

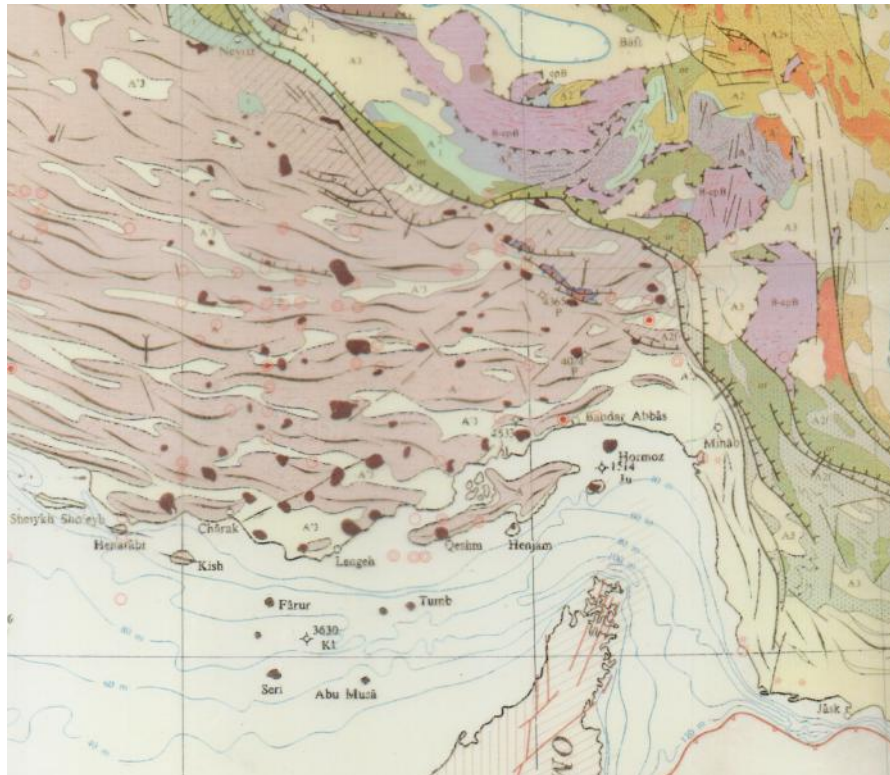
فرآیند شکست گسل در زمین لرزه دوگانه 23 آبان 1400 فین هرمزگان

