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Seismogenic source model of the 2019 Mw 5.9 East-Azerbaijan earthquake (NW Iran) through Sentinel-1 DInSAR measurements

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Aim of this work

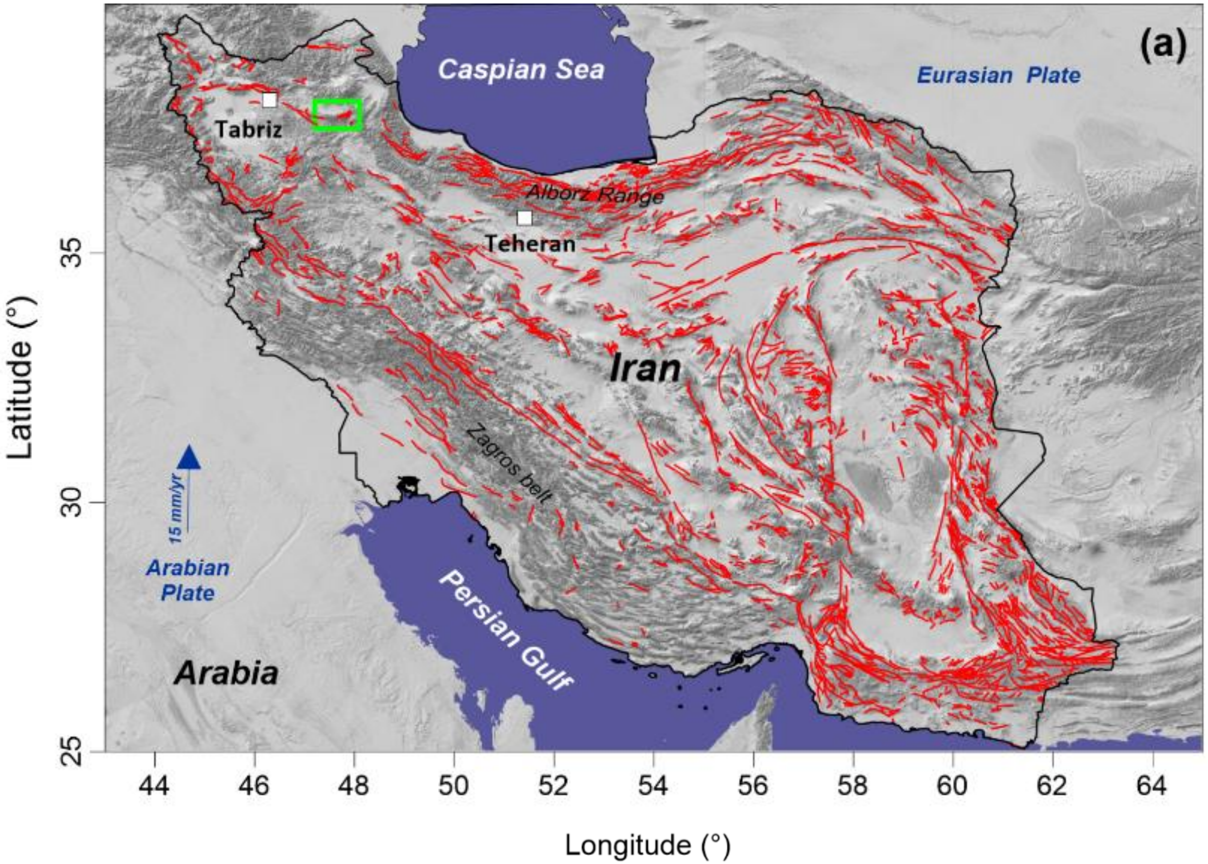
- We investigate the M_w 5.9 earthquake occurred on 7 November 2019 in the East-Azerbaijan region, in northwestern Iran, killing at least five people, injuring hundreds, and causing widespread damage to the surrounding villages.

  - We first exploit the Differential Synthetic Aperture Radar Interferometry (DInSAR) measurements obtained by processing the data collected by the Sentinel-1 (S1) satellite of the Copernicus European Program along ascending and descending orbits.

    - We apply an analytical modelling approach to the computed coseismic DInSAR displacements, with the aim of better constraining the kinematics of the main seismic source.

