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Rupture process of the 2014 Cephalonia, Greece, earthquake doublet (Mw6) as inferred from regional and local seismic data

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ABSTRACT

We study the 26 January and 3 February, 2014 (~Mw6) events in Cephalonia, combining weak and strong motion waveforms from regional and local stations. The hypocenter of the January 26 event is located at the southernmost tip of the Paliki Peninsula, at a depth of ~15 km. The centroid moment tensor (CMT) solution indicates rupture along a N20°E dextral strike-slip fault, dipping to the east. The hypocenter of the February 3 event is 10 km NNE of the first, at shallower depth (~5 km). The CMT solution of this event is highly uncertain. The kinematic slip model for the January 26 event indicates that the rupture was mainly confined to shallow depths, and it propagated upwards and towards NE. The major slip patches, when projected to the surface, cover the western part of the Paliki Peninsula and include the areas where surface ruptures were observed. Our preferred slip model for the event of February 3 is based on a published two-segment fault model. Although this is our preferred slip model, it is worth noting, that the single segment inversion provided a similar slip pattern. The rupture propagated predominantly southwards along both segments. The main slip episode on both segments occurred almost simultaneously. Total duration of the rupture propagation did not exceed 9 and 6 s, respectively. The 2014 Cephalonia doublet did not rupture the Cephalonia Transform Fault (CTF). The diffuse pattern of the aftershocks implies the activation of a network of faults on-shore the Paliki Peninsula, in accordance with the local stress field derived from aftershocks. The 2014 sequence has implications for the seismic hazard assessment: active faults in western Cephalonia exist on-shore; some have gentle dip angles; the strike-slip motions can be combined with thrust components; and the segmented ruptures may introduce time delays that increase the duration of strong ground shaking.

1. Introduction

Cephalonia (Greece) belongs to the Ionian Islands and is best known for its beautiful landscape and the strong and frequent earthquakes. The earthquake activity in 1953 benchmarks the history of Cephalonia, as the island was destroyed and more than 450 people lost their lives. This event was the startup point for the Hellenic Antiseismic Code whose provisions for the constructions in the Ionian Islands are the strictest over Greece (reference ground acceleration for ground type A (rock) equal to 0.36 g).

The focus of this work is the sequence that burst in Cephalonia Island on January 26, 2014 with an Mw6 earthquake and culminated on February 3 to another Mw6 event (Fig. 1). The reported epicenters of the two strong events and all aftershocks are spread along the western coast (Paliki Peninsula) of Cephalonia. No loss of life was reported and the constructions performed remarkably well (GEER/EERI/ATC report, 2014). The 2014 sequence attracted the attention of the scientific community and a number of publications are already available (Benekos et al., 2015; Boncori et al., 2015; Karakostas et al., 2014; Karastathis et al., 2015; Papadopoulos et al., 2014; Sakkas and Lagios, 2015; Valkaniotis et al., 2014). Despite the fact that the sequence was well recorded by the regional networks in Greece, there are still unresolved issues. Accurate location of earthquakes in Cephalonia is a challenge by itself, due to the absence of stations from the west and the sparse seismic coverage from the south. For example, in the west the closest seismic station is in Italy. As a result, in the related publications (Boncori et al., 2015; Karakostas et al., 2014; Papadopoulos et al., 2014), the location, the fault orientation and its dip polarity of the two strong events show considerable variability, reflecting the difficulties in the data analysis.

Another issue that further intrigued the scientists is the unclear, if any, connection of the sequence to the well-known dextral Cephalonia Transform Fault (CTF) that dominates along the western coast of the

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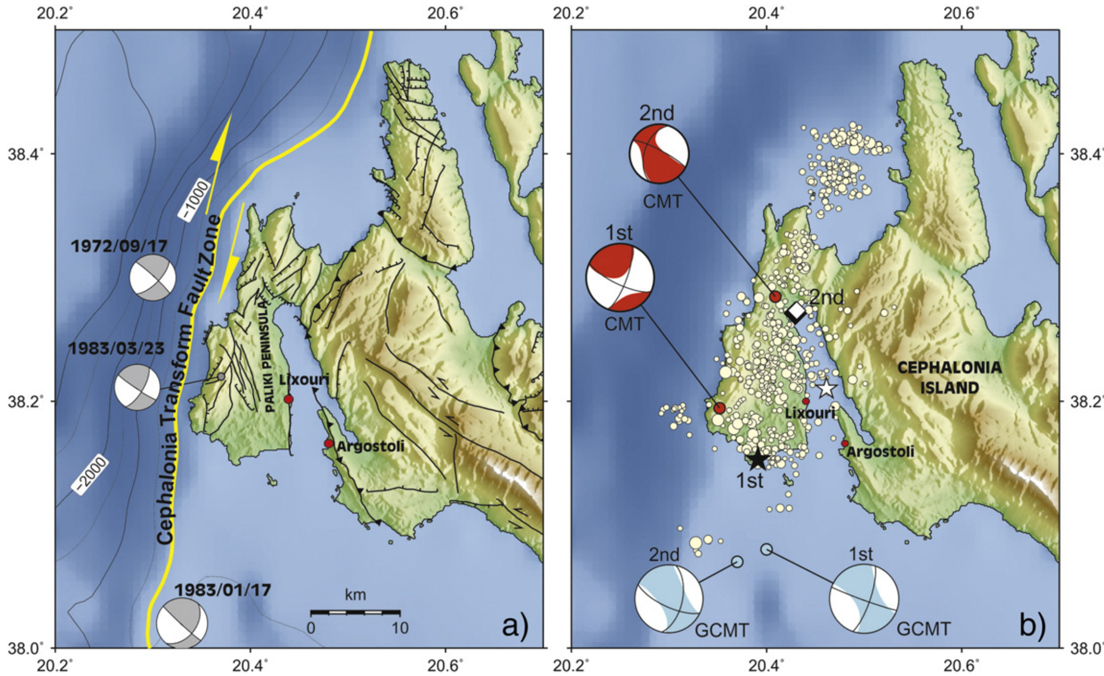

