Journal of Volcanology and Geothermal Research 267 (2013) 57–67

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

Seismicity, Vp/Vs and shear wave anisotropy variations during the 2011 unrest at Santorini caldera, southern Aegean

K.I. Konstantinou [a,*], C.P. Evangelidis [b], W.-T. Liang [c], N.S. Melis [b], I. Kalogeras [b]

[a] Dept of Earth Sciences, National Central University, Jhongli 320, Taiwan
[b] Institute of Geodynamics, National Observatory of Athens, POB 20048, 11810 Athens, Greece
[c] Institute of Earth Sciences, Academia Sinica, POB 1-55, Taipei 115, Taiwan

ARTICLE INFO

Article history:
Received 13 May 2013
Accepted 1 October 2013
Available online 10 October 2013

Keywords:
Santorini
Caldera unrest
Stress
Shear wave splitting
Aegean

ABSTRACT

The Santorini caldera has been the focus of several large explosive eruptions in the past, the last of which occurred in the early 1950s. The volcano was dormant until early 2011 when increasing number of earthquakes accompanied significant intra-caldera uplift. This seismic activity was recorded by 8 temporary as well as 19 permanent seismic stations that were installed on Santorini and nearby islands after the onset of the unrest. Using data from January 2011 until June 2012 we calculated accurate relative locations for 490 events utilizing both catalog and waveform cross-correlation differential travel times of P- and S-phases. The distribution of relocated events exhibits a large cluster between Thera and Nea Kameni islands along the caldera rim, suggesting the activation of a preexisting ring fault. All hypocenters are located between 5 and 11 km resulting in a sharp cutoff of seismicity above and below these depths. We also used P and S travel times in order to calculate average Vp/Vs ratios and estimated shear wave splitting parameters (fast direction φ, delay time δt) for events within the shear wave window. The Vp/Vs ratios at several stations exhibit a majority of values consistently below the regional one (~1.77). Their temporal variations can be explained as periods of gas influx and depletion in the upper crust beneath the caldera. A comparison of δt for a number of earthquake doublets shows a progressive decrease of delay times towards the end of the unrest probably as a result of cracks closing owing to stress relaxation. The seismological observations presented here are compatible with petrological models that suggest the existence of a deep (11–14 km) dacitic magma reservoir and a shallower (<5 km) rhyolitic magma chamber.

1. Introduction

Caldera unrest is a feature frequently observed at large silicic centers and heralds the onset of a new phase in their activity which may or may not be followed by an eruption (Newhall and Dzurisin, 1988). A salient characteristic of such unrest is deformation that is expressed through significant uplift rates within the caldera and is usually interpreted as the accumulation of magma and/or exsolved volatiles at depth. This is accompanied in most cases by a large number of microearthquakes as well as increased influx of gas leading to geochemical anomalies in fluid composition. In many instances the intensity of these phenomena after reaching a climax progressively dissipates, resulting in subsidence and decreasing seismicity rates. Well-studied examples of caldera unrest include Campi Flegrei in Italy (Carlino and Somma, 2010 and references therein) and Long Valley, California (e.g. Hill et al., 2003) where seismological, geodetic and geochemical observations were jointly analyzed. These two examples also vividly highlight the problem of trying to predict whether a large eruption is imminent and how it would affect densely populated areas around the caldera.

The Santorini caldera lies in the southern Aegean and was formed after several cycles of explosive volcanic activity over the last 400 ka (Fig. 1) (Bond and Sparks, 1976; Heiken and McCoy, 1984; Druitt and Francaviglia, 1992; Vougioukalakis and Fytikas, 2005). The last of these cycles started with a large eruption that occurred in the Late Bronze Age (about 1628 BC) involving hydrovolcanic activity and producing pyroclastic flows that destroyed early human settlements on the nearby islands. The eruption and its consequences are often blamed for the rapid demise of the thriving until then Minoan civilization of Crete. After this eruption several smaller ones followed in 197 BC, 1707, 1866, 1925, 1939 and 1950 AD according to the Global Volcanism Database of the Smithsonian Institution (http://www.volcano.si.edu). The small islands of Palea and Nea Kameni that lie in the center of the flooded caldera were created by this activity and are also thought to be the possible sites of future eruptions (Pyle and Elliott, 2006). Thera, the largest and most populated island in the Santorini complex, will be particularly vulnerable to hazards stemming from a future eruption such as ashfall, ballistic projectiles and toxic gas

* Corresponding author.
E-mail address: kkonst@ncu.edu.tw (K.I. Konstantinou).

0377-0273/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jvolgeores.2013.10.001