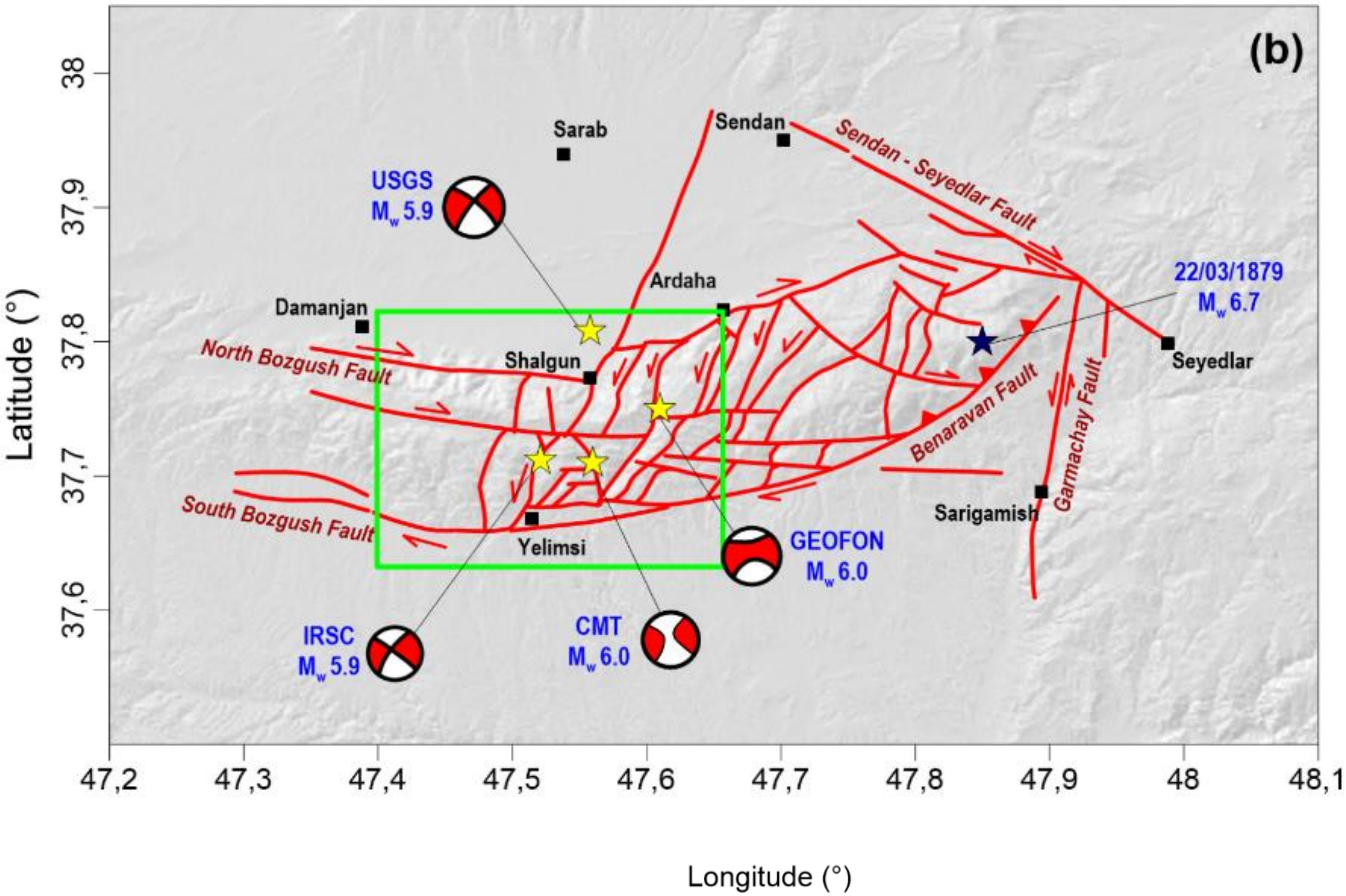
      - We perform an analysis of the Coulomb stress transfer on the nearby faults, in order to investigate possible fault interaction processes.

Tectonic setting



Tectonic Map of Iran (WGS84), where the main tectonic structures (https://catalog.data.gov/dataset/major-faults-in-iran-flt2cg-73f76) are reported with red lines. The green rectangle identifies the zone considered in the following panel and the reported plate velocity is derived from Reilinger, R. et al. 2006.

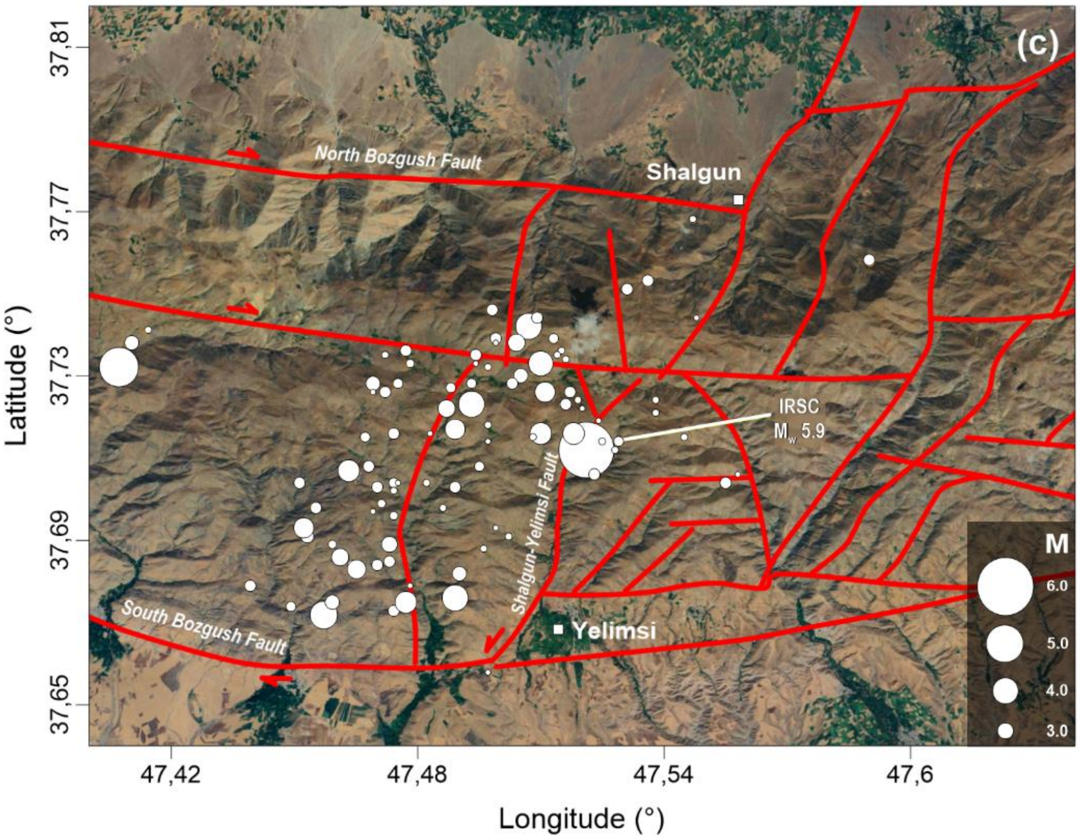
Tectonic setting



Detailed structural map of the considered seismogenic area, in which the main geological lineaments are highlighted by red lines (by Faridi et al. 2017).

