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Coseismic deformation analysis of the 1996 Ston–Slano (southern Croatia) M_L 6.0 earthquake: preliminary results using DInSAR and geological investigations

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Abstract: *The Dinarides, a NW-striking mountain chain along the eastern margin of the Adriatic plate, is the most seismically active zone in Croatia. Historical and instrumental records indicate ongoing tectonics concentrated within southern Dalmatia. Results of the DInSAR analysis of coseismic deformation and fault kinematics for the Ston–Slano 1996 M_L 6.0 earthquake are presented. Constructed interferograms suggest concentric fringe pattern of coseismic ground displacements, with maximum uplift of 26 cm and subsidence of c. 8 cm in the Podimoć area, approximately 8 km NW of 1996 Ston–Slano earthquake epicentre. The kinematic analysis of shear joint/fault data indicate compressional/transpressional stress field with NE–SW and locally NW–SE trending S_{Hmax}, coinciding with the present stress field. Considering the location of microseismic epicentre, analyzed interferograms and fault kinematics suggest that the earthquake rupture probably started near Slano, and proceeded towards NW along a reverse fault situated in the Adriatic offshore.*

Key words*: Ston–Slano earthquake, Croatia, DInSAR, interferogram, compressional stress field*

INTRODUCTION

The Dinarides are a fold and thrust belt oriented NW–SE along the eastern margin of the Adriatic microplate. Tectonically uplifted during Late Eocene to Oligocene (Pamić et al., 1998) it is still active due to ongoing convergence between the Adriatic and the European plate (≤4.17 mm/yr; Bennett et al., 2008). Recent seismic activity accommodated within collisional zone of the undeformed part of the Adriatic microplate and the Central Dinarides yields the most seismically active zone in Croatia, the area of southern Dalmatia (Markušić & Herak, 1999; Ivančić et al., 2001; Kastelic et al., 2013). Seismogenic sources are dominantly NW striking thrust faults (S_{Hmax} is NE–SW trending compression) with earthquakes confined to shallow crustal levels (≤20 km in depth; Herak & Herak, 1990; Tomljenović et al., 2009). Beside historical seismicity (*e.g.* the Dubrovnik earthquake of 1667), instrumentally recorded earthquakes (e.g. the 1996 Ston–Slano earthquake, M_w = 6.0) indicate ongoing tectonic activity along the mapped faults that represent potential seismogenic sources along the Dalmatian coastline.

In this work we address preliminary results of the DInSAR and geo-structural investigations in the region of the 1996 earthquake (the Ston–Slano area in southern Croatia) which could provide important insights into the local seismogenic assemblage. The Ston–Slano earthquake series, with the mainshock of September 5, 1996 (M_L = 6.0, I_{max} = VIII MSK), is the most important and the largest one in this epicentral area after the catastrophic Dubrovnik earthquake of 1667 (I_o = IX MSK). Described in detail by Markušić et al. (1998) and Herak et al. (2001), the mainshock caused devastation at several localities in the greater epicentral area, with maximum observed damage of VIII MSK in Ston, and Podimoć and Mravinca villages (**Fig. 1**). Herak et al. (2010) reported peak horizontal ground acceleration of 0.64 g in Ston. The sequence lasted for over a year, with more than 1800 aftershocks within 50 km from the mainshock's epicentre.

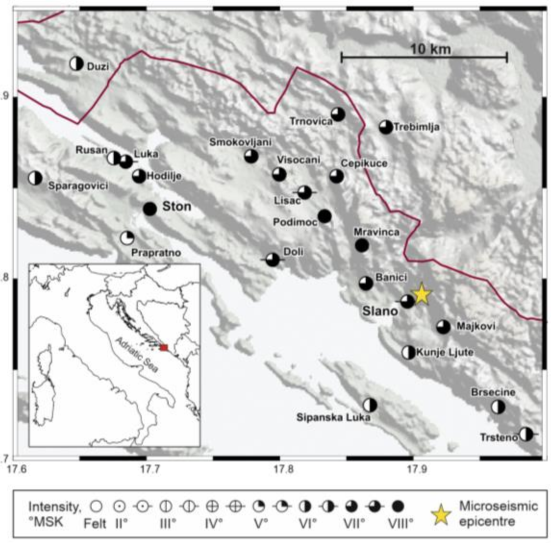


Fig. 1. *Observed intensities (°MSK) in the greater epicentral area of the Ston–Slano mainshock. The microseismic epicentre is shown by a yellow star. A small red rectangle in the overview map shows the geographical location of the area.*

METHODS

InSAR data analysis

The ground displacements caused by the 1996 Ston–Slano earthquake sequence were analyzed with the Differential