محمد رئیسی

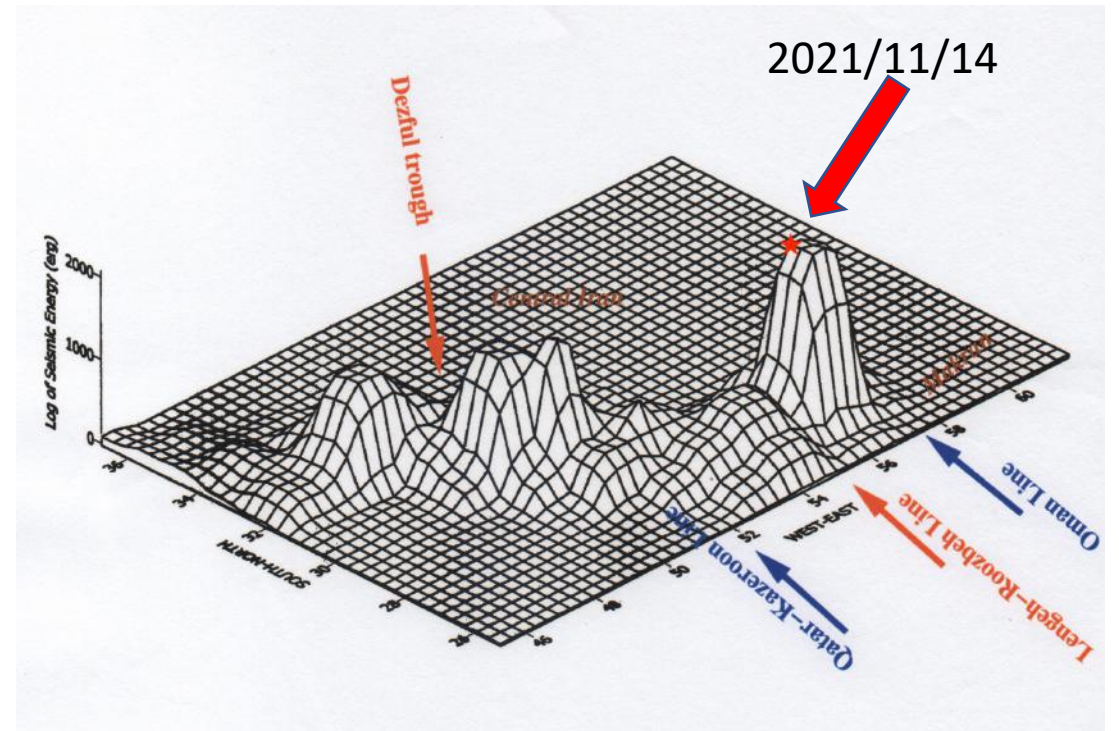
SeisAnalysis AS

The 2021/11/14 twin earthquakes

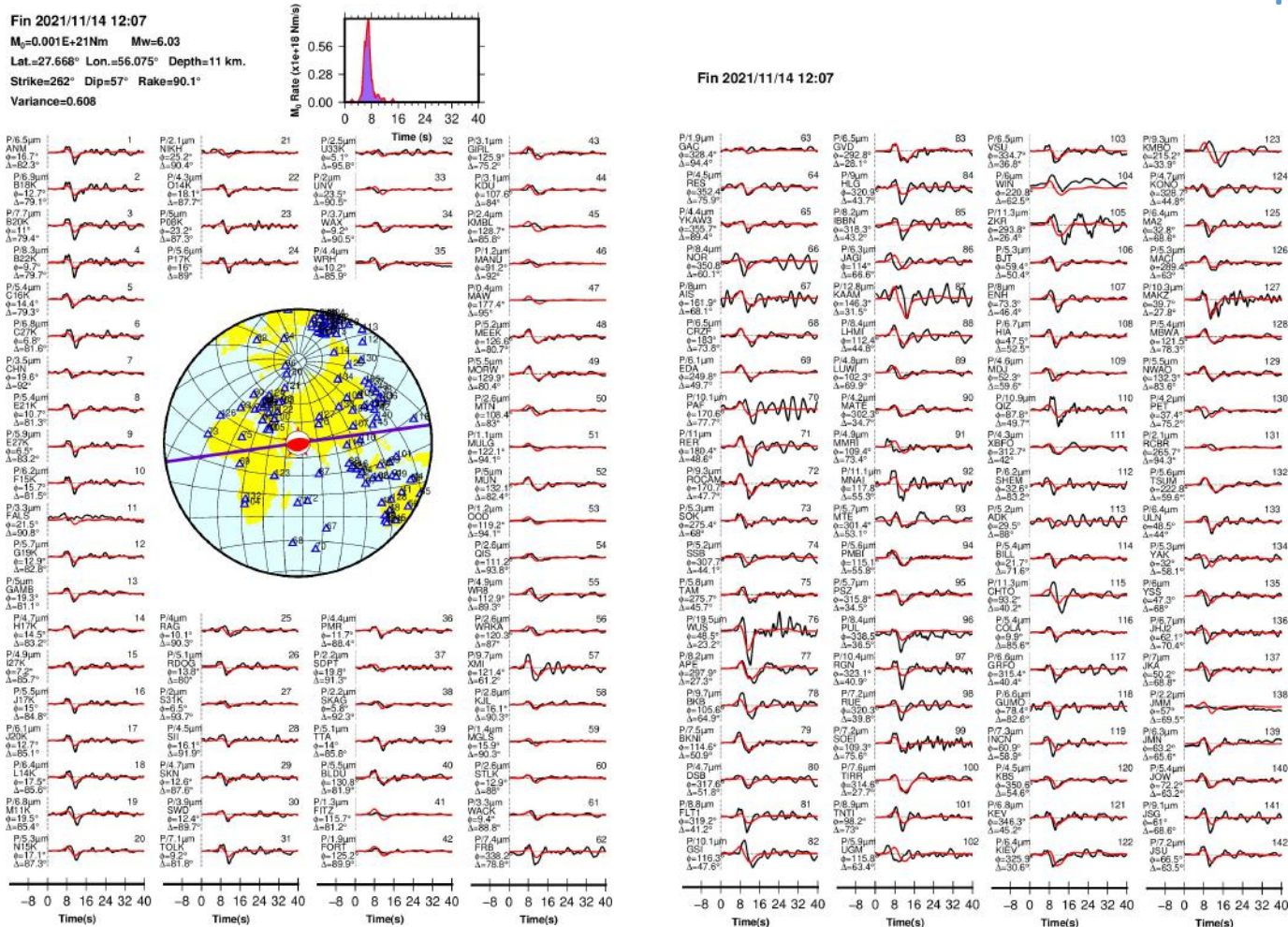
The western border of the main seismic energy release, **the Lengheh-Roozbeh Line**, roughly coincides with the largest salt domes in Zagros.



