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Improving the location of induced earthquakes associated with an underground gas storage in the Gulf of Valencia (Spain)

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ABSTRACT

On September 2013, increased seismic activity was recorded near the CASTOR offshore underground gas storage (UGS), in the Gulf of Valencia (Spain). According to the reports by the Spanish Instituto Geográfico Nacional (IGN), more than 550 events occurred during two months, the strongest having a magnitude of $M_w = 4.2$ which took place two weeks after the gas injection stopped. The low magnitude of the events (with only 17 earthquakes having m_{bLg} greater than 3), the lack of nearby stations, and the inhomogeneous station distribution made the location problem a great challenge. Here we present improved locations for a subset of 161 well recorded events from the earthquake sequence using a probabilistic nonlinear earthquake location method. A new 3-D shear-wave velocity model is also estimated in this work from surface-wave ambient noise tomography. To further improve the locations, waveform cross-correlations are computed at each station for every event pair and new locations are obtained from an inverted set of adjusted travel time picks. The resulting hypocentral solutions show a tighter clustering with respect to the initial locations and they are distributed in a NW–SE direction. Most of the earthquakes are located near the injection well at depths of about 6 km. Our results indicate that the observed seismicity is closely associated with the injection activities at the CASTOR underground gas storage and may have resulted from the reactivation of pre-existing unmapped faults, located a few kilometers below the reservoir.

1. Introduction

Starting on September 5, 2013 and during two months, a tight cluster of more than 550 earthquakes with m_{bLg} magnitudes ranging from 0.7 to 4.2 were located in the shallow offshore area of the Gulf of Valencia off the eastern coast of Spain. This seismic activity rate was extraordinary since, according to the IGN (Instituto Geográfico Nacional) earthquake catalog (http://www.ign.es, last accessed: April, 2015), only ten earthquakes with magnitudes 2.0 or greater had been recorded in this area in the previous thirty years, the largest were a m_{bLg} 3.3 event that occurred on January 10, 1981 and a m_{bLg} 3.1 on April 8, 2012 (Fig. 1). The sudden seismicity increase coincided in time with the initial phase of the injection of the base gas in a newly developed underground natural gas storage (UGS) facility (CASTOR) off the eastern Spanish coast. Besides the temporal coincidence, the epicentral area of the earthquake sequence was located close to the gas injection well. The base gas injection finished on September 16, 2013 but the high seismicity rate lasted until the end of October. According to the IGN reports, the strongest earthquake ($M_w = 4.2$) took place on October 1, 2013, two weeks after the gas injection stopped, and it was followed by two $M_w = 4.1$ events the day after. Seismic activity declined rapidly six weeks after the gas injection finished.

Several earthquakes from this sequence were felt with EMS intensities II or III by the population at the closest coastal villages (Alcanar, Vinarós, Benicarló, etc.) and caused high social and media impact. According to the seismic hazard map of Spain (IGN, 2013) horizontal peak ground acceleration values between 0.04*g* and 0.05*g* are expected in the area for a 475-year return period. These levels are the lowest considered in the current Spanish seismic regulations (NCSR-02, 2003), but they do not take into account the occurrence of seismicity induced by human activities. According to the IGN historical macroseismic database, six earthquakes with maximum EMS intensity V have occurred in this region prior to the year 1920. It is worth noting that the surrounding region is densely populated and industrially developed, with singular infrastructures such as nuclear power plants, and those of the chemical and oil industry. This situation led the

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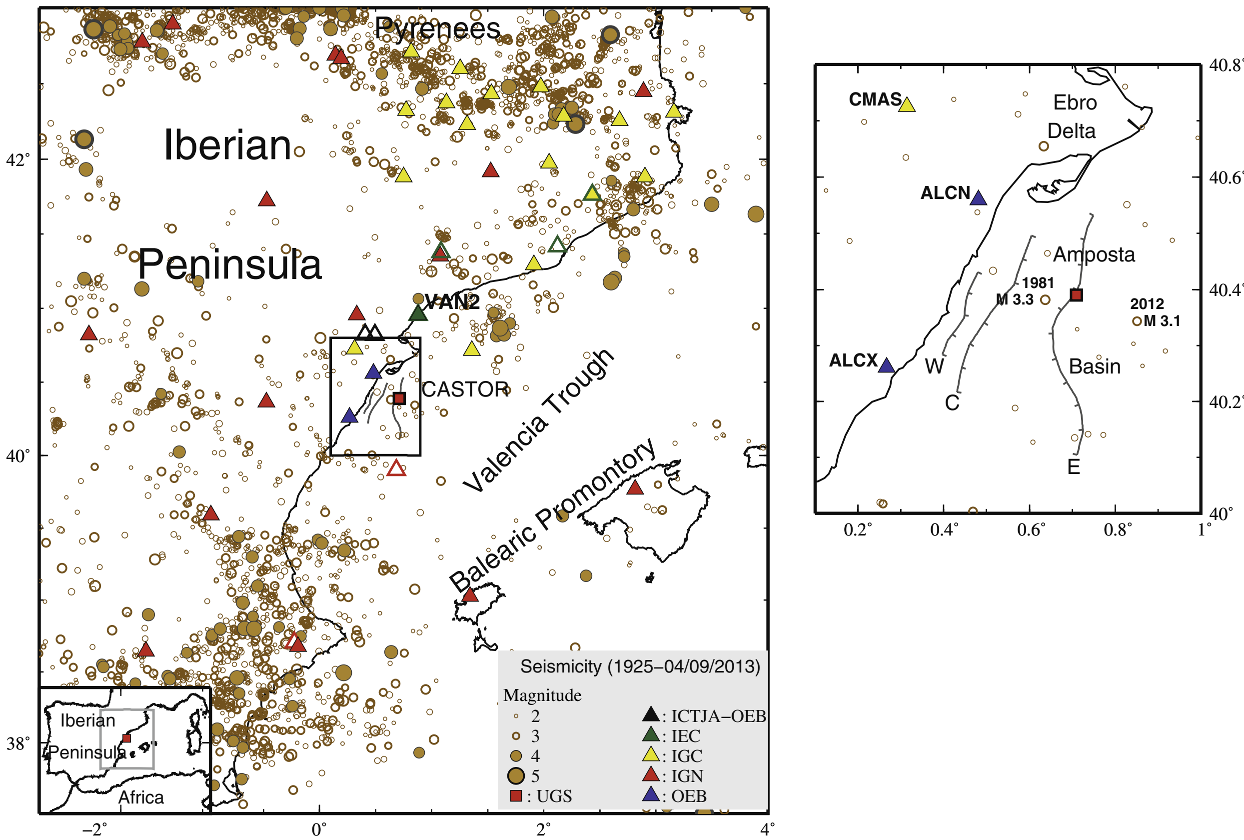

