The March 2021 Thessaly Earthquake Sequence

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Introduction

Greece, the seismically most active country in Europe, has a longstanding tradition of earthquake research. Fundamental insights into earthquake physics and fault behaviour came from the study of Greek earthquakes and many modern concepts of earthquake geology have been developed here. Among the many strong earthquakes that hit Greece throughout its long history, perhaps the 1981 Gulf of Corinth earthquake series (Jackson et al., 1982; Vita-Finzi & King, 1985; Collier et al., 1998) had the largest impact on modern earthquake science. The deadly 1999 Athens Earthquake (Papadopoulos et al., 2000; Tselentis & Zahradník, 2000; Pavlides et al., 2002) triggered renewed efforts to map the active faults of Greece and to collect data on their slip rates and earthquake recurrence intervals. This was done by various means. Large-scale studies used geomorphological observations to better understand the distributed deformation of the crust both on mainland Greece and on the islands (e.g., Goldsworthy et al., 2002; Tzanis et al., 2010; Chatzipetros et al., 2013). Paleoseismic studies and tectonic geomorphology techniques were applied to many faults throughout the country (e.g., Benedetti et al., 2002; Chatzipetros et al., 2005; Kokkalas et al., 2007; Palyvos et al., 2010; Grützner et al., 2016, Koukouvelas et al., 2017; Copley et al., 2018). These data were used to build databases for active faults in Greece (Pavlides et al., 2010; Caputo et al., 2012, Ganas et al., 2013). In addition to these efforts, new methods have been developed to translate the fault data into better seismic hazard estimates (e.g., Papanikolaou et al., 2013; Deligiannakis et al., 2018).

Despite all these efforts, the 2021 Thessaly Earthquake Sequence occurred on faults that were previously unknown. The sequence included a M6.3 mainshock on March 3 and a M6.0 event 32 hours later. An M5.6 event on March 12 followed as well as thousands of smaller aftershocks. This was the most significant earthquake sequence in Thessaly in 41 years, and the largest event in this area of Greece since the major upgrades of the seismological, strong motions and geodetic networks. The sequence raised numerous questions related to fault interactions, blind faulting, near- and far-field ground motions, damage distribution, earthquake triggering, liquefaction phenomena and seismic hazard and seismotectonics of the Northern Thessaly. Today, remote-sensing data are available from several satellites and other platforms. Seismological and geodetic networks have improved significantly in the last decades. These new data allow investigating the Thessaly Earthquakes in detail. This Special Issue contains several papers that deal with such new data to characterise the seismogenic structures that ruptured in March 2021. Other studies deal with potential precursor phenomena and with disaster relief efforts. The Thessaly Earthquake sequence helps to better understand the regional tectonic setting, but it also sheds light on knowledge gaps that still exist despite many years of active tectonics research in Greece. As such, the Thessaly Earthquakes teach us how to save lives in the future.

Papers in the Special Volume

Mavroulis et al. focus on the disaster management. Since the earthquake series damaged many of the old houses without reinforcements in Thessaly, provisional shelters needed to be provided for hundreds of people. The earthquakes, however, happened during the third wave of the COVID-19 pandemic, which lead to a challenge: the emergency housing had to also comply with the anti-virus measures such as distancing and testing. This was amongst other measures achieved by providing more and different shelters than usual, by innovative approaches to supply distribution, and by isolation of infected people. The authors show that the infection rate in the area affected by the earthquake did not increase compared to other areas. Thus, this approach can be used as good practice in similar situations.

The paper by **Ganas et al.** deals with a wide range of methods that allow identifying the sources of the three main shocks. Geodetical (InSAR and GNSS) and seismological (aftershock distribution and p-wave arrivals) data show that normal motion occurred on (W)NW-(E)SE striking faults. The first two earthquakes ruptured NE-dipping faults; the third earthquake ruptured a SW-dipping structure. InSAR data allowed to map the ground deformation of the individual events and revealed that no significant postseismic deformation occurred on the previously unknown faults. The authors furthermore document several coseismic phenomena such as dilatational cracks and widespread liquefaction. With their paper the authors demonstrate the advantages of combing seismological data with geodetic information, especially when it comes to disentangling the deformation during three events close in time.

The Acceleration Deformation Method was tested by **Chatzopoulos** using the Thessaly Earthquake example. This method analyses the seismicity patterns preceding large earthquakes. Chatzopoulos uses the Tsallis Entropy approach to test if there was a spatio-temporal significant increase of seismicity before the Thessaly main shock. He shows that two different approaches of data processing, symmetrical and non-symmetrical, both indicate a significant increase of seismicity preceding the 3rd of March, 2021, main shock.

Karakostas et al. report on seismic monitoring of the Thessaly Earthquakes with a regional seismological network and a local network installed after the main shock. Aftershock distribution and focal mechanisms point to almost pure dip-slip faulting with an NNE–SSW direction of extension. Using regionally recorded seismic waveforms, the authors compute finite–fault slip inversions for the two largest earthquakes of the sequence and report rather low rupture velocities. The largest earthquake (M_W6.3) had more than 1 m of slip at depths between 3 and 7 kilometres, although the fault rupture did not reach the surface. The second main (M_W6.0) shock still had more than 20 cm of slip in ca. 5 km depth. Using the finite slip models, synthetic shake maps were produced for the two strongest earthquakes and compared to macroseismic data. This study sheds light on the source parameters of the Thessaly Earthquakes and the strong motion caused by them.

Spingos et al. investigate the problem of Earthquake Early Warning Systems (EEWS) using the data from the Thessaly Earthquakes. They estimate the integral of the squared velocity from the first few seconds of the wave train after the P-wave arrival at local permanent stations. These data are used to establish scaling relationships for the peak ground accelerations that occur when later, and more energetic, seismic phases arrive. Such scaling relationships are needed to automatically compute the expected shaking from initial earthquake data to achieve a meaningful EEWS. The few seconds of potential warning time between the alarm and the strongest shaking can save lives. A special emphasis is put on local site effects that can significantly modify the shaking.

The Neogene-Quaternary tectonic regime of the Thessaly region is in the focus of the paper by **Galanakis et al**. The authors provide background on the geological setting and document abundant coseismic effects such as cracks, liquefaction, and mass movements.

They furthermore provide data on the mechanism and location of the main shocks. In their paper, Galanakis et al. show that the causative fault of the main shock manifests as the boundary between the Alpidic basement and the alluvial deposits. Although the faults that ruptured were not previously identified as active, geological data point to long-lived activity. These findings may inform future hazard assessments and provide a useful case study for neighbouring regions.

The paper by **Kouli et al.** deals with a remote sensing approach to study possible precursors of the Thessaly Earthquake series. Using a 10 years' time series of land surface temperature data from the MODIS sensor (Moderate Resolution Imaging Spectroradiometer), the authors analyse the epicentral area adopting the Robust Satellite Technique. They interpret preseismic, coseismic and post seismic thermal anomalies as being related to the seismogenic faults that ruptured in March 2021.

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