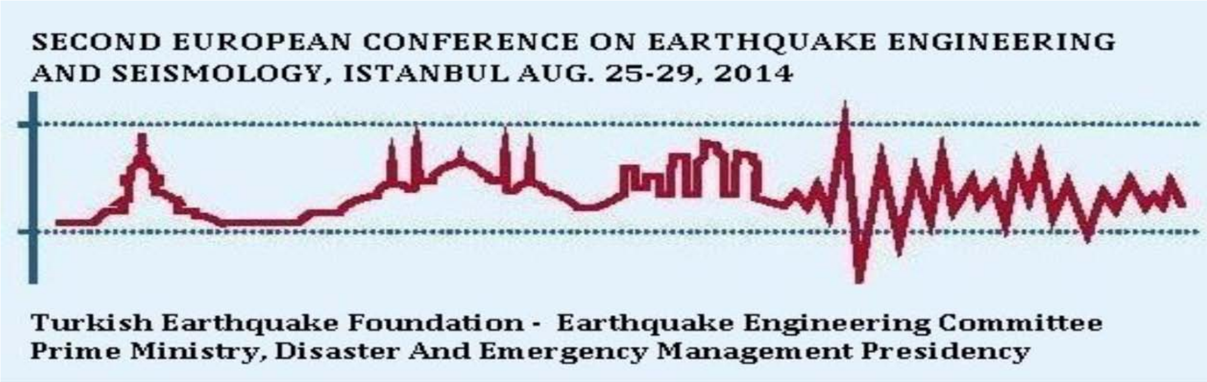

SEISMIC ANISOTROPY AND GROUND DEFORMATION RESULTS IN THE SANTORINI VOLCANIC COMPLEX

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The Santorini (Thera) Volcano is one of the most active in the Eastern Mediterranean area. A major Plinian eruption in the middle of the 17th century BC, causing a massive regional tsunami (Sigurdsson et al., 2006) and resultant destruction of the Minoan civilization, formed essentially the present caldera of the Santorini Volcanic Complex (SVC; e.g. Druitt and Francaviglia, 1992) which consists of Santorini, Therassia, Aspronissi and the Kammeni (Palea and Nea) Islands. After that catastrophic episode, the volcano has been relatively quiet. The last significant eruption with lava outpour occurred in 1950 (Heiken and McCoy, 1984). Since early 1980, no significant ground deformation has been observed or inferred by microgravimetric and EDM studies (Lagios, 1995; Stiros et al., 2010).

The seismicity of the SVC area was moderate to low (Makropoulos et al., 2012) until the initiation of the unrest period in 2011 which lasted for approximately one year. During this period intense seismic activity was observed, for the first time during the instrumental era, in the Santorini Caldera. Accurate event locations were determined using recordings of the stations belonging to the Hellenic Unified Seismological Network (HUSN), the HYPOINVERSE algorithm (Klein, 1989) and local 1-D velocity model, while the duration magnitude was calculated according to the formula proposed by Kaviris et al. (2007). As a next step a relocation procedure was carried out, by applying the HYPODD (Waldhauser and Ellsworth, 2000) algorithm, yielding 1493 events classified in five spatial groups one of which, comprising of 536 events, lies within the Caldera.

The existence of seismic birefringence was observed during the analysis of the waveforms of the three component stations, provoking an anisotropy study. Events lying within the shear-wave window were initially traced, taking the critical angle equal to 45˚. The selected events are characterized by clear and impulsive shear wave phases, whose amplitudes are larger on the horizontal components. Events that fulfill the strict selection criteria, applied to avoid effects of the free surface and to reject converted phases, were obtained for eight stations of the SVC area, seven in Santorini and one on Therasia Island. For each case the polarigram (Bernard and Zollo, 1989) and the hodogram representations were used to determine the anisotropy direction, the time delay between the two split shear waves and the source polarization direction. These methods have succesully been applied for anisotropy studies in Greece (i.e. Papadimitriou et al., 1999; Kaviris et al., 2010).

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More than 300 splitting parameters results were determined, revealing the existence of two main aniosotropy directions, as anticipated by the activation of the Santorini Caldera area. The first, determined for three stations of the SVC area is in a general NE-SW direction, while the second, striking NW-SE was obtained for five stations. The existence of two different directions can be explained by the Anisotropic Poro-Elasticity (APE) model, proposed by Crampin and Zatsepin (1997). This stress-sensitive model is based on the changes occurring in the saturated cracks, initially aligned due to the general stress field, being able to interpret anisotropy directions that are not in agreement with the dominant stress field. The NE-SW anisotropy direction is coherent with the general fault direction and the regional extensional stress field (Dimitriadis et al., 2009). On the other hand, the NW-SE anisotropy directions for three stations are in an almost radial distribution towards the Santorini Caldera.