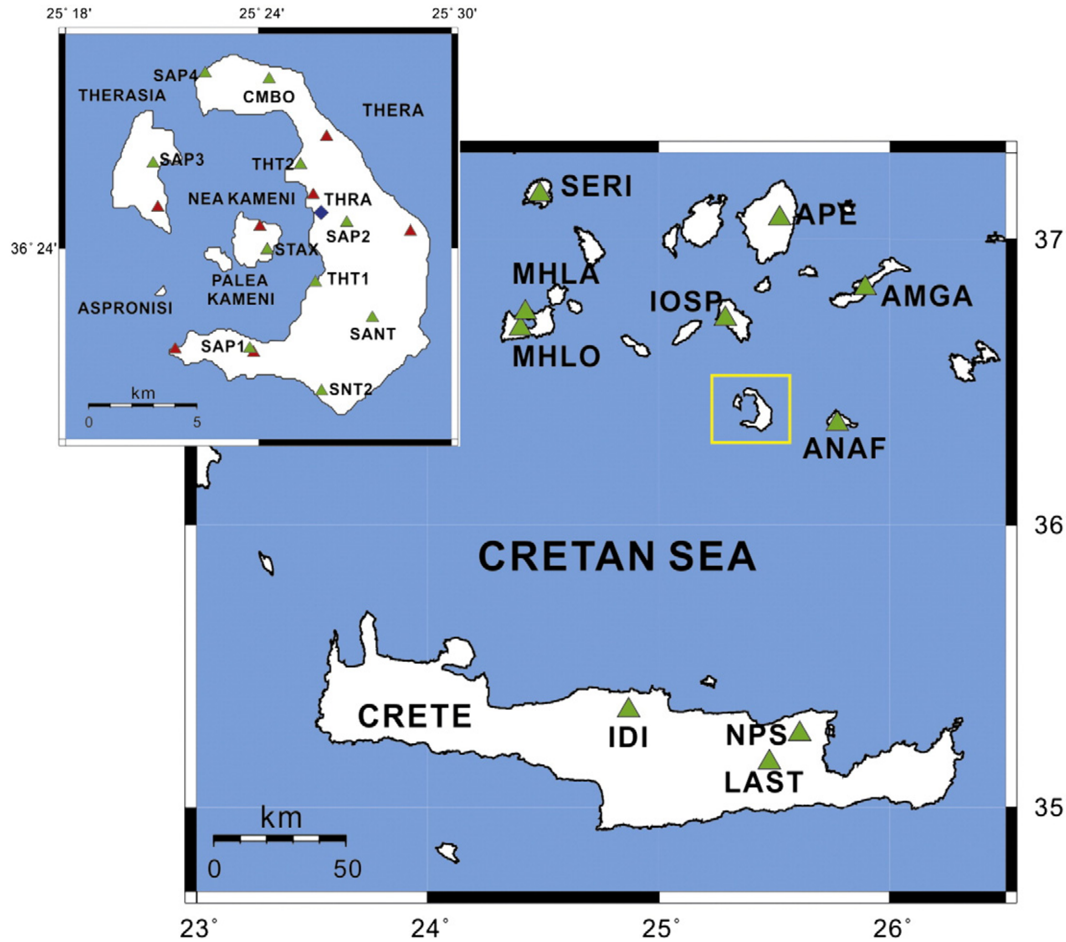

Fig. 1. Map of the southern Aegean where the location of the Santorini island complex is highlighted with a yellow square. The inset at the left hand side of the map shows an enlarged map of the five islands comprising the island complex. Seismic stations are shown as triangles, where the green color signifies three-component broadband instruments while the red color represents vertical component ones. The blue diamond corresponds to station THRA which is a three-component accelerometer located in the town of Fira.

release. This situation is exacerbated by the fact that Santorini is a favorite tourist destination and attracts hundreds of thousands of visitors every year.

Since its last eruption in 1950 the volcanic system has been relatively quiet and the only observed activity was the emission of low-temperature hydrothermal fluids and occurrence of sporadic micro-earthquakes (Dimitriadis et al., 2009). This apparent quiescence ended in early 2011 when seismicity rates steadily increased above background levels (Chouliaras et al., 2012) and significant deformation in the form of uplift was detected in the permanent GPS stations around the caldera. Several studies have analyzed and interpreted the geodetic observations (GPS and InSAR) covering the time period from the start of the unrest in January 2011 until the end of 2012 (Newman et al., 2012; Parks et al., 2012; Foumelis et al., 2013; Lagios et al., 2013; Papoutsis et al., 2013). The concept of a Mogi source was used in order to identify the point of maximum uplift and all of the aforementioned authors generally agree that this point is located within the flooded caldera, to the north of Nea Kameni island at a depth of about 4 km. The deformation rates were estimated between 140 and 180 mm yr^{-1} corresponding to a volume rate of accumulated material in the range of 6×10^6 m^3 and 24×10^6 m^3 per year. Maps of the seismicity that accompanied the deformation were published in the aforementioned studies showing one large cluster of events extending from Thera to Palea Kameni in a NE–SW orientation, without however, providing any depth estimates. These locations were extracted from the seismicity catalogs of the Aristotle University of Thessaloniki and the National Observatory of Athens.

In this work, we focus on the seismological characteristics of the 2011 unrest placing special emphasis on (a) shear wave anisotropy which has been used successfully in the past as an indicator of the state of stress in a volcanic system (Gerst and Savage, 2004; Savage et al., 2010; Unglert et al., 2011) and (b) the Vp/Vs ratio whose variations may provide information about the elastic rock properties. We first give an overview of available data and then embark on obtaining accurate locations of events that occurred during the unrest using catalog as well as differential travel times from waveform cross-correlation. Based on these locations estimated travel times are used to calculate ratios of Vp/Vs and their temporal variation is constructed. Shear wave splitting parameters (fast polarization direction and delay time) are also estimated from observed S-phase waveforms. The temporal variation of splitting parameters is investigated by identifying event doublets that have occurred at different times within the study period. Finally, all these results are interpreted in conjunction with the geodetic/geochemical observations and a plausible scenario that explains these temporal and spatial variations is discussed.

2. Data and earthquake locations

Prior to the 2011 unrest SANT was the only permanent three-component seismic station on Santorini equipped with a broadband