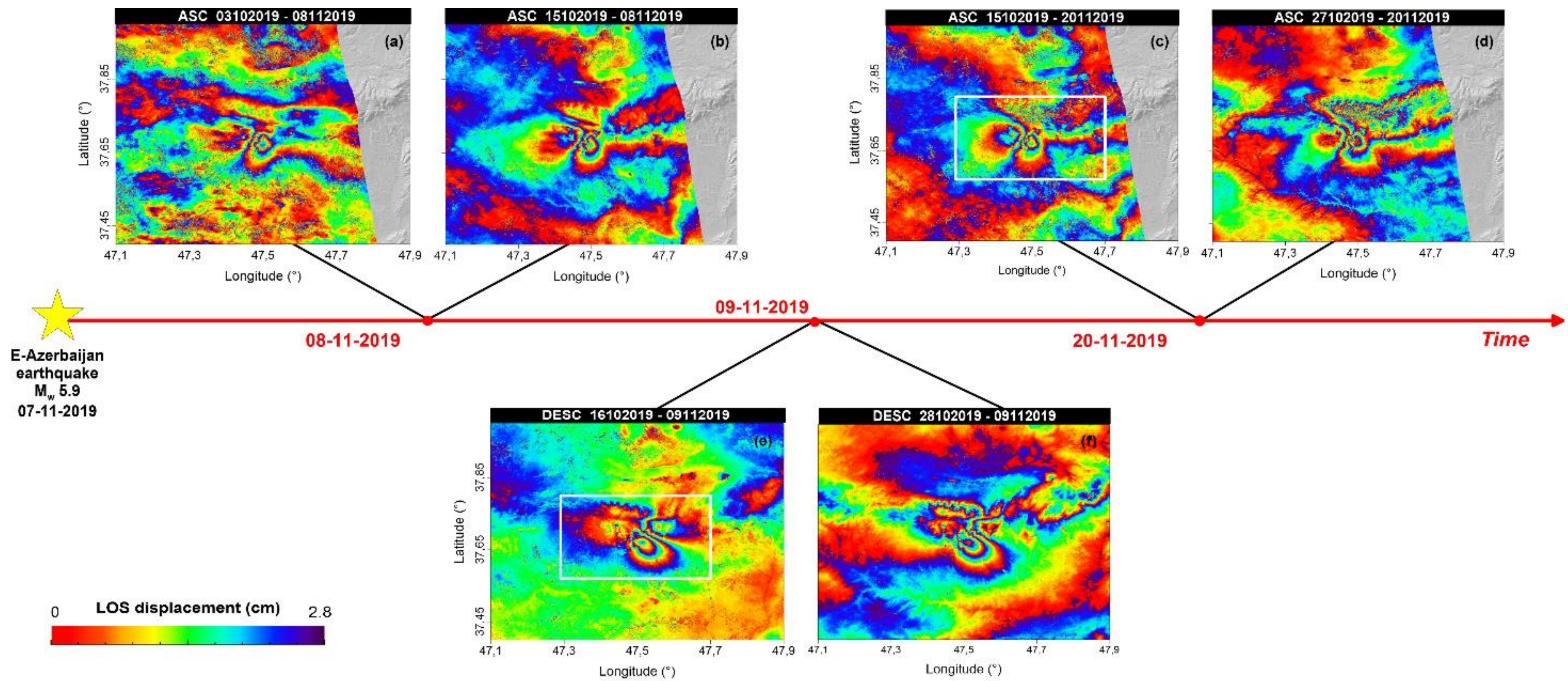
The different proposed epicentral locations and focal mechanisms are also shown, as well as the strongest historical event occurred in the considered area (black star). The green rectangle identifies the zone considered in the following panel.

Tectonic setting



Distribution of the seismicity recorded from 7 to 9 November 2019 (white dots), shown as a function of magnitude (the higher the magnitude, the bigger the circles). The main local structures are also indicated with red lines (Faridi et al. 2017). In all the panels, the reported data are superimposed on the 1 arcsec Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) of the zone.

