Simultaneous optimisation of two sources of the 2012 Ahar earthquake doublet (Mw 6.4 and 6.3, Iran) based on InSAR data, GNSS data and seismic waveforms

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On August in 2012 a Mw6.4 earthquake hit the region near the town Ahar in NW Iran. With only 11 minutes delay it was followed by another large and close by Mw6.3 earthquake. The 2012 Ahar earthquakes have been unexpected in their large magnitudes and the activated faults are poorly studied. A mapped east-west striking surface rupture is attributed to the first earthquake, which shows a strike-slip mechanism. The second earthquake is reported to have a thrust mechanism and a deeper hypocenter, but is much more poorly constrained than the first earthquake. The short time interval between those two earthquakes made it impossible to distinguish their effects in the available static surface displacement data based on InSAR and GNSS, and difficult in global seismological records. Any source analysis using static displacement data and/or teleseismic waveforms therefore has to rely on the corresponding cumulative surface displacements and recorded waveforms of the first earthquake, respectively. In contrast, in regional waveform data, the seismic phase arrivals of both earthquakes are well separated in time. To tackle the coupling of the earthquakes we conducted a combined-data study that solves for the individual sources of the earthquake doublet simultaneously in a non-linear probabilistic finite-fault optimisation. In our combined-data study we improve the constraints on the doublet sources, particularly the second earthquake. We use InSAR data from RADARSAT-2 acquisitions and published co-seismic displacement vectors based on GNSS data. For the InSAR data, unfortunately, only measurements of an ascending orbit are available. The seismological data are teleseismic (distance larger than 1000 km) and regional waveform recordings (distances less than 1000 km). For the modelling we use Green's functions of a layered regional velocity model and rectangular, constant-slip rupture models.

Our non-linear, finite-fault optimisation makes use of Bayesian bootstrap data weighting, which enables a very efficient estimation of model parameter uncertainties. This method accounts for modelling and data errors and can sample non-Gaussian posterior probabilities of model parameters. Our results show that the two earthquakes activated two different faults. The first earthquake ruptured a shallow east-west striking dextral fault extending from the surface
vertically down to approximately 8 km depth (6 to 14 km confidence). The second earthquake ruptured a north to north-east striking fault with a dip of about 40 degree with an oblique rupture mechanism. The fault activated by the second earthquake seems to be located below the first one, at levels deeper than 9 km and a bit shifted to the west. We verify our results with model-independent seismic multi-array backprojection of the radiated seismic energy.

We used the python-based software toolbox Pyrocko for the data processing. The included module Grond implements the Bayesian bootstrap optimisation approach. Both are open-source under the GNU General Public License and available on pyrocko.org. The RADARSAT data used in this study have been provided through the RADARSAT-2 SOAR-EU loan agreement #16736. This research is further supported by the German Research Foundation DFG through an Emmy-Noether-Grant.