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# Development of a 3D velocity Model for Improving the Location of Potentially Induced Earthquakes in the Gulf of Valencia

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## SUMMARY

On September 2013, unusual seismic activity was detected around an underwater gas storage plant in the gulf of Valencia (Spain). According to the reports by the Spanish National Geographic Institute, more than 550 occurred during two months, the strongest having a magnitude of Mw=4.2, which took place after the gas injection activities halted. The low magnitude of the events (only 17 earthquakes had magnitudes greater than 3), their long event-to-station distance, and the inhomogeneous station distribution, made the location problem to be a great challenge. Here we present a preliminary relocation of this earthquake sequence using absolute and relative methods. We also present a new 3D shear-wave velocity model estimated from inversion of Ambient Noise Tomography data which will serve to obtain more accurate seismic-wave travel times to improve the earthquakes location in this area. The interpretation of the results in terms of the tectonic structure of the region is in progress.

## Introduction

On September 2013, unusual seismic activity was detected around an underwater gas storage plant in the gulf of Valencia (Spain). In the last 14 years the earthquake rate recorded in this area was around 1 event per year, but it changed to several hundred per month from September to November 2013. According to the reports by the Spanish National Geographic Institute, more than 550 occurred during two months, the strongest having a magnitude of Mw=4.2, which took place after the gas injection activities halted. This sudden seismicity increase was simultaneous to the start of gas injection activities in a depleted oil reservoir offshore the eastern Spanish coast (Figure 1a). Besides this temporal coincidence, the epicentral area of the earthquake sequence was located close to the gas injection well, according to the Spanish National Geographic Institute (IGN) catalogue. The gas injection activities halted on September 17, 2013, but the high seismicity rate lasted until the end of October.

Earthquake magnitudes ranged between mbLg 1.8 and 3.0 during the gas injection. Earthquakes with higher magnitudes occurred from seven days after the gas injection was halted. The strongest earthquakes had magnitudes greater than 4 and occurred on October 1, 2013 (Mw = 4.2) and were followed by two earthquakes the day after (Mw = 4.1). Several earthquakes from this sequence were felt with intensities II or III by the population at the closest coastal villages and they caused a high social and media impact.

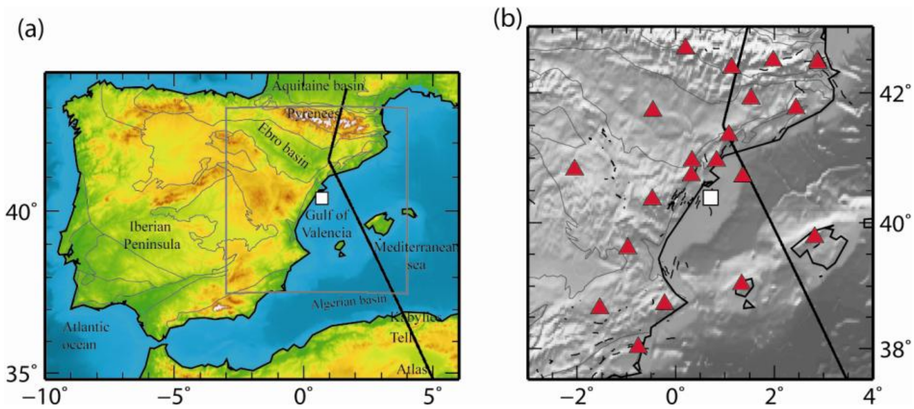


***Figure 1*** *(a) Map showing the location of the gas injection facility (white square).The grey lines are the contours of the Iberian peninsula geologic provinces. The black line denotes the profile shown in Figure 3. The grey square indicates the limits of Figure 1b. (b) Map showing the locations of the seismic stations (red triangles) used to locate the earthquakes. The dashed black lines indicate faults.*

Although there is a temporal and spatial coincidence of the earthquake sequence with the gas injection activities, the uncertainties of the hypocenter locations do not allow to relate the earthquakes to a specific fault or to identify the temporal evolution of the seismicity to evaluate correctly the seismic hazard. These uncertainties are due, in part, to the long distance from the recording seismic stations to the epicentral area (Figure 1b), to the azimuthal gap of the network geometry and to the small magnitude of these earthquakes.

