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ORIGINAL PAPER

Static stress changes associated with normal faulting earthquakes in South Balkan area

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Abstract Activation of major faults in Bulgaria and northern Greece presents significant seismic hazard because of their proximity to populated centers. The long recurrence intervals, of the order of several hundred years as suggested by previous investigations, imply that the twentieth century activation along the southern boundary of the sub-Balkan graben system, is probably associated with stress transfer among neighbouring faults or fault segments. Fault interaction is investigated through elastic stress transfer among strong main shocks ($M \geq 6.0$), and in three cases their foreshocks, which ruptured distinct or adjacent normal fault segments. We compute stress perturbations caused by earthquake dislocations in a homogeneous half-space. The stress change calculations were performed for faults of strike, dip, and rake appropriate to the strong events. We explore the interaction between normal faults in the study area by resolving changes of Coulomb failure function (ΔCFF) since 1904 and hence the evolution of the stress field in the area during the last 100 years. Coulomb stress changes were calculated assuming that earthquakes can be modeled as static dislocations in an elastic half-space, and taking into account both the coseismic slip in strong earthquakes and the slow tectonic stress buildup associated with major fault segments. We evaluate if these stress changes brought a given strong earthquake closer to, or sent it farther from, failure. Our modeling results show that the generation of each strong event enhanced the Coulomb stress on along-strike neighbors and reduced the stress on parallel normal faults. We extend the stress calculations up to present and provide an assessment for future seismic hazard by identifying possible sites of impending strong earthquakes.

Keywords Coulomb stress · Foreshock—main shock triggering · Greece and Bulgaria

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Introduction

The Krupnik–Kresna, SW Bulgaria, earthquake of April 1904, with a reported magnitude of $M_s7.8$ (Christoskov and Grigorova 1968), was one of the strongest events in the eastern Mediterranean region, causing extensive damage in a broad area that has been added to the casualties caused by its stronger foreshock ($M_s7.2$) that occurred just 23 min earlier. The next ‘‘twin’’ seismic excitation in Bulgaria took place in 1928 with a foreshock of $M6.8$ on 14 April, following by its stronger mainshock (M7.0) just four days later (18 April). The 1931 Valandovo earthquake (M6.7), located in the border area between northern Greece and Former Yugoslavian Republic of Macedonia (FYROM), was preceded by a strong foreshock (M6.0) one day before, although there is no information on the fault associated with this latter event. The Thessaloniki, northern Greece, earthquake of 20 June 1978 (M6.5) was preceded by a moderate (M5.8) event originated in a neighbour fault segment on 23 May 1978. This repeated pair-event occurrences motivated the investigation on possible foreshock—main shock triggering.

Each earthquake alters the state of stress in its surroundings, and it is natural to investigate the stress changes associated with the first shock in each pair of events in order to evaluate the potential for the consequent event occurrence. Coulomb stress changes are widely used in the literature to seek for fault interaction between large magnitude earthquakes as well as to model aftershock patterns and seismicity rate changes over long-time windows (Harris 1998; Stein 1999 among others). Such studies exploring fault interaction have been compiled for the broader Aegean area during the last years for strike-slip events (Nalbant et al. 1998; Papadimitriou and Sykes 2001; Papadimitriou 2002), normal faulting (Papadimitriou and Karakostas 2003; Papadimitriou et al. 2005) as well as between strike-slip and subduction earthquakes (Messini et al. 2005). The results of the above studies revealed that the vast majority of the earthquakes whose triggering was inspected, were located inside areas of positive static stress changes.

In the present study, we investigate the stress perturbations caused by the stronger earthquakes that occurred in the area of Bulgaria and northern Greece since 1904, when the first strong main shock of the instrumental era occurred. This involves incorporation of both tectonic loading and coseismic slip. Therefore, the scope of this research is to define the geometry of the faults associated with the occurrence of strong earthquakes ($M \geq 6.0$) and their kinematics, and then by making use of this information to compute the static stress changes for the whole study area. The computations reveal the stress interactions between the faults and are important in determining where the next strong events, outside the seismogenic volume, might occur. The identification of currently being stress enhanced sites contributes to the evaluation of future seismic hazard in the study area. In the case of seismic excitations involving multiple strong events in addition to the main shock, like the earthquake pairs in our study area, such investigation comprising determination of a strong earthquake location and mechanism, together with the knowledge of nearby major faults, may be useful in post-event imminent hazard estimates.

Seismotectonic setting

North of the western continuation of the North Anatolian Fault the Aegean extensional regime is present in south Balkan region, namely central and southern Bulgaria, northern Greece, FYROM and eastern Albania (Fig. 1). The southern Balkan forms the northern part of the Aegean extensional system although deformation is not as great as in the southern Aegean part (Burchfiel et al. 2000; Tranos et al. 2006). To the east, the region of central Turkey lying between the north and east Anatolian Faults is actively moving westward relative to Eurasia as a coherent unit (Reilinger et al. 1997; McClusky et al. 2000). In western Turkey this westward–southwestward moving region is affected by extensional tectonics that is more prevalent into the Aegean and mainland Greece due to the north–south spreading of the Aegean microplate (McKenzie 1972). This extension occurs as far north as central Bulgaria. Recent investigations (Burchfiel et al. 2000; Nakov et al. 2001) suggest that the northern boundary of the Aegean extensional regime passes through north central Bulgaria, supporting McKenzie's interpretation based on limited seismological data that a poorly defined crustal boundary passes through that same region (McKenzie 1972).

The northern boundary of the Aegean extensional system is defined by the sub-Balkan graben consisting of nine east–west trending grabens located in central Bulgaria that are complexly faulted with faults on both flanks, but the main faults occur along the northern side (Tzankov et al. 1996). Master graben-forming faults are south dipping, low-angle normal faults (dipping c. 30° or less) which have been cut by steeper (60–80°) young to active normal faults at the base of Stara Planina Mountains. Most of the active and young faults, being normal, with a few of them with strike-slip component, strike generally E-W, WNW-ESE, NW-SE and rarely NE-SW, and they bound basins of quaternary sedimentation (Nakov et al. 2001). There is a continuous to discontinuous line of faults that trend through central Bulgaria and mostly lie along the south flank of the Stara Planina Mountains. The faults bound the sub-Balkan graben system for which Tzankov et al. (1996) suggested that the faults dip gently south and have a long-term slip rate of 1–2 mm/year. The faults continue both east to the Black Sea, where they bound narrow and less