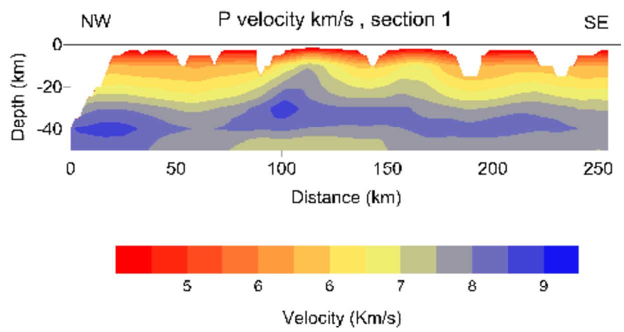
Fig. 5: Horizontal sections of S-velocity anomalies. Solid lines show the existing faults and dotted lines show possible strike-slip faults, and black dots show the epicenters location given by tomography program and inclined gray line represent the SWIM fault zone (SFZ).

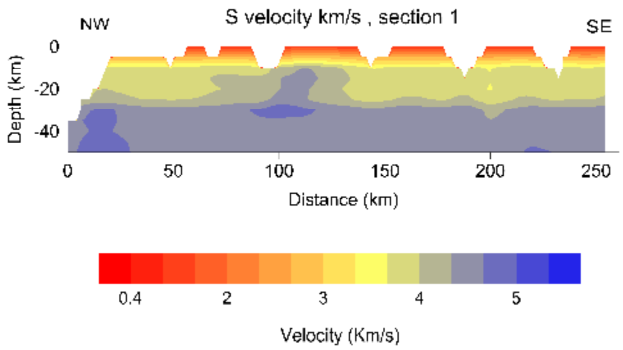
Profile 2 (Figure 6b) clearly shows that the Gorringe bank is an anomaly that involves a mantle uplift and that this topographic feature comes from deep within the mantle. This feature clearly stands out in the tomograms of Figures 4 and 5 at depths of 10 km, 15 km and 25 km. A similar feature is shown by vertical section 1 (Figure 6b) which shows a mantle uplift at the level of the São Vicente fault coinciding with the Marques de Pombal Plateau (Figure 5 of [30]). Thus, the Marques de Pombal Plateau is associated to an anomaly related to a deep mantle uplift as well.

Finally, our velocity profiles of Figure 6 do not show any indication of subduction to the SE of our study area.



(a)





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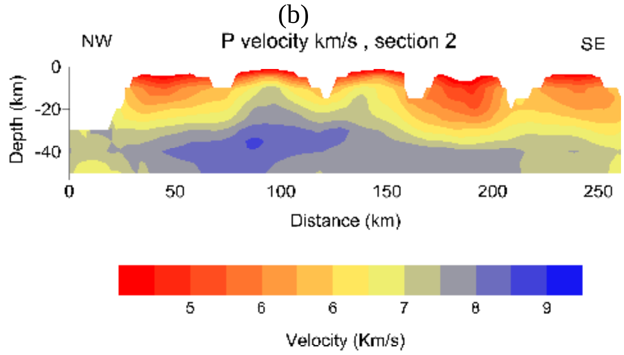
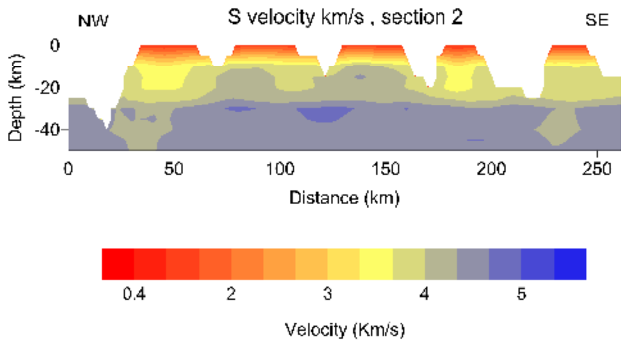




(b)

Fig.6 : Positions of profiles 1 and 2 (a), And P- and S-velocity distribution in vertical cross-sections 1 and 2, (b).

VII. Conclusion

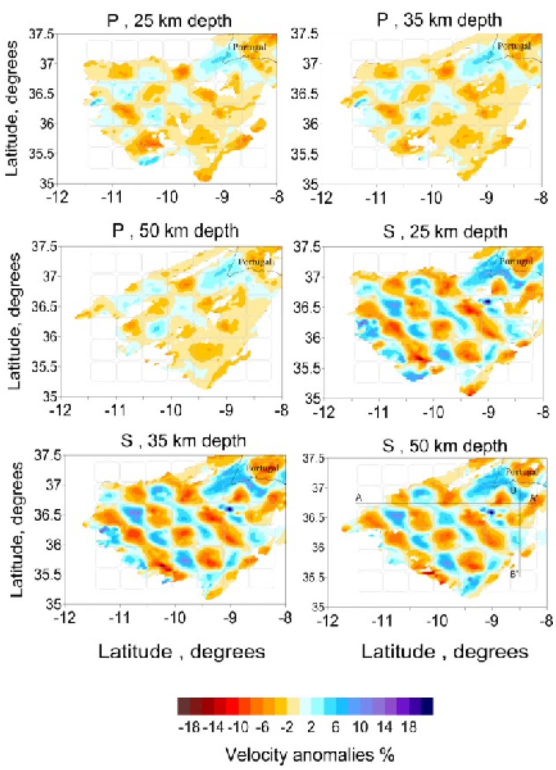
The recorded OBS seismicity data set used in this study has revealed a wealth of new information. Thus, these data reveal that most of the seismicity in the Gulf of Cadiz occurs at depths that vary between 20 and 80 km. Very few events occurred at depths shallower than 20 km. Prominent clusters of seismicity are found to be associated with the Gorringe bank, at the SW branch of the horseshoe fault and along the Marques de Pombal Plateau and the São Vicente fault. Diffuse seismicity is observed offshore to the south of Portugal and very little seismicity along the accretionary wedge. A NW-SE band of seismicity is further observed to the SW of our study area. The hypocenters along this band have depths that vary mostly from 35 to 80 KM.