The velocity reference models used also affect the accuracy of the earthquake locations, especially if the area is highly heterogeneous. There are several 2D crustal seismic models from deep reflection and refraction profiles (e.g., *Torné et al.*, 1992; *Vidal et al.*, 1998; *Roca et al.*, 2004) close to the epicentral region. As far as we know, however, a 3D seismic crustal model of the Western Mediterranean region does not exist. Inversion of surface-waves dispersion curves computed with Ambient Noise Tomography (ANT, *Sabra et al.*, 2005; *Shapiro et al.*, 2005) allow computing shear-wave velocity crustal models at a regional scale. In this work we improve the preliminary hypocentral locations of this earthquake sequence and present a 3D shear-wave seismic model from ANT results that can be used to compute the seismic-wave travel times more accurately to obtain more precise earthquake locations.

## Earthquake location method

In this study we use two algorithms to solve the location problem. The first one is the NonLinLoc software package (Lomax et al.,2000; http://alomax.free.fr/nlloc/) which provides a probabilistic solution to the location problem by means of a non-linear earthquake location technique. The location algorithm is based on the formulation proposed by Tarantola and Vallete (1982). The travel-times between each station and all nodes of a 3D spatial grid are calculated by means of the Eikonal finite-difference algorithm of Podvin and Lecomte (1991). To compute the complete, probabilistic solution in terms of the Probability Density function (PDF) in 3D space for the hypocenter location, we use in this work the Equal Differential Time (EDT) likelihood function (Font et al., 2004) which is robust in the presence of data outliers. In this study, the maximum likelihood hypocenter and the PDF have been estimated using the accurate and reliable Oct-Tree Importance sampling algorithm. This location method can be used with either 1D or 3D velocity models.

The obtained locations are then relocated using the HYPODD software package of Waldhauser and Ellsworth (2000). It is a double difference algorithm that provides accurate relative hypocenter locations by minimizing the effects of un-modeled velocity structure without the use of station corrections. It is a reliable algorithm that has proved be very useful for relocating small magnitude earthquakes. The algorithm estimates relative locations within earthquake clusters by minimizing residual travel time differences for a pair of earthquakes at a single station. In this work, we chose the conjugate Gradient Least Squares (LSQR) method to minimize the travel time residuals which is capable to handle large earthquake populations.

## Locations using a 1D velocity model

The accuracy of seismic locations is closely related to the velocity reference model used for its determination. In this study we used a 1D velocity model to perform a preliminary location. It is based on the 2D velocity model of Vidal et al. (1998) who interpreted a deep seismic reflection profile in the Valencia through area. Phase readings were obtained from the National earthquake catalogue of the IGN for the time period September 10 to November 4, 2013. The locations of the earthquakes, which occurred offshore, are largely conditioned by the geometry of the monitoring network. For this reason, we only used data from 51 earthquakes with magnitudes greater than 2. Moreover, in order to close as much as possible the azimuthal gap, data from seismic stations located less than 300 km from the gas injection facility were considered. The earthquake locations obtained with NonNinLoc are shown in Figure 2.

Relocation results using the double difference HYPODD software (Figure 3) show a redistribution of earthquakes in a variety of depths. The new hypocenter locations present a different pattern depending on the date of occurrence. Earthquakes occurred during the injection up to three days after it was stopped (on September 17, 2013) have a scattered distribution of epicentres and depths. The following earthquakes (from September 20 to September 30, 2013) are confined to a small area in a vertical plane with North-South direction. The third hypocenter subset comprises the biggest events with magnitudes Mw > 4.0. This subset appears to occur northeast of the previous subset of events and is located between 2 and 5 km in depth. The earthquakes appear to be located to the east of the Amposta fault.
Deeper analysis of these relocations will allow us to interpret the history of the seismicity evolution during this time period and to correlate it with human made changes and/or with the activation of local faults.

## Development of a 3D velocity model

3D velocity models play an important role in improving location accuracies of small events. In this study we computed the first 3D shear-wave velocity model for the region from joint inversion of group and phase velocity of Rayleigh wave fundamental mode. Input dispersion curves were obtained by *Silveira et al.* (2013) using Ambient Noise Tomography. For the analysis, we first inverted phase and group dispersion curves from 8 s to 30 s of period in a grid of 0.5ºx0.5º to get a 1D shear wave velocity model at each node. We defined a model composed of three layers of constant velocity over a half-space, with parameters varying in a wide searching space. The accepted values at each node have a L2-norm lower or equal to 0.2 km/s. We only allow optimum models with velocity increasing with depth. Combining all the 1D estimates we obtained a final 3D velocity model for the whole area.