Fig. 1. a) Map of Cephalonia Island showing focal mechanisms of post-1966 earthquakes with Mw > 6 (beach-balls) and mapped faults on-shore (Lekkas et al., 2001); the Cephalonia Transform Fault (CTF) zone is highlighted, and black contours denote the sea bathymetry. b) Relocated epicenters of the two major events: the black star denotes the epicenter of the 1st event on Jan 26, 2014 and the black diamond denotes the epicenter of the 2nd event on Feb 3, 2014. For comparison we have included the relocated epicenters for the 1st (gray star) and 2nd (gray diamond) events reported in Karastathis et al. (2015). The CMT solutions for the two events, as calculated here and as reported in GCMT catalog are also shown (beach-balls marked accordingly). The relocated aftershocks (yellow circles) are scaled proportionally to their magnitude.

Ionian Islands (Louvari et al., 1999; Scordilis et al., 1985) and is rather described as a ramp in the bathymetry (Shaw and Jackson, 2010). Two branches were identified along CTF — the Cephalonia segment in the south, where the typical focal mechanisms have parameters: strike 38°, dip 63° and rake 172°, and the Lefkada segment in the north with: strike 14°, dip 65° and rake 167° (Louvari et al., 1999 and references therein). The strike-slip motions, often combined with a thrust component, are not confined along the CTF only. On the contrary, a broad zone, ~100 km wide, up to the western Peloponnese is characterized by strike-slip motions (Kiratzi, 2014; Louvari et al., 1999; Shaw and Jackson, 2010). The available fault databases include a few strike-slip fault segments offshore Cephalonia (Caputo et al., 2012), and a network of mapped faults onshore (Lekkas et al., 2001).

Below we briefly review the knowledge that has been accumulated so far. Prior to the 2014 sequence, a change in the long-term deformation of the Cephalonia Island was geodetically detected. It started in ~2003 and until 2010 the western peninsula of the Cephalonia Island (Paliki Peninsula, Fig. 1a) was uplifting at a rate of 1 cm/yr in an abrupt contrast with the subsidence of the rest of the Cephalonia Island (Lagios et al., 2012). Karakostas et al. (2014) relocated the sequence and concluded that the two major shocks were related to two adjacent fault segments, striking almost N–S and dipping to the east. Karastathis et al. (2015) relocated the sequence using the equal differential time and probabilistic non-linear approaches, accounting for the effects of the laterally varying crustal structure. They showed that the January 26 and February 3 events could be related with fault planes dipping to east and west, respectively. Papadopoulos et al. (2014) made a preliminary comprehensive analysis of the 2014 sequence. Their results support predominantly downward and upward rupture propagation for the January 26 and February 3 events, respectively. They concluded that the 2014 sequence ruptured a fault segment which is the SSW-wards continuation of the Lefkada segment as this was defined in Louvari et al. (1999).

Valkaniotis et al. (2014) analyzed geological effects, such as liquefaction, rock falls, and landslides, concluding that primary (co-seismic) fault surface ruptures were most probably not produced. The abundant surface cracks with cm-size offsets in the northern part of the Paliki Peninsula, ~38.29°N, were interpreted as due to close proximity of the ruptured fault to the earth surface (with unclear relation to either of the events). Boncori et al. (2015) inferred static ground displacements related to the event of 3 February from InSAR images. Their results were better modeled by a two-segment fault for this event.

Here we use weak and strong motion waveforms from local and regional stations to constrain kinematic rupture models of the two major events. For brevity, hereafter we refer to the January 26 and February 3 earthquakes as the 1st and 2nd event, respectively. In particular, we pay careful attention to the determination and consistency of their hypocenters, centroid moment tensors (location and faulting parameters), and fault plane geometries. We discuss the two events not only in terms of their source properties, but also in terms of the difficulties encountered during their source inversions. In this context, we discuss why the moment tensor solutions, as reported by different agencies, are quite similar for the 1st event, whereas those reported for the 2nd event vary significantly and include large non-double-couple components.

The paper is structured as follows: the data and methods used are briefly described; observed data of 1st and 2nd event are investigated, each following a hierarchic scheme (starting from the hypocenter location and calculation of the centroid moment tensor, continuing with specification of fault plane, ending with slip inversion). Finally, the two events are compared to each other, and to aftershocks, and they are collectively discussed in terms of the local stress field and seismic hazard.

2. Data and methods

Broad-band waveforms were retrieved from the Hellenic Unified Seismic Network (HUSN). We adopted the manual P and S phase picks from the Geodynamics Institute of the National Observatory of Athens and added manual picks from available local strong motion stations