Sentinel-1 DInSAR measurements

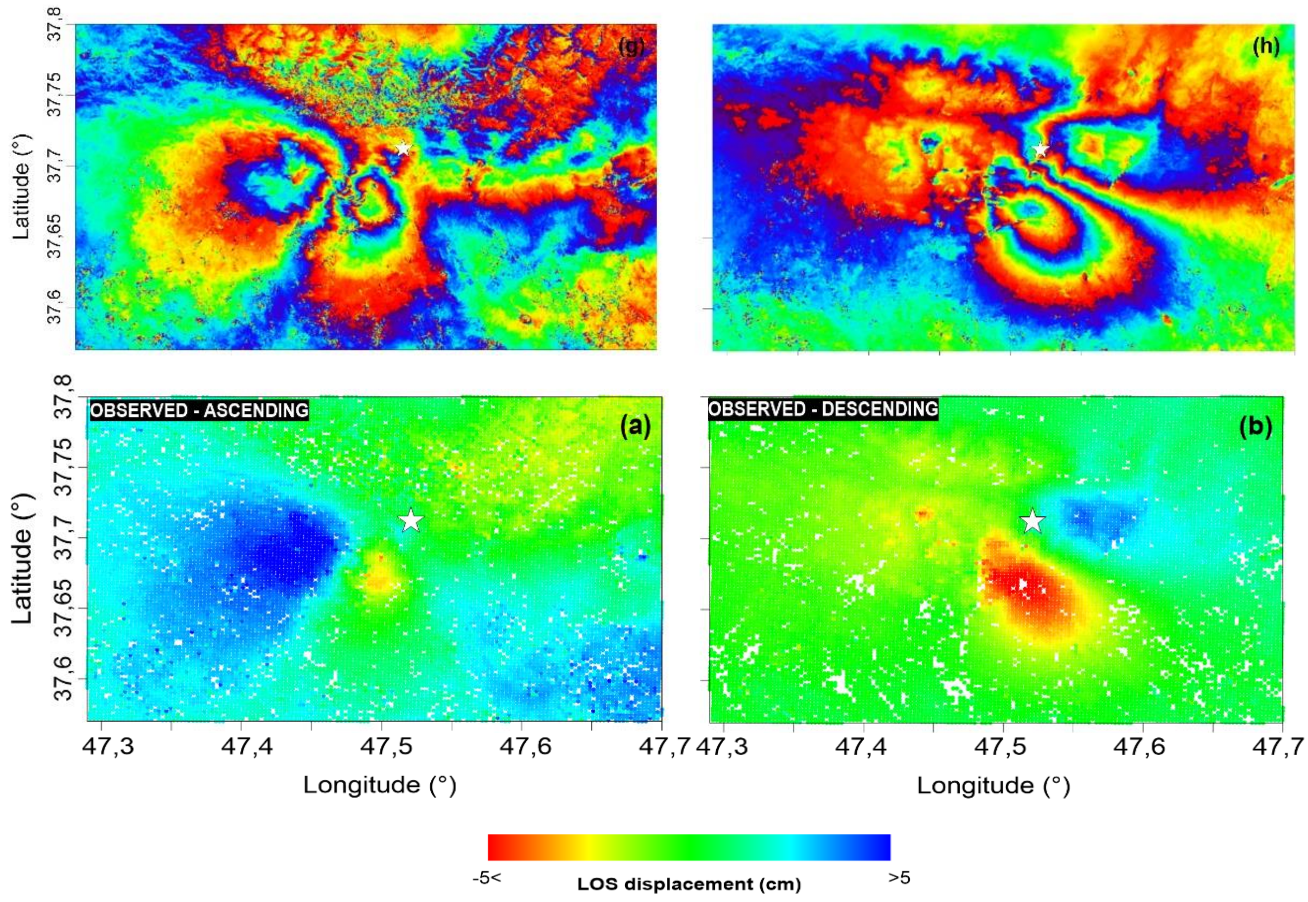


Exploited DInSAR measurements. Interferograms (wrapped) generated from Sentinel-1 data pairs acquired along ascending (ASC) orbits on (**a**) 3 October and 8 November 2019, (**b**) 15 October and 8 November 2019, (**c**) 15 October and 20 November 2019, (**d**) 27 October and 20 November 2019, and along descending (DESC) orbits on (**e**) 16 October and 9 November 2019 and (**f**) 28 October and 9 November 2019. The yellow star represents the Mw 5.9 E-Azerbaijan mainshock.