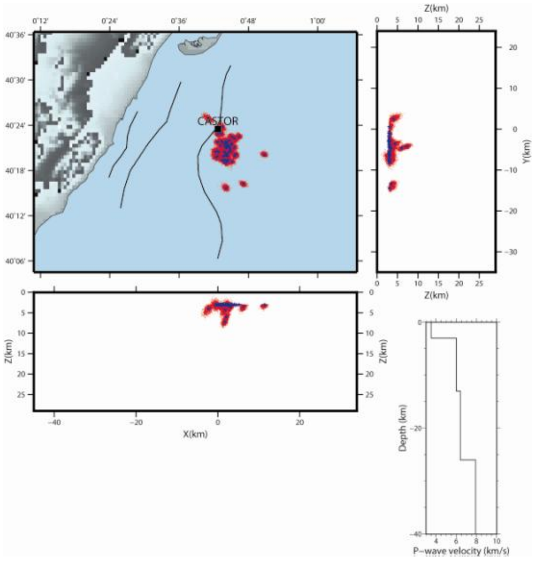


***Figure 2** Locations obtained with NonNinLoc software and the P-wave velocity model used (Vidal et al., 1998). Grey lines on the map are the main faults of the region.*

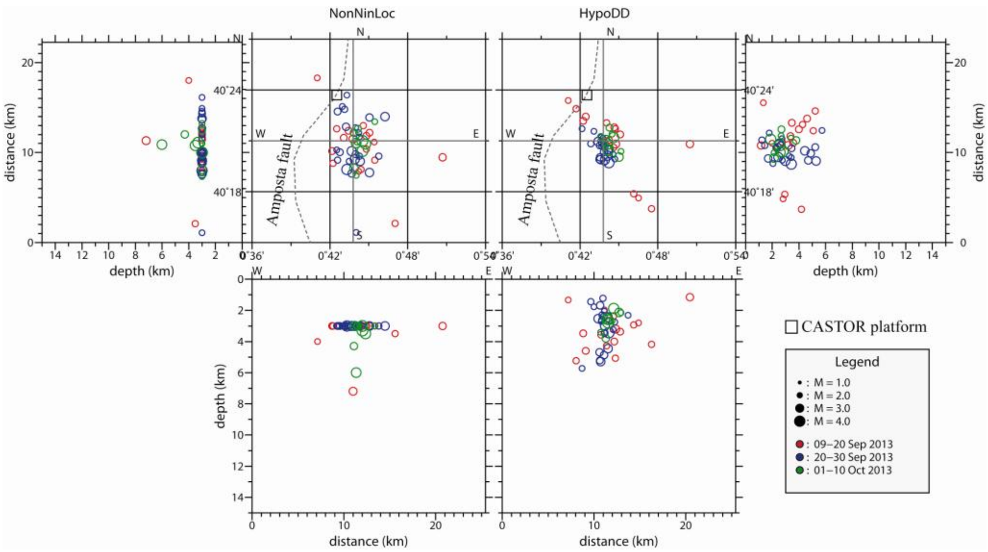


***Figure 3** Comparison of absolute and relative hypocenter locations.*

Figure 4 shows the results of the 3D shear-wave velocity model obtained. It covers the whole area from the crust to the upper mantle with a horizontal resolution of 0.5º (~55 km). Although a detailed interpretation of this model is not the objective of this paper, we compare it with other lithospheric studies and tectonic features to validate our results. The model shows low velocities (~2.5–2.7 km/s) in the Valencia Trough (VT) thus indicating a deep sedimentary basin (Figure 4a). It is observed that the velocities obtained for the VT are lower than the 2.9 km/s of the 2-D P-wave velocity model of *Vidal et al. (1998)*, considering $v_P/v_S$ equal to 1.75. Inland, at 10 km depth, we observe a velocity dichotomy between western and eastern Pyrenees. The low velocities on the western part correspond to Meso-Cenozoic ranges and the high central-eastern velocities with the axial zones of the range. At this depth we find the highest velocities offshore (~3.9 km/s) on the Northeastern part of the VT where geodynamical models infer a backarc extension during the Western Mediterranean evolution (e.g., *Doglioni et al.*, 1999). Deeper, at 20 km, we obtain the highest velocities (4.0-4.6 km/s) along the Algerian Basin and the Valencia Trough, in contrast with the low velocities in the Balearic Promontory in accordance with a thicker crust on this area than on the vicinity basins. High velocities of this order are also observed onshore indicating the presence of a thinner crust than the surrounding inland areas. At 40 km, highest offshore mantle velocities are found along the Balearic Promontory and at the North of the Algerian Basin. In contrast, the lowest inland crustal velocities are found beneath the central Pyrenees indicating a thick crustal root on this part of the orogen.

