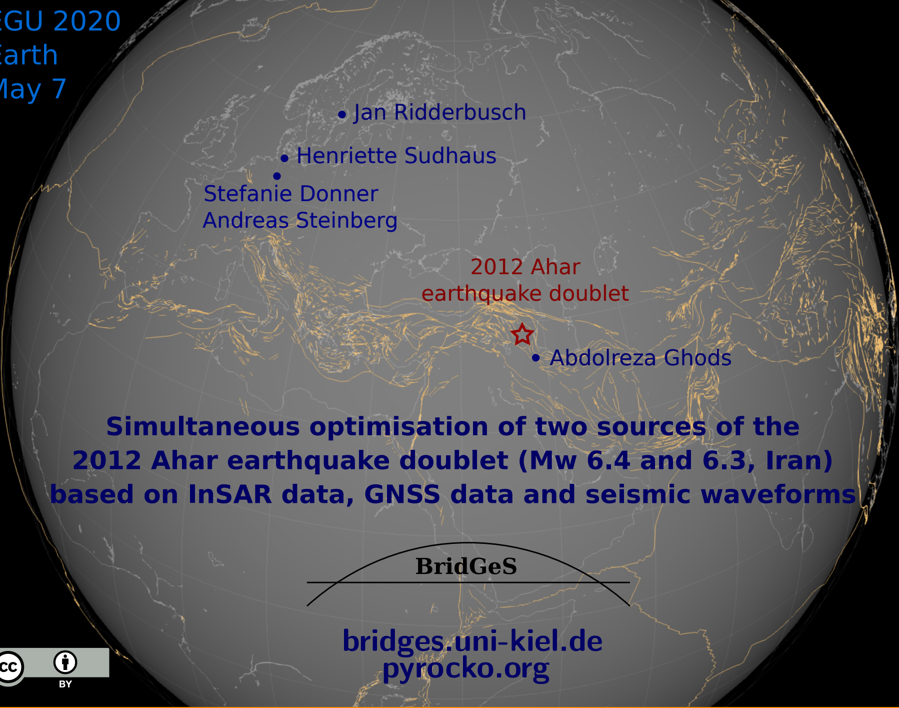
EGU 2020
Earth
May 7



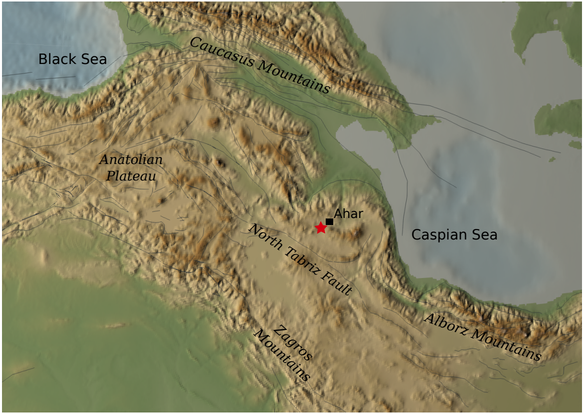
Jan Ridderbusch
Henriette Sudhaus
Stefanie Donner
Andreas Steinberg
Abdolreza Ghods

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

BridGeS

bridges.uni-kiel.de
pyrocko.org

Tectonic setting in NW Iran



The Ahar earthquake doublet took place in North-East Iranin the Azarbaijan region.

This region is located within the Alpine-Himalayan orogenic belt of continental collision.

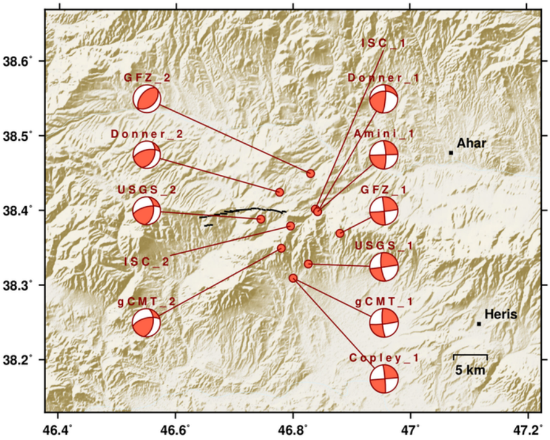
For a detailed description of the regional tectonics consult ➠ Faridi at al. (2017).

A seismotectonic introduction of the region and seismological source studies of the Ahar earthquake doublet can be found e. g. in ➠ Donner et *al.* (2015)

Plot and title plot are generated with the new ➠ Pyrocko geoviewer Sparrow.