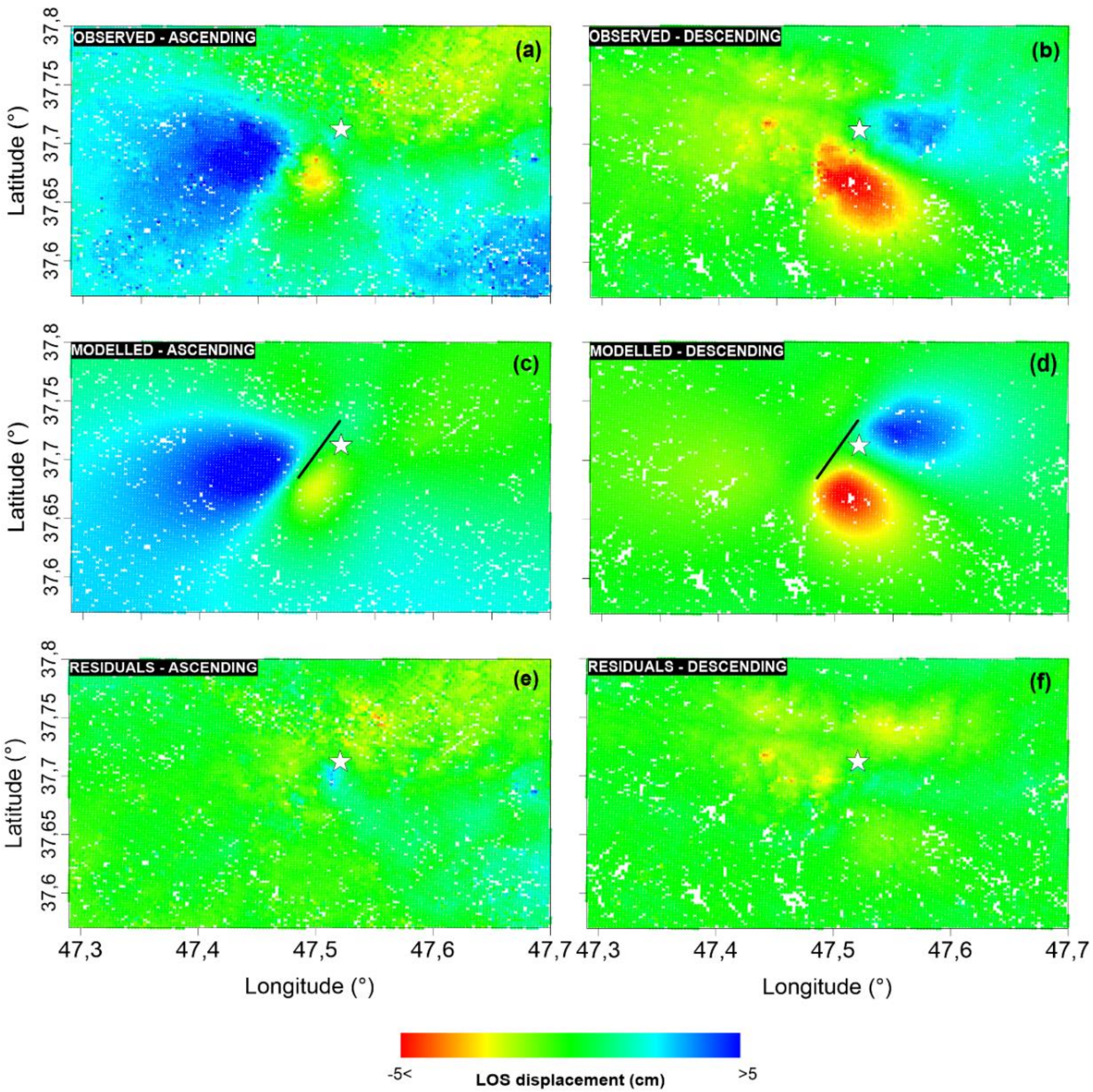
Sentinel-1 DInSAR measurements

DInSAR data pair: 15102019-20112019
Orbit: ascending - Track: 174

DInSAR data pair: 16102019-09112019
Orbit: descending - Track: 6



Analytical modelling: Non-Linear inversion



We jointly inverted the S1 DInSAR displacements acquired from ascending and descending orbits, by performing a consolidated two-step approach that consists of a non-linear optimization to constrain the fault geometry assuming a uniform slip, followed by a linear inversion to retrieve the slip distribution on the fault plane.

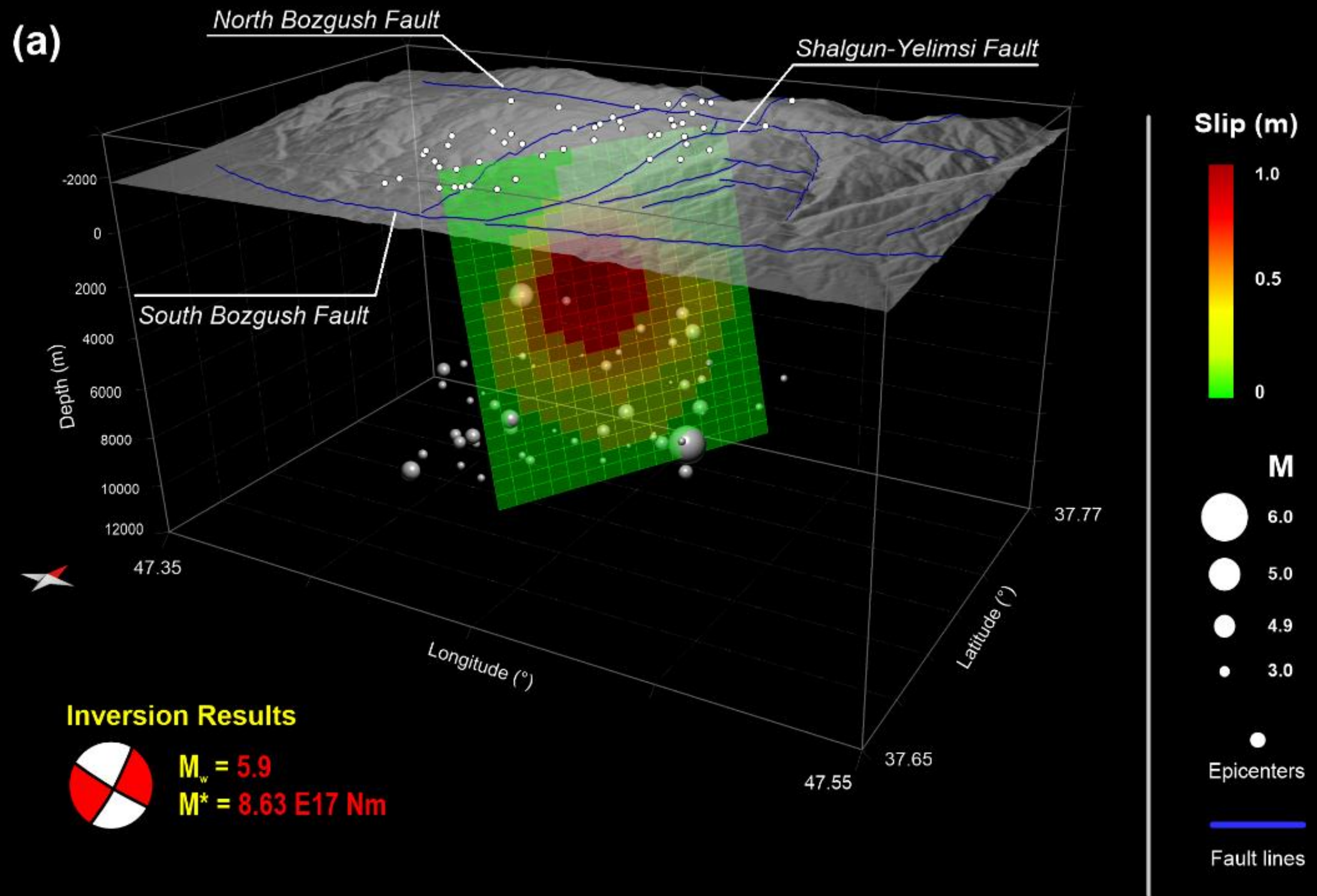
Source modelling results. Line-of-sight (LOS) projected displacement maps for S1 ascending (a) and descending (b) orbits interferograms. LOS projected displacement maps computed from the retrieved analytical model for the S1 ascending (c) and descending (d) orbits interferograms reported in panels (a) and (b). Their corresponding residual maps are shown in (e) and (f), respectively. The white star and the black line indicate the Mw 5.9 E-Azerbaijan mainshock and the retrieved fault plane solution, respectively.