To validate the model we compare it with the well-known seismic lithospheric structure from numerous deep seismic refraction/reflection profiles along the TRANSMED II transect shown in Figure 1a. These crustal results are compiled and summarized in *Roca et al.* (2004). Our model shows minor differences with the TRANSMED II transect from the Pyrenees to the South of the Algerian basin. Beneath the Kabilies-Tell-Atlas region our velocity model shows a thinner crust in agreement with the geophysical-petrological model of *Carballo et al.* (2014). Moreover, there is a good agreement between the crustal bodies defined by *Carballo et al.* (2014) based on previous studies and our crustal velocities from the North to the Algerian Basin. Further to the south our crustal velocity distribution does not fit their crustal bodies.
These preliminary results show high crustal heterogeneity of the area that will affect the seismic-wave travel times coming from different azimuths. This is not considered when using 1D velocity models to solve the earthquake location problem. The use of an accurate velocity model may help to obtain better locations in spite of the distant and inhomogeneous azimuthal station distribution of the region.

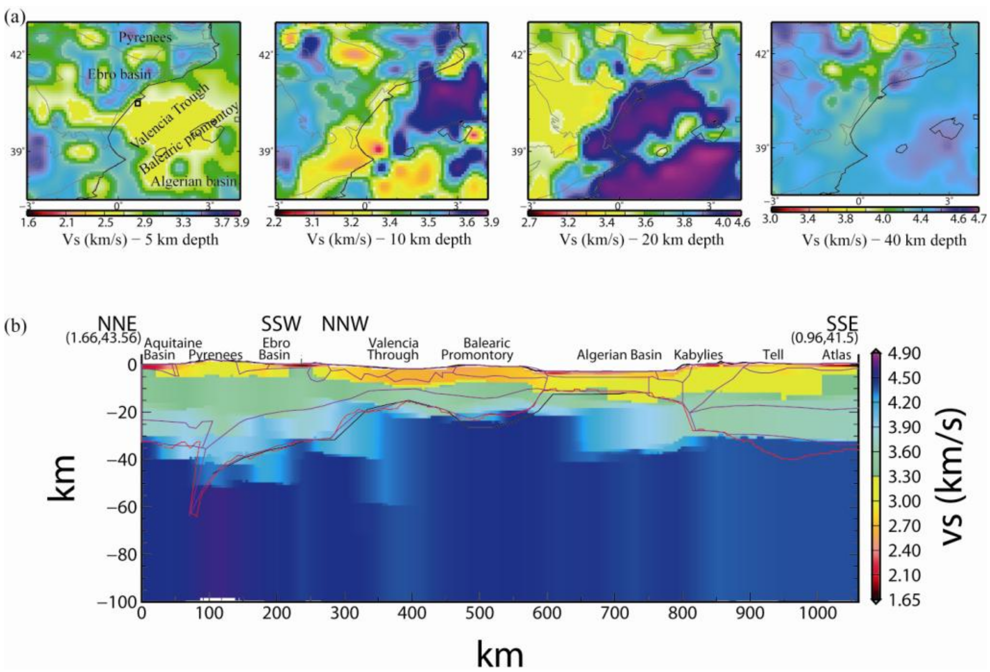


***Figure 4*** *Preliminar 3D shear-wave velocity model. (a) Horizontal sections at different depths. (b) Cross-section along profile shown in Figure 1a. The black line indicates the moho from Vidal et al. (1998); thered line the moho from Roca et al. (2004); and purple lines crustal bodies and moho from Carballo et al (2014).*

**Conclusions**

Absolute and relative hypocenter relocations of the earthquake sequence occurred around a gas injection facility in the Gulf of Valencia show that the events occurred at shallow depths to the South of the gas injection well and to the East of the Amposta main fault. The locations, however, need to be further improved to follow in detail their temporal evolution and to correlate them with a possible activation of the fault system.

As a step towards getting more accurate earthquake locations in the region, we have developed a preliminary 3D shear-wave velocity model computed from surface-waves ambient noise tomography. Our results agree with the main tectonic features of the region and with some previous 2D lithospheric studies. They show seismic heterogeneity in the area that affects seismic-wave propagation. This model will be used to improve the travel time computation accuracy to get more precise earthquake locations in this region.

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