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A detailed seismic anisotropy study during the 2011–2012 unrest period in the Santorini Volcanic Complex

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ABSTRACT

The Santorini Volcanic Complex (SVC) is an area in the Southern Aegean (Greece) which has been characterized by low seismicity rates for the last decades, especially in the Santorini Caldera where they have been very low until 2010. This pattern changed completely in February 2011, when intense microseismic activity was initiated within the Caldera. During the manual analysis of the events, the shear-wave splitting phenomenon was observed, revealing the existence of an anisotropic upper crust in the SVC area. A detailed anisotropy study has been conducted using 231 events within the shear-wave window that fulfilled the selection criteria. The polarization direction of the fast shear-wave, the time-delay between the two split shear-waves and the source polarization direction were calculated after visual inspection, using both the polarigram and the hodogram representations. This procedure, applied for eight local stations, resulted in the determination of 340 splitting parameters. The obtained mean anisotropy directions are not homogeneous, revealing a complex regime in the activated area. Nevertheless, these results are explained by the APE model, related to the stress-sensitive behavior of fluid-saturated microcracked rocks. A detailed analysis of the temporal evolution of both the time-delay and anisotropy direction was carried out. The time-delays measured in the "band-1" window exhibit gradual increase and sudden drop that can be related to imminent bursts of seismicity, as well as to the major M_w = 5.1 and 5.2 events which took place about 40 km SW of Santorini on 26 and 27 January 2012, respectively. On the other hand, no significant temporal variations or 90° flips of the S_{fast} polarization direction were observed.

1. Introduction

The Santorini Volcanic Complex (SVC) is a part of the Greek Volcanic Arc, situated in the back arc of the Greek subduction zone, and consists one of the most important volcanic centers of the Aegean (Papazachos and Comninakis, 1971; Angelier et al., 1982). The SVC consists of five different islands: Santorini, Therasia, Aspronisi, Palea Kameni and Nea Kameni. The spatial distribution of the first three islands forms a ring inside which Palea and Nea Kameni lie (Vougioukalakis, 2002).

Concerning the tectonic setting of Santorini (Fig. 1), the continental crust under the island complex is approximately 30 km thick, while the region at the NE of the island is characterized by alternating horsts and grabens, separated from each other by normal NE–SW trending faults (Perissoratis, 1995; Piper and Perissoratis, 2003). These faults are formed by an extensional stress field trending NNW–SSE (Mercier et al., 1989), with the local compressional field in a NE–SW direction, and are passing below the submarine volcano Colombo and the Santorini Caldera (Druitt et al., 2002). They are also characterized as a kind of 'flower type' structure which was developed above a strike-slip fault running below the Columbo tectonic line (Sakellariou et al., 2010) and the Columbo cape (Vespa et al., 2006). These faults are the pathways through which the generated underlying magma reaches the surface, forming the Columbo volcanic chain (Nomikou et al., 2014a). Another important formation is the Kameni line of faults (Pyle and Elliott, 2006), which lies under the islands of Nea and Palea Kameni and the submarine volcano Columbo, trending NE–SW.

The volcanic activity of the island was initiated 0.6 million years ago and the formation of the present caldera took place after the Minoan explosion in 1610–1650 B.C. (Fouque, 1879; Bond and Sparks, 1976; Heiken and McCoy, 1984; Papadopoulos and Chalkis,

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1984; Fytikas et al., 1990; Druitt, 2014; Nomikou et al., 2014b). Since 1640 B.C. 13 explosions are known to have taken place, with the most recent one being in 1950. Present volcanic activity is produced from the two main volcanic centers of the island, namely Nea Kameni, situated at the centre of the caldera and the submarine volcano Columbo, approximately 7 km NE of Santorini.

Previous GPS studies in Santorini have shown that during 2006, 2008 and 2010 relative motions were almost absent in the area, indicating a very slow convergence rate until 2010 (Newman et al., 2012). Afterwards, Nea Kameni and SW Santorini present subsidence, while all the other parts of the SVC complex appear to be uplifted with the maximum value observed at Cape Columbo (Lagios et al., 2013). The larger horizontal displacement is determined at the SW part of Santorini (37 mm) and at Therasia (31 mm) with a NW direction. The northern part of Santorini is characterized by 15–21 mm horizontal displacement pointing NW (Papageorgiou et al., 2007).

The seismic activity of the volcanic arc of the Aegean, a part of which is the SVC area, is lower compared to the fore arc zone (Makropoulos and Burton, 1984; Delibasis et al., 1995). A great part of the seismicity is concentrated along a SW–NE trending zone, between Santorini and Amorgos Islands. The majority of these earthquakes are shallow, whilst a small amount takes place at the Benioff zone, between 100 km and 150 km depth (Hatzfeld et al., 1993; Bohnhoff et al., 2006). The observed shallow seismicity is caused by the activation of normal faults (Dimitriadis et al., 2009). A significant number of earthquakes have also occurred in the area of the Columbo volcano (Kolaitis, 2011). The majority of these epicenters is concentrated at the upper 5–8 km of the crust and is probably related to the magma accumulation below this submarine volcano (Bohnhoff et al., 2006). Focal mechanisms of these earthquakes indicate the existence of strike-slip faults (Dimitriadis et al., 2009).