Analytical modelling: Non-Linear inversion

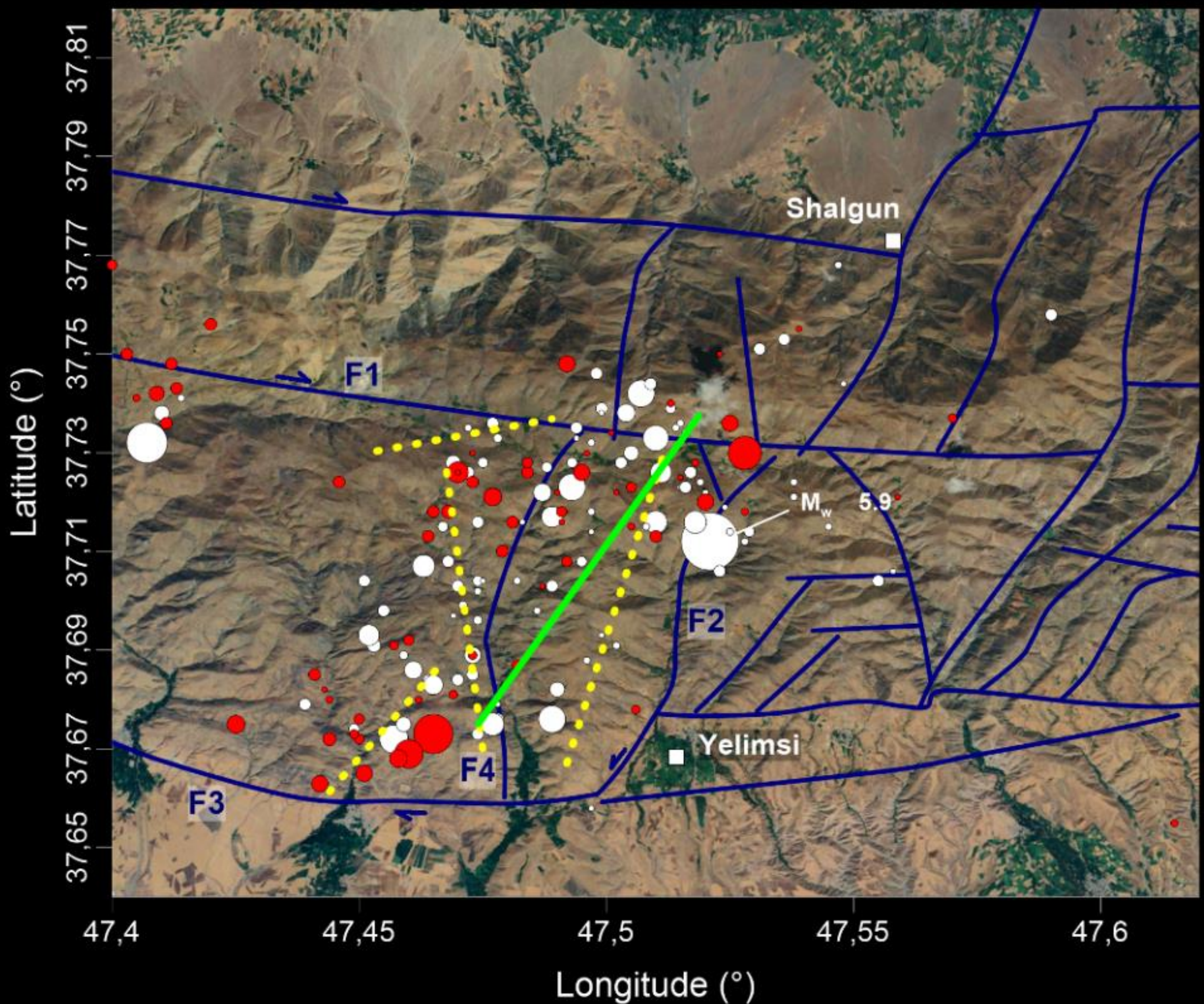
Parameter	Best-fit
Length (m)	6219.80 (±1540)
Width (m)	5629.90 (±2530)
Center Depth (m)	3096.60 (±633)
Dip (deg)	79.29 (±7)
Strike (deg)	29.17 (±5)
Rake (deg)	−4.94 (±7)
East (m)	720,969.80 (±667)
North (m)	4,176,230.30 (±737)
Slip (m)	0.73 (±0.23)

Best-fit parameters of the seismic source retrieved from non-linear inversion modelling. The 1-σ uncertainty is also reported.