Seismic energy release in Zagros and Makran (1964-1995)

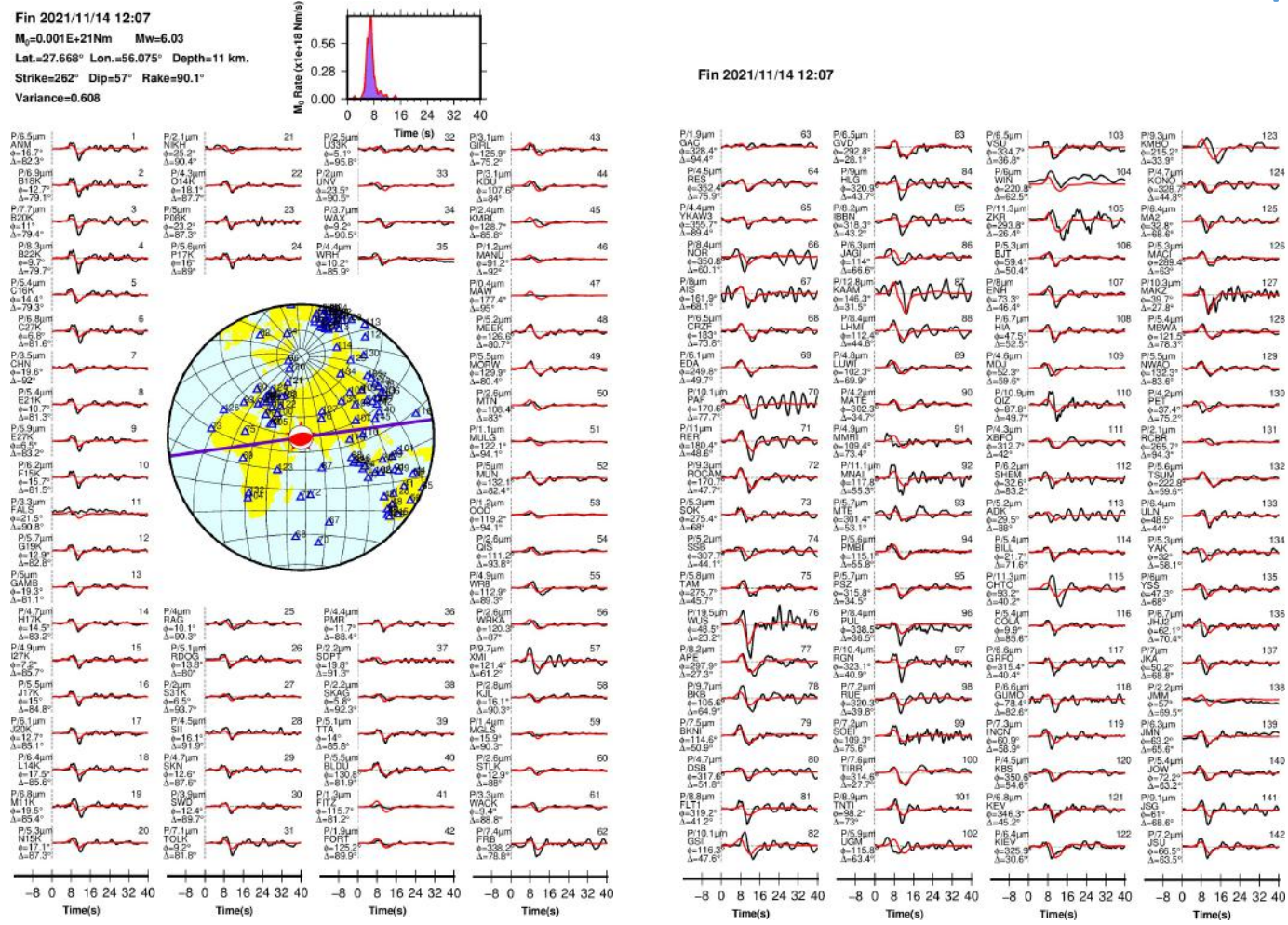


Body-waveform slip inversion of the 2021/11/14 12:07, the **first** Fin earthquake

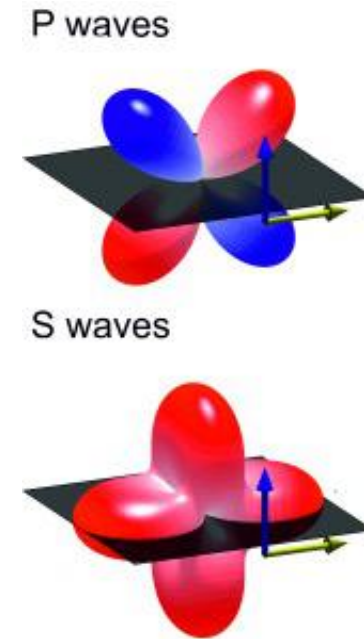


- The black lines are the recorded waveforms while the red lines show the synthetic ones.
- 151 P-wave recordings in the epicentral distances of 24° to 96° are used.