Fault lines are from the ➠ GEM data base.

Source location analyses results



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.

"ISC_1(2)": ➽ ISC Catalog

"USGS_1": ➽ USGS Catalog

"gCMT_1": ➽ gCMT Catalog

References of the shown locations:

"Copley_1": ➽ Copley et *al.* (2014) also the mapped fault trace (black)

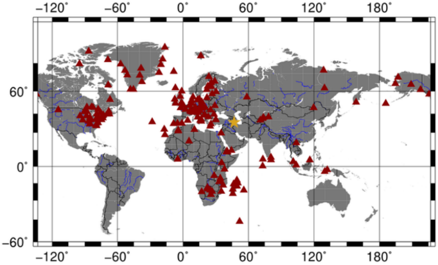
"Donner_1(2)":
➽ Donner et *al.* (2015)

"Amini_1": ➽ Amini et *al.* (2018)

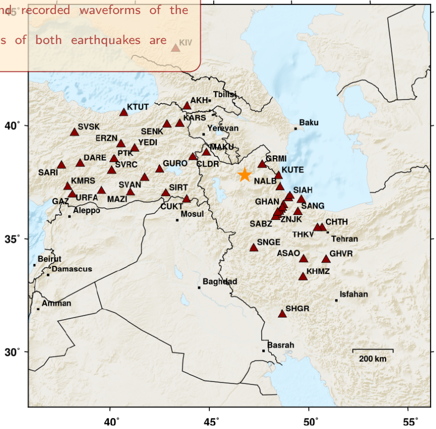
"GFZ_1(2)": ➽ Geofon Catalog

Seismological data

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 (next slide), 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.



Distribution of global station recordings

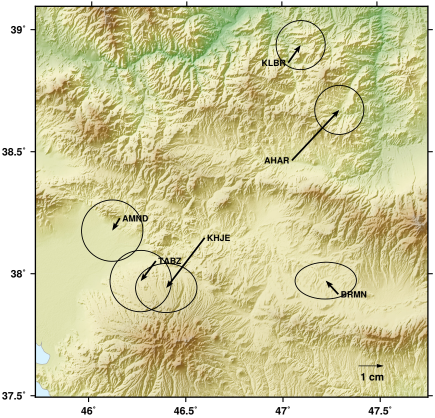


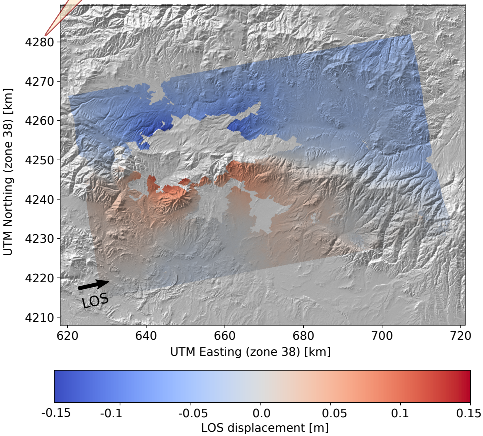
Distribution of regional station recordings

CAU
BridGeS

Geodetic Data

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.
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.

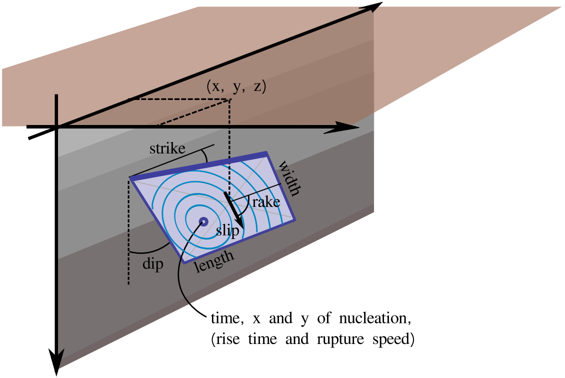




GNSS displacements shown and used are published by Yadaf et *al.* (2016)

Forward modelling with Pyrocko-GF

For the modelling we use Green's functions of a layered regional velocity model and two rectangular, constant-slip rupture models. The foward modelling methods are described in Heimann et al. (2019).
Find out more about the modelling tools visiting the Pyrocko-GF documentation.