Analytical modelling: Linear inversion



Analytical modelling: Linear inversion

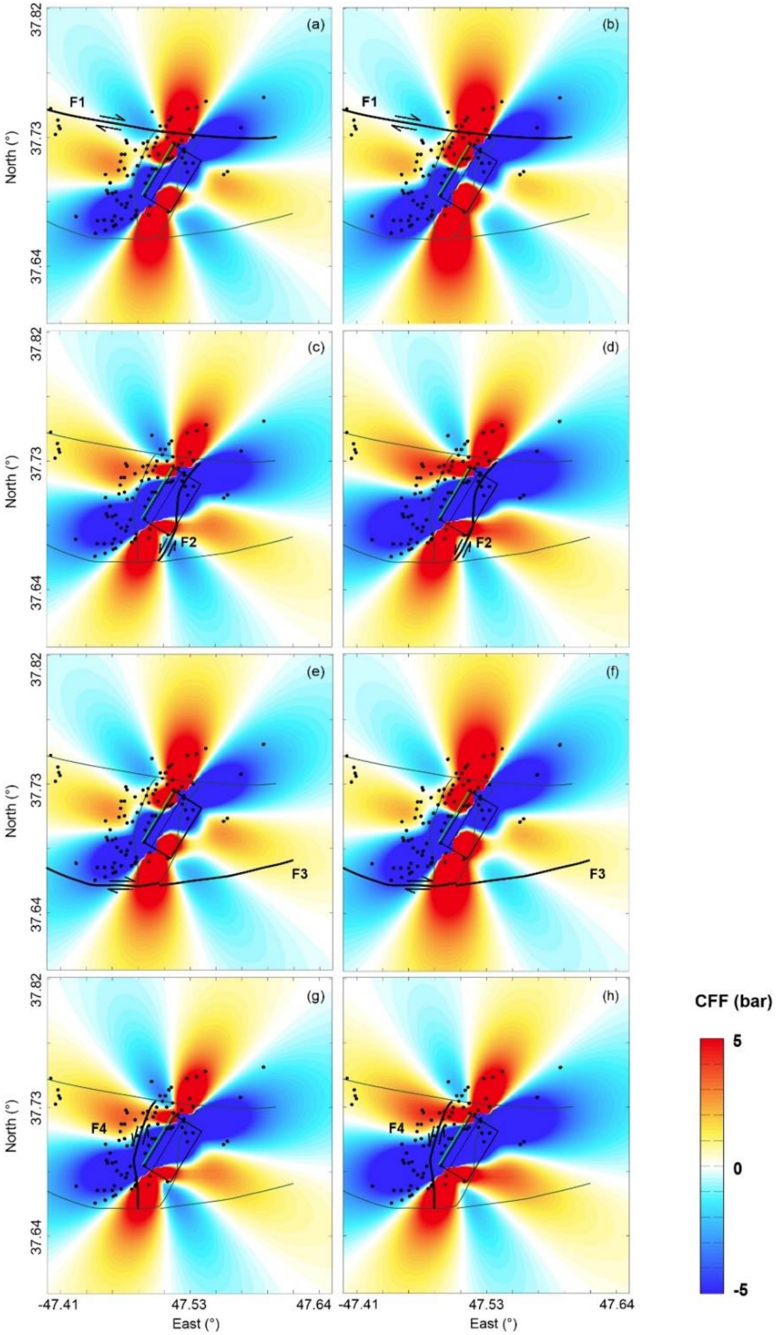


Seismicity distribution recorded from 7 to 9 November 2019 (white circles) and from 10 November to 24 December 2019 (red circles) is shown as a function of magnitude (the higher the magnitude, the bigger the circles). The retrieved fault and the distribution of the fractures generated by the seismic event are reported with the green line and the yellow dashed lines, respectively. The main local structures (Faridi et al. 2017) are also indicated with blue lines (F1, F2 = Shalgun-Yelimsi Fault, F3 = South Bozgush Fault and F4) and are superimposed on the 1 arcsec SRTM DEM of the zone.

Coulomb Failure Function

Coulomb Failure Function. Coulomb stress change maps computed at a reference depth of 5 km. For each selected receiver fault (F1, F2 = Shalgun–Yelimsi Fault, F3 = South Bozgush Fault and F4) mechanism, we tested two effective friction coefficients: μ’ = 0.4 reported in panels (**a**,**c**,**e**,**g**), and μ’ = 0.6 in panels (**b**,**d**,**f**,**h**). The aftershocks recorded during the period 7 November–24 December 2019 are reported with black dots. Solid lines represent the receiver faults on which the Coulomb stress change is calculated, whereas lines are not involved in that specific computation. All the reported geological structures are derived from Faridi et al 2017.

Overall, our results indicate that the main event may have encouraged (i.e., positively stressed), with a positive loading, the activation of all the considered receiver faults. This is confirmed also by the distribution of the aftershocks (black dots) that occurred in proximity or exactly on the considered faults.



Discussion

- By analyzing the hypocentral distribution of the earthquakes nucleated after the mainshock and until 24 December 2019, we remark that the seismicity shows an evident southeast-dipping high angle alignment, which is in good agreement with our modelled fault plane.

- We suggest that our solution reveals a minor fault located west of the Shalgun–Yelimsi Fault and not mapped in the geological maps available in the open literature, whose kinematics is compatible with that of the surrounding structures and with the local and regional stress states. Moreover, Zamani and Masson (2014) and Faridi et al. (2017) have furnished a detailed reconstruction of the subsurface geology of the considered seismogenic area and have produced some geological sections of the examined region.