- This slip inversion lacks contribution of S waveforms due to interference with the waveforms of the second event.

Body-waveform slip inversion of the 2021/11/14 12:07, the first Fin earthquake



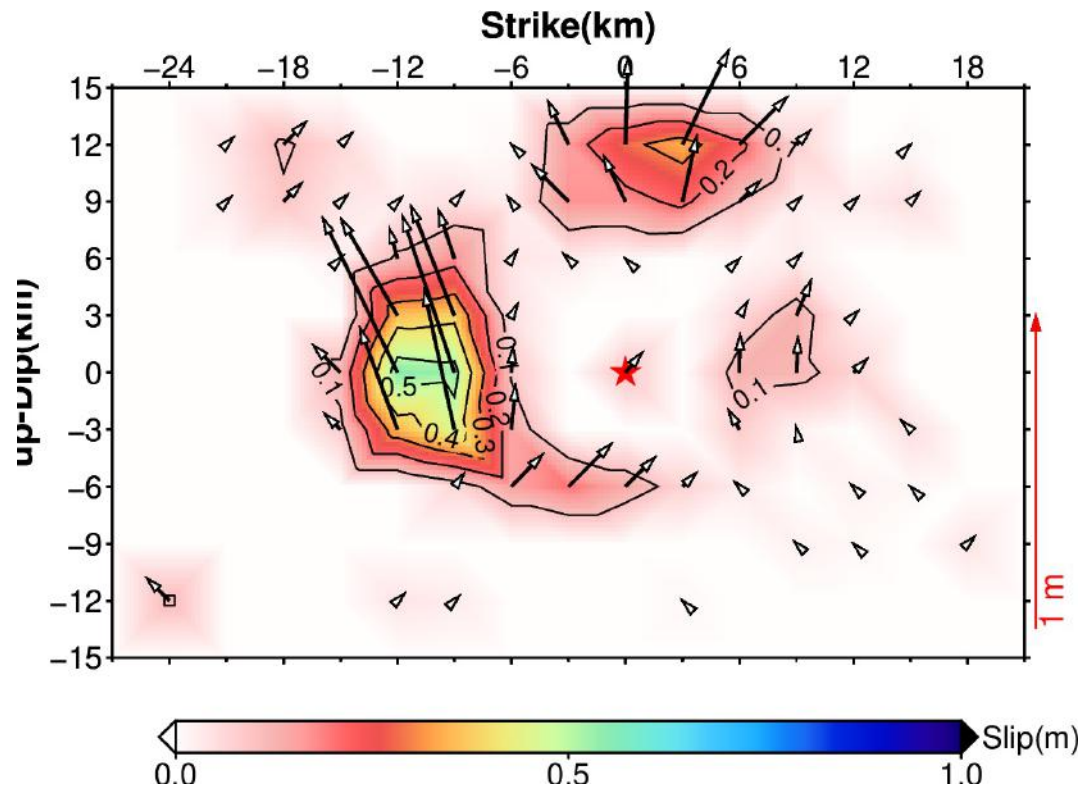
S-waves sample along the fault plane, while P-waves take-off from the fault plane.