Fig. 1. Seismicity map of the eastern Iberian Peninsula according to the IGN seismic catalog. Triangles indicate the location of the seismic stations from the networks compiled in this study. Filled triangles are analyzed stations. Empty triangles indicate stations that were not used for various reasons (their position is close to another station, they were deployed after the seismic sequence, etc). The red square indicates the location of CASTOR underground gas storage (UGS). The W, C and E denote the Western, Central and Eastern Amposta faults, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Spanish government to suspend the activities and put the project on hold (BOE, 2014).

Accurate hypocentral locations are important to identify lineaments associated with faults and other seismically active structures. However, in this case the location uncertainties of the available seismic catalog are significant due to the lack of seismic stations in the epicentral area (Fig. 1). The nearest station is located inland, approximately 26 km to the NW of the injection well. Moreover, the azimuthal gap of the network geometry is high because of the lack of offshore seismic stations. This gap is partially closed to the NE and to the SE at larger distances (65 and 160 km, respectively). The reference velocity models used also affect the accuracy of the earthquake locations, especially if the area is highly heterogeneous. In consequence, it has been difficult to resolve the faults associated with the observed seismicity (e.g., Cesca et al. 2014).

In this work we obtained high-precision earthquake locations for a subset of 161 well recorded earthquakes in the sequence. We observe that the quality of the locations is greatly conditioned by the uneven azimuthal geometry and large epicentral distances of the available recording stations. Nevertheless, our results demonstrate that a major improvement in location accuracy can be achieved with the use of an accurate three-dimensional (3-D) velocity model and differential times among event multiplets obtained through waveform cross-correlation (Fig. 1).

2. Setting

The study area is located in the western margin of the Valencia Trough, which is a NE–SW trending extensional basin characterized by low strain and low-to-moderate seismicity. The seismic sequence was located offshore, in the Amposta Basin, close to the Western, Central and Eastern Amposta faults (Fig. 1). The Western and Central Amposta faults are 18 km and 35 km long, respectively, and dip 60° toward the SE. The Eastern Amposta fault is 51 km long and dips 60° to the NW (Roca and Guimerà, 1992; Perea, 2006; Perea et al., 2012). The stress field in the northwestern Valencia Trough is characterized by a normal-faulting

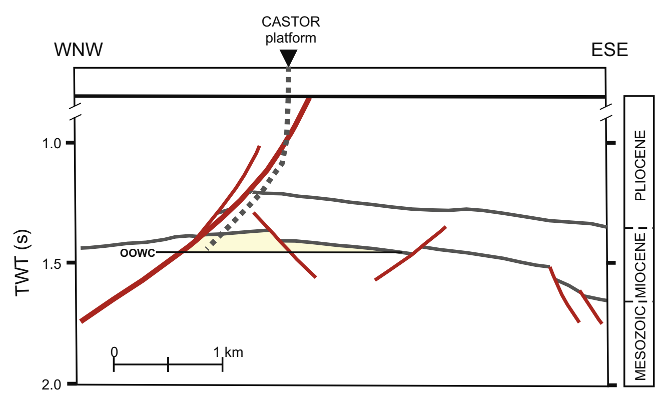

Fig. 2. Sketch of the Amposta structure along the WNW–ESE seismic profile of Seemann et al. (1990). The vertical scale is plotted in two-way traveltime. The approximate location of the Castor well (dashed line) is shown together with the original oil–water contact (OOWC) at 1940 m in depth. The yellow area is the rough location of the gas reservoir. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)