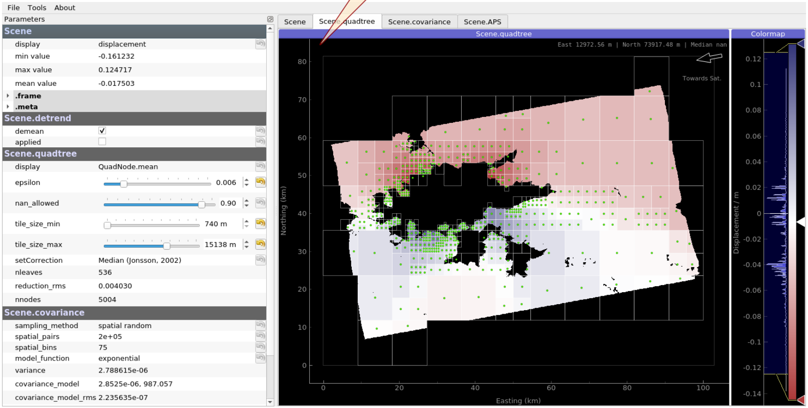


InSAR data post-processing

Post-processing of InSAR displacement maps was accomplished using the pyrocko tool kite, with the tasks:

- of masking unwrapping errors
- potential empirical correction of atmospheric noise
- irregular data subsampling using a quadtree algorithm
- estimation of turbulent atmospheric noise statistics and setup of the error variance-covariance matrix
- formatting of the data for the modelling with the pyrocko optimization tool Grond.

Find out more about kite visit the ➠ kite documentation and watch ➠ this EGU2020 presentation.



C A U

BridGeS

Bayesian Source optimization - Grond

GROND is a direct-search optimization algorithm. The optimization strategy resembles Simulated Annealing algorithms.

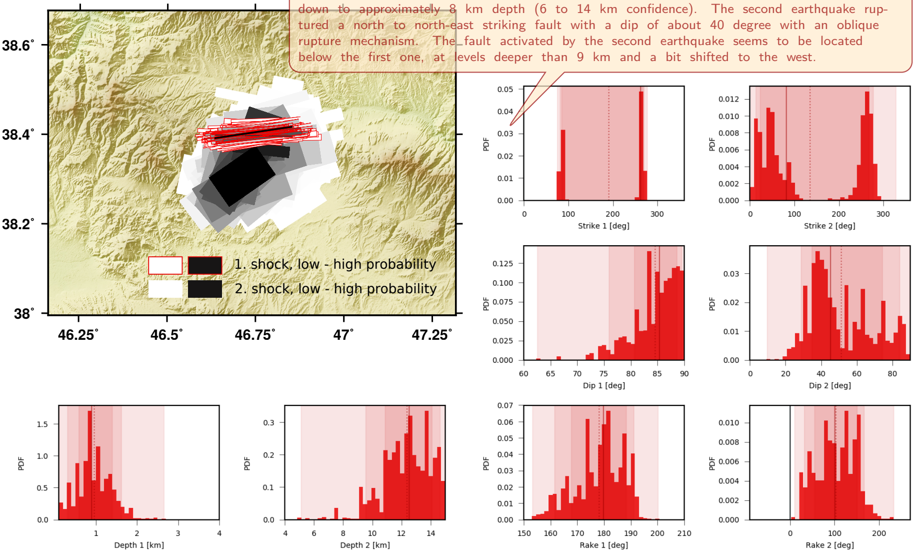
Grond does not only optimize though. By internal Bayesian bootstrapping of data weights it keeps record of a chosen number of slightly perturbed and independent optimizations, from which one can form Bayesian model ensembles.

To explain Grond is beyond the frame of the presentation, please consult the documentation for details and code here ➠ Grond.

BridGeS

Results: Sources

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.



C A U

BridGeS

Results: Data fits

A selection of ensemble fits at stations with epicentral distances smaller than 1000 km (out of about 30 stations).
The dark grey lines are the observed waveforms. Red traces are synthetics from models with an overall good data fit, blue traces are from models with slightly less good overall fits. The trace misfit is shown below the waveforms.