The historical seismicity in the study region, presented with stars in Fig. 1, is relatively low. Four large earthquakes have occurred close to the Santorini Caldera in 198 B.C., 46 A.D., 1707 A.D. and 1866 A.D. (Papazachos and Papazachou, 2003; Stucchi et al., 2013). The largest (46 A.D., $M = 6.5$) was considered to be a

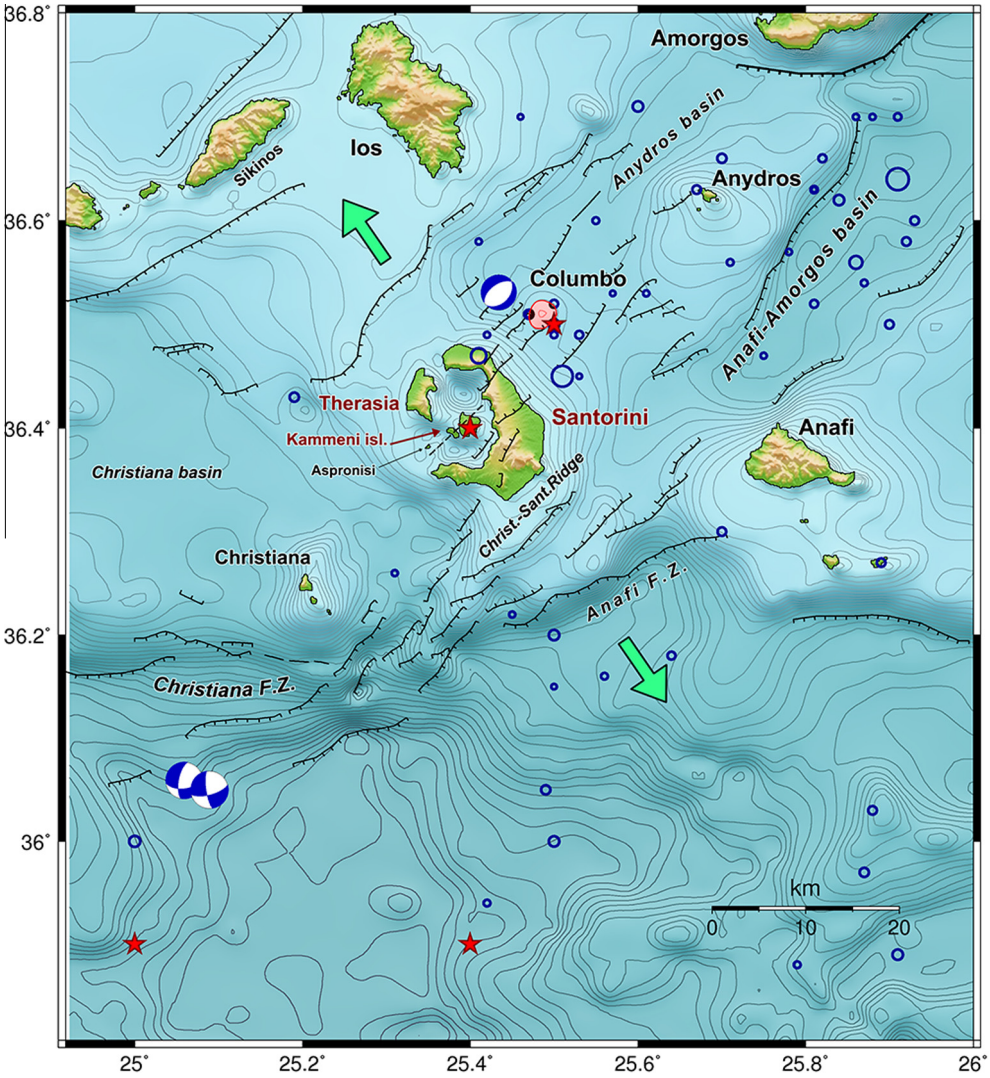

Fig. 1. Seismotectonic map of the broader area of the Santorini Volcanic Complex. Historic earthquakes are depicted by red stars (after Papazachos and Papazachou, 2003; Stucchi et al., 2013), while earthquakes with $M_w \geqslant 4.0$ that have occurred during the period 1900–2009 are represented by open blue circles (after Makropoulos et al., 2012). The displayed focal mechanisms belong to the major events of 26 June 2009 in Columbo and of 26–27 January 2012 in the Christiana fault zone. Green arrows show the approximate direction of regional extension. Fault lines are after Feuillet (2013), Sakellariou et al. (2010). The instrumental seismicity catalogue (1900–2009) and focal mechanisms data are available online in the website www.geophysics.geol.uoa.gr. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)