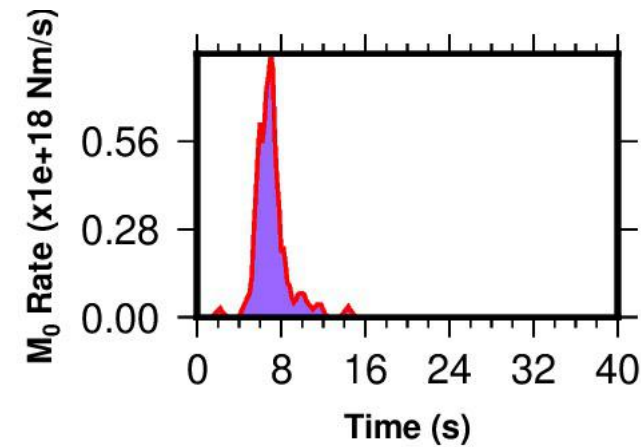
Modified after <https://www.mathworks.com/matlabcentral/mlc-downloads/downloads/submissions/43524/versions/1/screenshot.png>

Slip distribution of the 2021/11/14 12:07 earthquake

The slip distribution of the first earthquake indicates a **vacancy** in the middle.



The source time function indicates a main energy release of about **8 s**, with sharp increase and decrease.



Fin 2021/11/14 12:07

$M_0=0.001E+21Nm$ $M_w=6.03$

Lat.=27.668° Lon.=56.075° Depth=11 km.