- The retrieved fault solution can be related with the reconstruction of the stress states performed by Zamani and Masson (2014). The origin and kinematics of the local left-lateral strike-slip faults, such as the causative fault of the considered E-Azerbaijan earthquake, and the related seismicity, can be linked to the accommodation of the nearly N–S shortening between the Arabian and Eurasian plates, with the subsequent eastward extrusion of regional crustal scale blocks.

- We further remark that, if we should consider as seismogenic source a structure consistent with the reported location and orientation of the Shalgun–Yelimsi Fault, the geodetic inversion of the exploited DInSAR measurements would result in a best-fit solution whose residuals are significantly worse than those achieved for our model. This is an additional confirmation of the validity of our findings.

Conclusions

Our main findings can be summarized as follows:

- The source model reveals a rather shallow seismic structure approximately NE–SW-striking and characterized by a left-lateral strike-slip, southeast-dipping faulting mechanism. The retrieved source reveals a minor fault not mapped in the geological maps available in the open literature, but it is characterized by a kinematics compatible with that of the surrounding structures, the local and regional stress states and with some of the field observations.

- Starting from the retrieved fault model characteristics and by considering the known surrounding geological structures, we have performed an analysis of the Coulomb stress transfer on the nearby faults, in order to investigate possible fault interaction processes. Our results indicate that the considered receiver faults may have been positively stressed by the main event and this is confirmed by the aftershocks distribution.

- The analysis of the seismic events nucleated along the left-lateral strike-slip minor faults of the East-Azerbaijan Plateau, such as the one analyzed in this work, is essential to improve our knowledge of the seismic hazard estimation in northwestern Iran.

remote sensing

MDPI

Article

Seismogenic Source Model of the 2019, M_W 5.9, East-Azerbaijan Earthquake (NW Iran) through the Inversion of Sentinel-1 DInSAR Measurements

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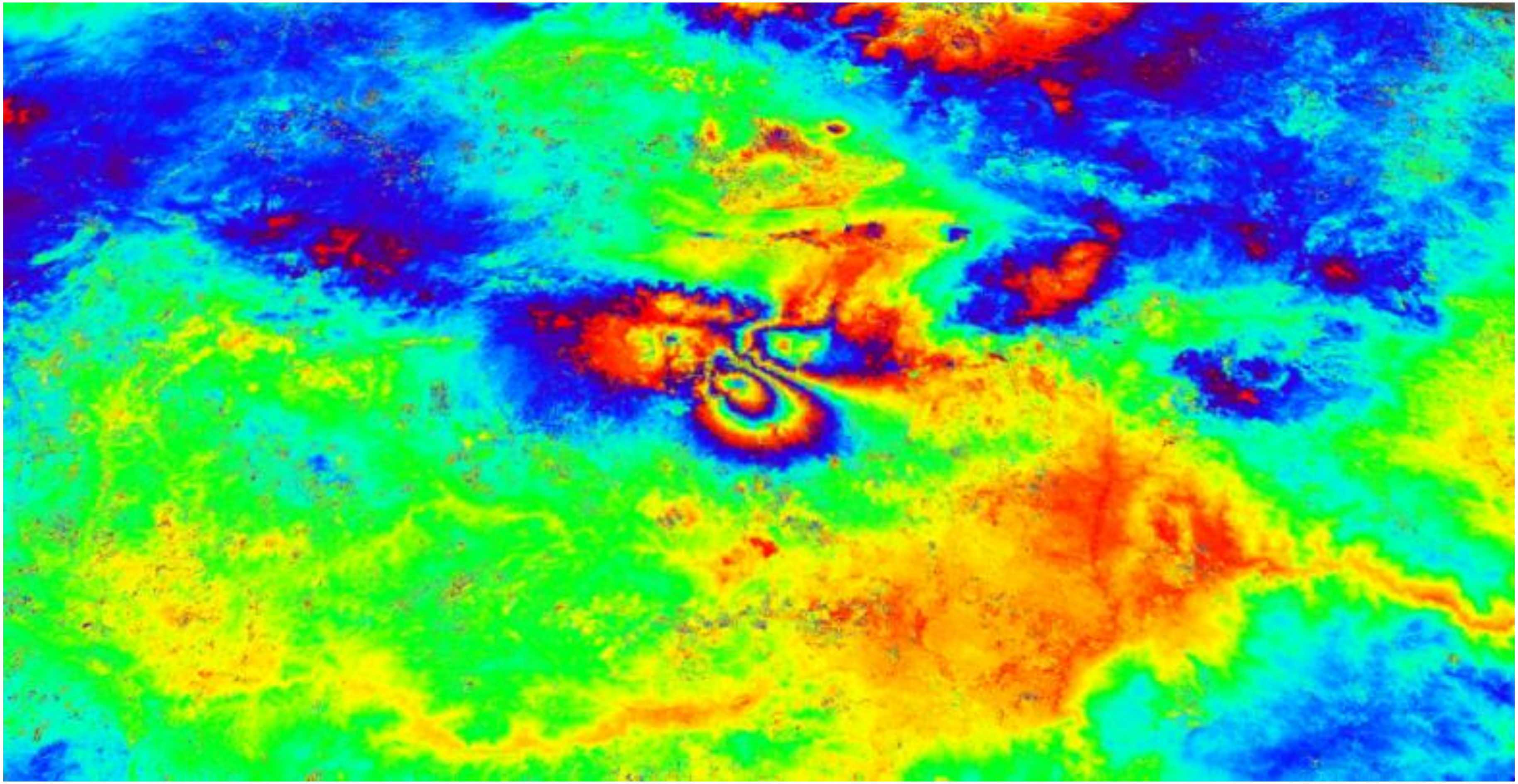

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