SAR Interferometry (DInSAR) technique applied on the ERS2 data scenes of descending track 451 (see Massonnet & Feigl 1998). The ERS2 data were obtained by satellite launched by ESA that was equipped with SAR instrument operating at C-band (5.66 cm wavelength) under the look angle of 23°. The first scene was acquired on 9th of August 1996, before the earthquake sequence, whereas the second one was acquired afterwards, on 25th of July 1997. For ERS2 data processing, we used the InSAR Scientific Computing Environment (ISCE) software developed at NASA's JPL and Caltech (Rosen et al. 2012). The software processing flow comprises focusing, coregistration, interferogram generation, flat earth and topographic correction, phase unwrapping and geocoding. Moreover, an external DEM SRTM 1 arc second (30m x 30m) was used for topographic correction, whereas coseismic interferogram phase noise reduction was achieved by adaptive Goldsten-Werner filter (Goldstein & Werner, 1998). The phase unwrapping, reconstruction of the full interferogram waveform, was performed with a minimum cost flow (MCF), statistical-cost, network-flow (SNAPHU) algorithms (Chen & Zebker, 2001), which finally resulted in wrapped and unwrapped coseismic interferograms. Afterwards, unwrapped phase values were converted to one-dimensional "line-of-sight" (LOS) displacements.

Field investigation and geo-structural analysis

To address fault kinematics in relation to the past and the present stress fields, geological and structural investigations in the Ston–Slano area were focused along the mapped faults (**Fig. 2**), which mark tectonic contacts between the Mesozoic and Eocene deposits. In an area about 25 km long and 5 km wide structural data on outcrop-scale shear joint/fault planes were collected. Structural survey addressed measurements of dip direction and dip angle of shear joint/fault planes, orientation of slickensides defined by azimuth and plunge, and sense of movement. During initial campaign, we gathered about 100 shear joint/fault plane data within the three mapped fault zones. Collected structural data were separated into kinematically homogeneous pair datasets and processed through software Tectonics FP inversional method (Ortner et al., 2002). Using the P–T axis method (Turner 1953; Marrett & Allmendinger 1990) the theoretical maximum (σ1), intermediate (σ2) and minimum stress axes (σ3) were calculated, whereas by applying Right Dihedra Method (Angelier & Mechler, 1977) we derived the synthetic focal mechanisms for the analyzed fault segments, i.e., paleo-synthetic focal mechanisms representative of the paleostress field.

RESULTS

InSAR results and ground coseismic displacement

The DInSAR wrapped interferogram shows surface displacements in radar LOS represented as phase changes from –π to π radians. The coseismic ground displacements caused by an earthquake event are visible as the concentric fringe pattern (**Fig. 3a**). The absolute surface displacements were reconstructed during the phase unwrapping step, which followed conversion of angular LOS surface displacements to metric values in vertical direction. The unwrapped interferogram (**Fig. 3b**) shows maximum uplift of 26 cm and subsidence of –8 cm within around 10 km wide zone between two NW-striking faults in the area of Podimoć, NW of the Ston–Slano earthquake microseismic epicentre (**Figs. 1 & 3b**).

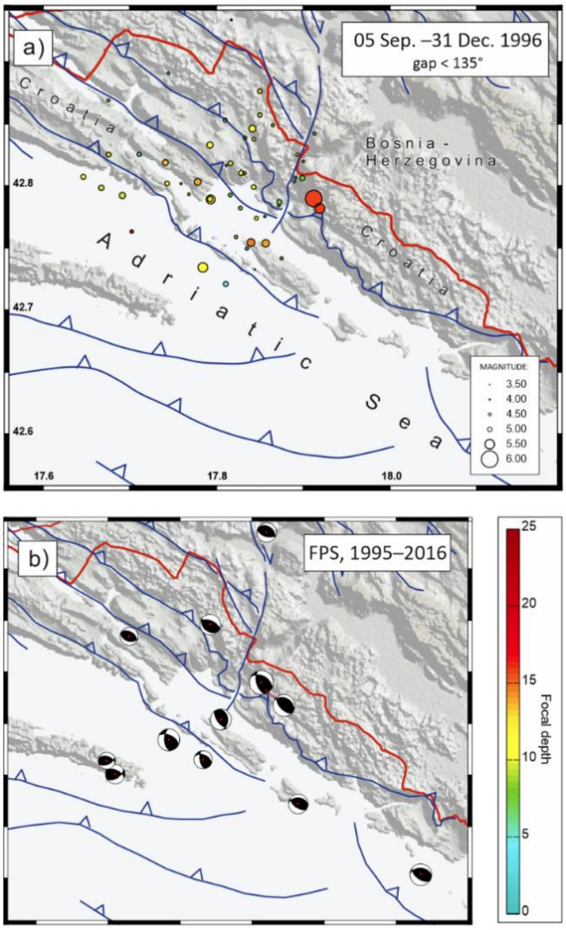
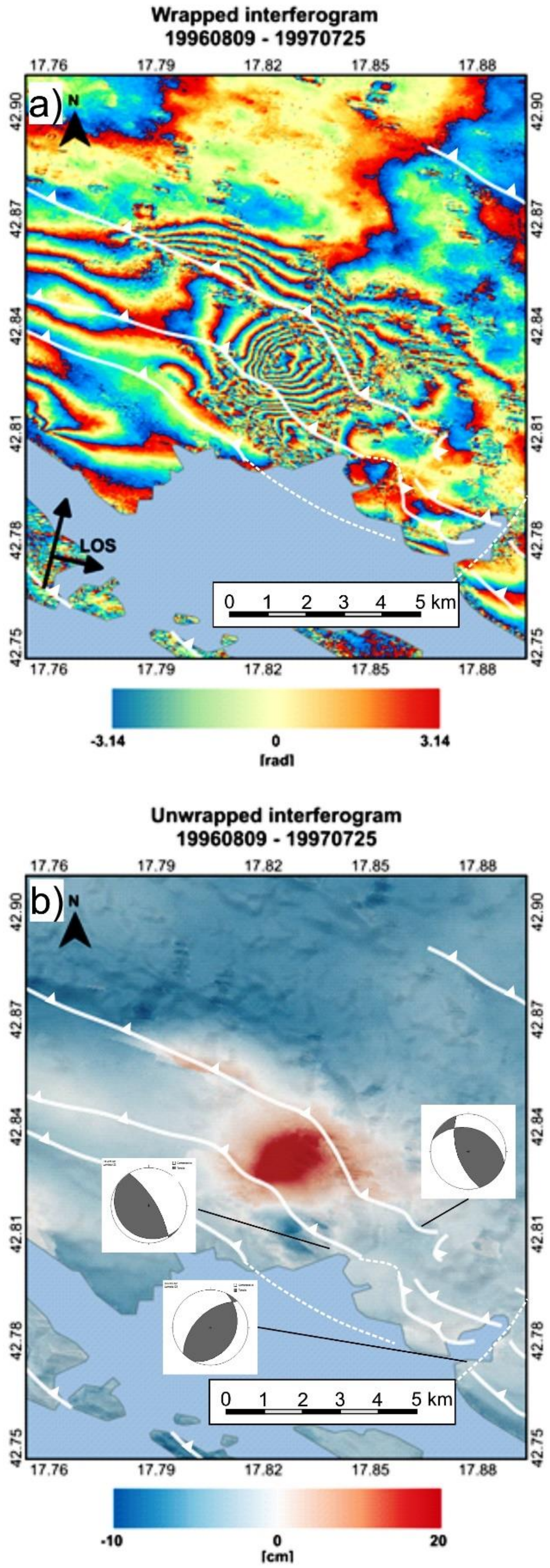