full waveform 1. shock

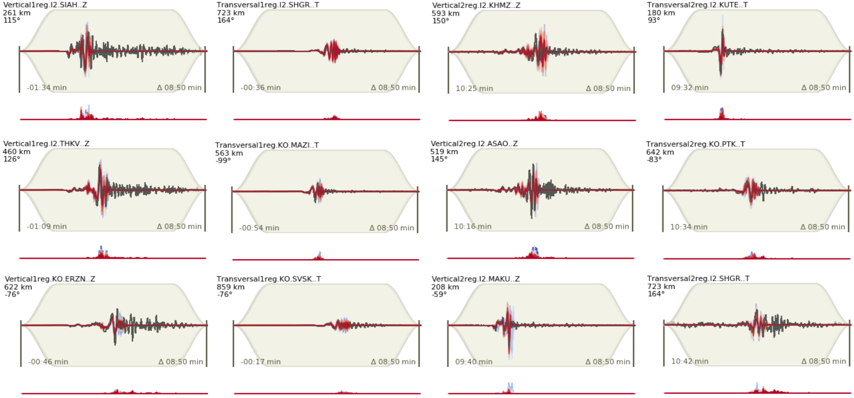
full waveform 2. shock

Z- component

T- component

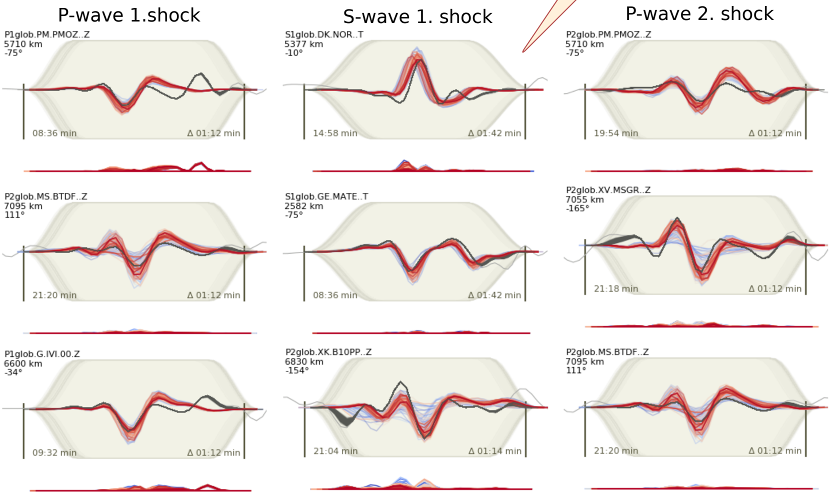
Z- component

T- component



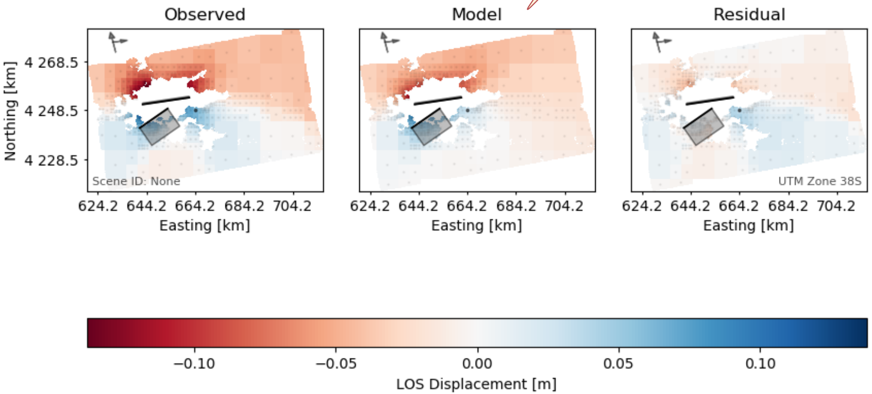
Results: Data fits

A selection of ensemble fits at stations with epicentral distances larger than 1000 km (out of about 30 stations).
See plot description on the previous slide.

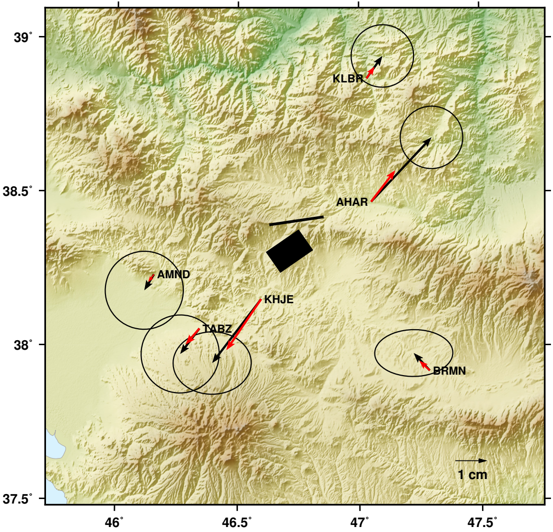


Results: Data fits

The fit to the pattern of the InSAR displacement is good. The signal is slightly underestimated. Only the first shock contributes significantly to the surface displacement. The second earthquake is too deep for a strong contribution in this regard.