The tomographic inversion of the recorded seismic data yielded results that indicate that patterns of velocity anomalies within the study area are generally oriented along NE-SW and NW-SE directions. Both the P- and S-velocity distributions show that a low velocity zone is found at the SE of our study area. At shallow depths, this LVZ is interpreted as corresponding to thick sediments associated with the accretionary wedge. The velocity tomograms indicate that the Moho underneath the Gulf of Cadiz has an average depth of 30 km.

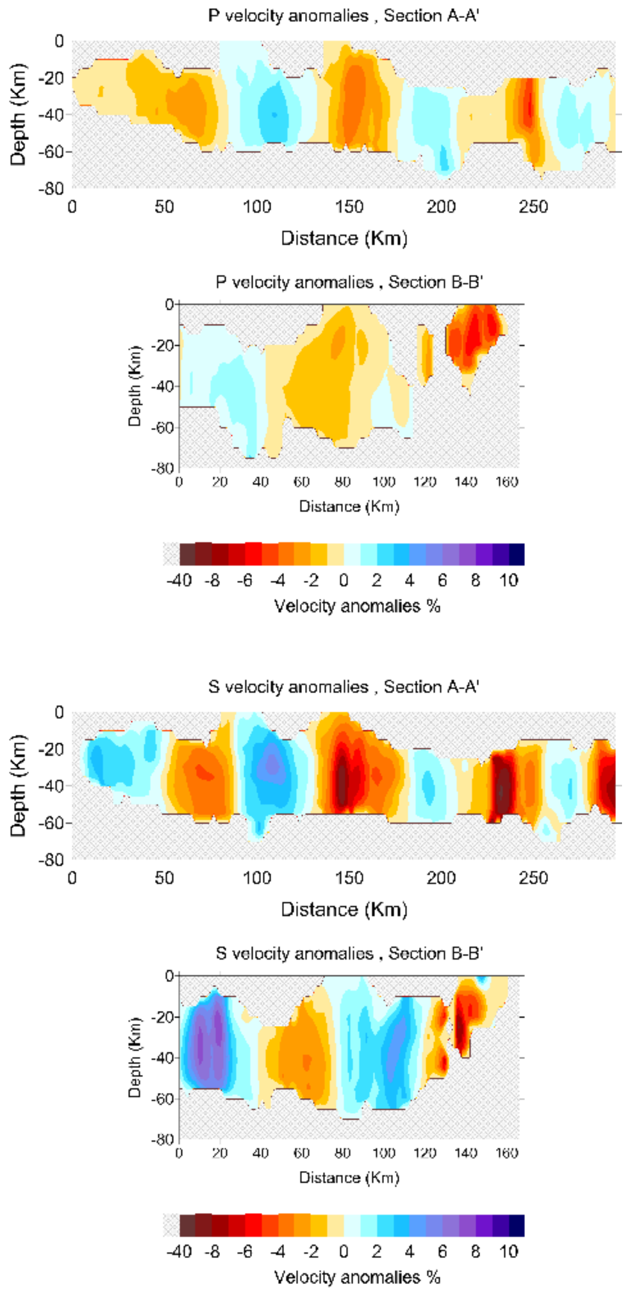
On the other hand, higher velocity anomalies are found to the NW and to the north of our study area. The NW anomaly coincides with the Gorringe bank, and its prolongation in depth clearly shows that this bank is not a surficial feature, but is rather connected to a deep mantle uprising. Similarly, our inversion results show that the Marques de Pombal Plateau is related to a deep mantle anomaly. Both the Gorringe ridge and the Marques de Pombal Plateau anomalies are associated with high levels of seismicity, thus, indicating that the mantle process behind their uplift is likely to be still ongoing.

Appendix

The checkerboard test is a reliable technique that helps examine the resolution of the used data, before inversion. We performed several series of synthetic tests in order to get the optimum parameterization parameters. The average amplitude of noise was defined at 0.1 s and 0.1 s for P and S waves, respectively. Figures 7 show the result of checkerboard tests, in map view at depths between 25 and 50 km and in two vertical sections AA’ and BB’. It can be seen that in the upper section the periodic anomalies are reconstructed in most parts of the study area.



(a)



(b)

Fig. 7: Checkerboard test performed for P and S waves in horizontals sections (a), and vertical sections (b).

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