Fig. 2. a) Reliably located epicentres of the 1996 Ston–Slano earthquake sequence. b) Fault-plane solutions (FPS; lower hemisphere stereographic projection, compressive quadrants are black) for the earthquakes in the period 1995–2016. Surface traces of faults (after Raić et al., 1980; Tomljenović et al., 2009 with references therein) are shown by blue lines, with barbs on the hanging wall of reverse faults.

Fig. 3. a) Wrapped interferogram of the 1996 Ston–Slano earthquake sequence. b) Unwrapped interferogram of the 1996



Ston–Slano earthquake sequence with scale of coseismic deformation. Based on structural data we derived paleo-synthetic focal mechanisms, a representative of the paleostress fields. Lower hemisphere stereographic projection, compressive quadrants are grey. Surface traces of faults (after Raić et al., 1980; Tomljenović et al., 2009 with references therein) are shown by white lines, with barbs on the hanging wall of reverse faults.

Fault-slip analysis and paleostress field

The collected shear joint/fault plane data within the three mapped NW-striking fault zones in the Ston–Slano area characterize fault segments with mostly reverse NNE-dipping fault planes (**Fig. 3b**) and tectonic transport towards SSW. Additionally, both reverse NW- and SE-dipping planes were observed. The kinematic analysis according to computed stress axes (**Fig. 3b**) indicate dominant compressional/transpressional stress field with NE–SW and locally NW–SE trending S_{Hmax}.

Beside compressional/transpressional stress field, a few collected structural fault kinematic data also indicate local NE–SW oriented extension as well as dextral and sinistral motion along the NNE–SSW striking planes.

DISCUSSION

From **Figs. 1** and **2** it is seen that the most damaged area was around Podimoć, coinciding with the zone of maximum observed coseismic displacement, which is located about 8 km to the NW from the Slano microseismic epicentre (where the rupture had started). The preliminary structural data analyses indicate that observed shear joint/fault plane groups were formed within compressional/transpressional paleostress field with NE–SW and locally NW–SE trending S_{Hmax}. This implies positive correlation between observed paleostress field and the present stress field (compare **Figs. 2b** and **3b**), which favor possibility of structural reactivation and neotectonic activity of observed fault segments in the study area.

The Ston–Slano mainshock rupture started near Slano at the depth of 15–20 km, most probably on a reverse fault with a surface trace located further to the SW, in the Adriatic offshore. As the average expected fault-length for a magnitude 6.0 earthquake on a reverse fault of about 9 km (Wells & Coppersmith, 1994) closely matches the distance between the epicentre and the area of the largest coseismic displacement, we propose that, due to source geometrical properties, strata thickness and rheological heterogeneities, coseismic rupture propagated mostly unilaterally about 8 km towards NW, to the Podimoć area, where a bulk of accumulated seismic energy was released.

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