Results: Data fits

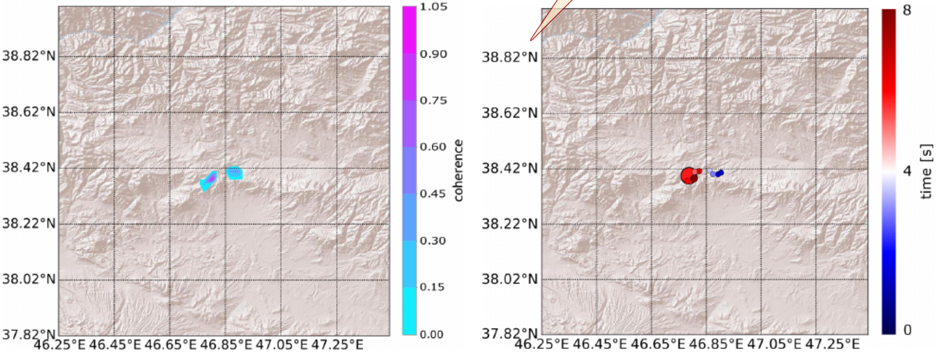


For the GNSS displacements we also find a good overall fit (red) to the signal (black) with a slight underestimation of the total displacements. The source surface projections are shown with dark boxes.

Multi-array Backprojection

a model-independent waveform analysis

Calculating a multi-array backprojection for the first Ahar earthquake using teleseismic waveforms at frequencies above the corner frequency of 0.24 Hz, we find two pulses of high-energy wave radiation (high coherence) as shown in the left figure. The time evolution on the right shows these pulses to be start and stop phases of an unilateral rupture from east towards west.
The locations well corresponds to the mapped surface trace and the fault model locations of the first earthquake.



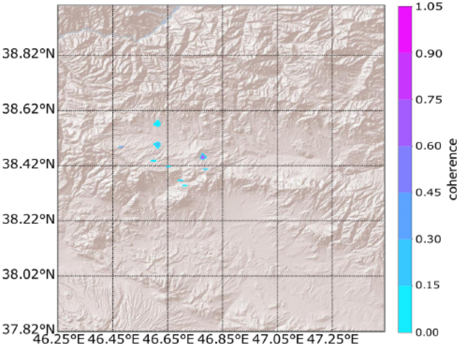
CAU BridGeS

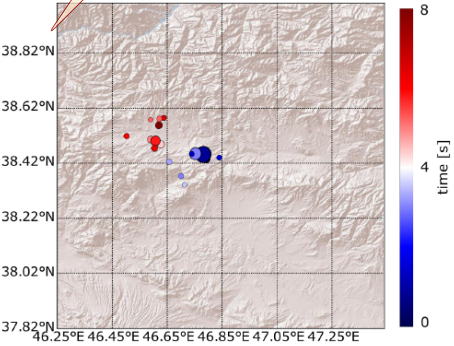
Multi-array Backprojection

a model-independent waveform analysis

For the second Ahar earthquake we get more than two energy pulses. They show a larger spread in east-west and in north-south direction compared to the results of the first earthquake. All the pulses are located further west and north compared to the kinematic modelling results (slide 9) of the second earthquake.

You may be interested in another application of this multi-array backprojection. In this case check out the presentation of Hicks et *al.* on the 2016 Romanche earthquake.





Summary

We present a non-linear Bayesian fault slip optimization that simultaneously searches for two best fitting sources of the Ahar earthquake doublet.

We combine an InSAR displacement map, GNSS displacement vectors and regional as well as global seismic waveform recordings in one common model framework.

We propagate data and partly model uncertainties to robustly estimate the model parameter uncertainties.

All software implementations are open-source and publicly available (some under development).

Check out these other applications of our software tools to earthquake source analyses at EGU2020:

- On the 2017 November 12 Mw 7.3 Sarpol-Zahab earthquake sequence by Jamalreyhani et *al.*
- On the 2016 Romanche earthquake by Hicks et *al.*
- On the 2019 Ridgecrest earthquakes by Isken et *al.*

BridGeS

Acknowledgements

... and thank you for support!

Emmy Noether-Programm

Deutsche Forschungsgemeinschaft DFG

GFZ

CAU BridGeS