A tomographic algorithm, LOTOS-10 code (Koulakov, 2009), designed for simultaneous inversion of Vp, Vp/Vs ratio and source coordinates was used in the current study. The LOTOS code requires as input the data of station coordinates and the arrival times from locally recorded seismicity. A nodal representation was employed, since the velocity field that is reconstructed by a three-dimensional grid does not assume a specific geometry of heterogeneities, while checkerboard tests are performed in order to reproduce the procedure of real data processing and check the inversion results reliability. The collapsed regions of the Santorini Volcanic Complex (SVC) are characterized by a shallow and broad low Vp anomaly down to 8 km depth that it is mainly observed in the south-southeast of Nea Kammeni Island. Two selected cross sections, performed at N37°E and N127°E directions reveal an almost circular-shaped anomaly of high Vp/Vs ratio between 4 and 7 km depth coinciding with a narrow zone of low Vp and Vs perturbations, to the north of Nea Kammeni Island, which can be connected to the magmatic chamber.

The GPS network in SVC was first installed in 1994 and remeasured several times up to December 2012 (Lagios et al., 2013). Station No. 07 (SW of Santorini) was chosen as local reference station, because of its location on the center of the Alpine basement in Santorini and its anticipated better geological and tectonic stability compared to other parts of the complex. A strong radial ground deformation is evident, for the period 2011- June 2012, particularly at the northern part of the caldera with amplitudes ranging from 30-60 mm, while the uplift is up to 30-65 mm. In the southern part of the caldera, the horizontal GPS displacement vectors are of much smaller values (up to 29 mm), showing also a differentiation from the radial pattern observed in the northern part of the caldera. Displacement vectors ranging from 12-29 mm are noticed pointing SW in the southern part of Santorini, together with the broader area underlied by the Alpine basement where the motion is to SE, demonstrating the regional motion with respect to ITRF2008. The strain field was also calculated based on the GPS displacement vectors. The evident extensional pattern observed in both axes of the strain field is very clear in the northern part of the caldera.

For the GPS remeasurement period June to September 2012, the overall image of the ground deformation is significantly different from the previous one. Small displacement amplitudes that do not exceed 12 mm were observed in both horizontal and vertical components at almost all of the stations. The radial pattern of deformation that was prevailing previously does not exist anymore in the northern part of the caldera. The deformation amplitudes have been reduced at the Kammeni Islands by an order of magnitude. The horizontal vectors have been rotated to an almost SSE direction. In south Santorini, the deformation seems to preserve the previous pattern of motion but with decreased amplitudes.

The radial type of deformation observed particularly at the northern part of the caldera deduced by the DGPS results (period 2011 to June 2012) constitutes a typical case of a magma influx at a certain depth producing this deformation represented by an expanding Mogi point source (Mogi, 1958). Modelling attempts were performed to determine if pressure changes in the high-level magma chamber could account for the observed deformation. It was found that the best fit of the offshore Mogi source is located at coordinates [25^{o} 23’ 19.774” E, 36^{o} 25’ 33.352” N] in WGS’84 datum, at a depth of $4{,}900^{+500}_{-500}\,\mathrm{m}$, and $V = 8.2^{+2.9}_{-1.0} \times 10^{6}\,\mathrm{m}^{3}$ with respect to ITRF2008. Generally, a fairly good match was achieved for most of the stations, particularly for the horizontal component, even though the calculated vertical components seem to be higher than the observed ones.

The joint interpretation of the DGPS and shear-wave splitting studies revealed coherent results of displacement vectors and mean anisotropy directions for the majority of the sites. However, certain discrepancies that were mainly observed in the central-western part of Santorini may be attributed to the local geological and tectonic characteristics of this area, where the maximum deformation during the unrest period was measured. A significant outcome of the comparison between the tomographic and the ground deformation studies is that the activated magmatic chamber was identified in the same volume, within the Santorini Caldera, north of Nea Kammeni Island. The latter significant result emphasizes the importance of multidisciplinary studies in such complex environments.

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