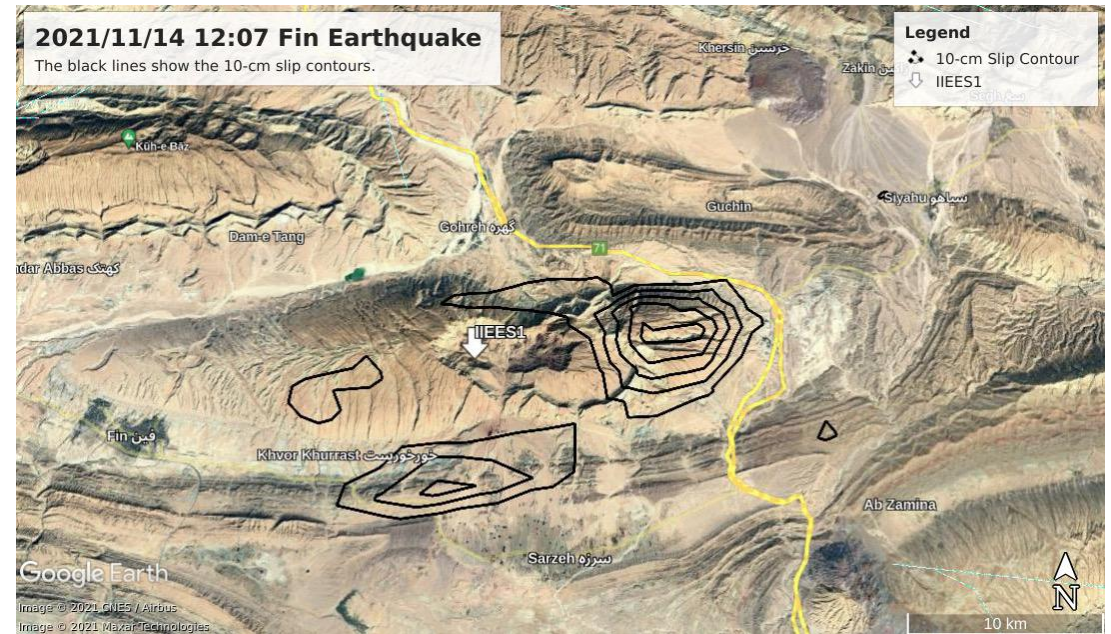
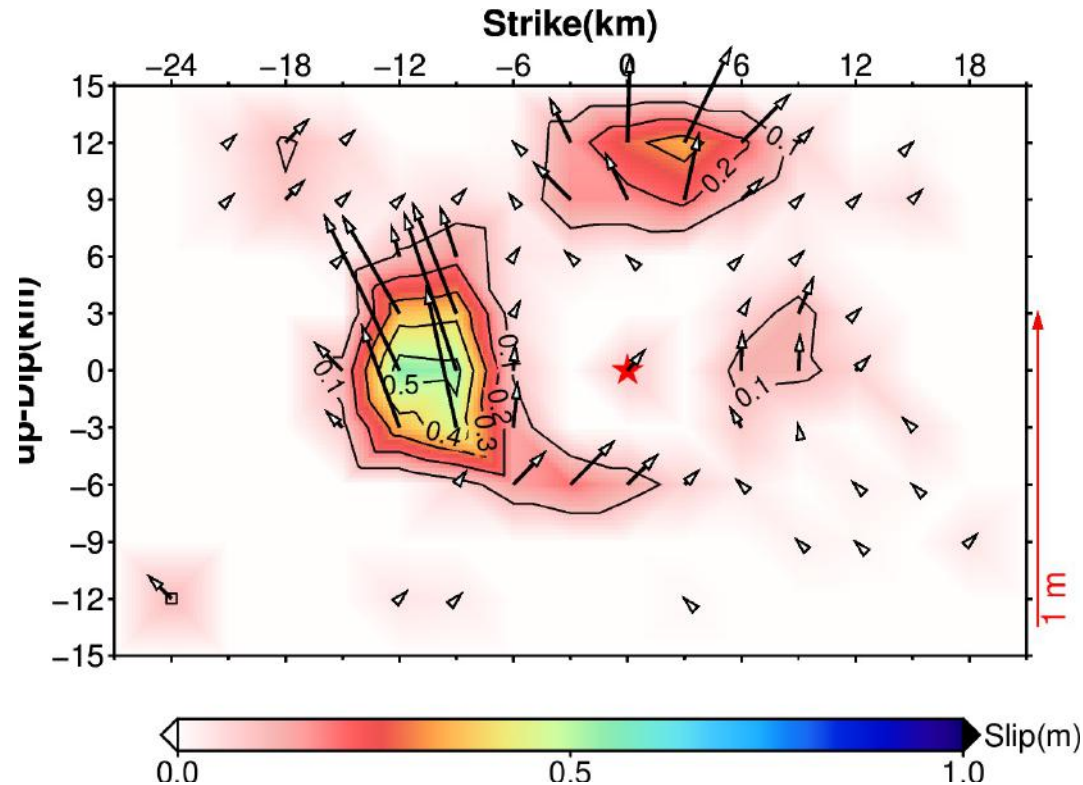
Strike=262° Dip=57° Rake=90.1°

Variance=0.608

Slip distribution of the 2021/11/14 12:07 earthquake

The slip distribution of the first earthquake indicates a vacancy in the middle. This area coincides with location of the **salt diapor**.

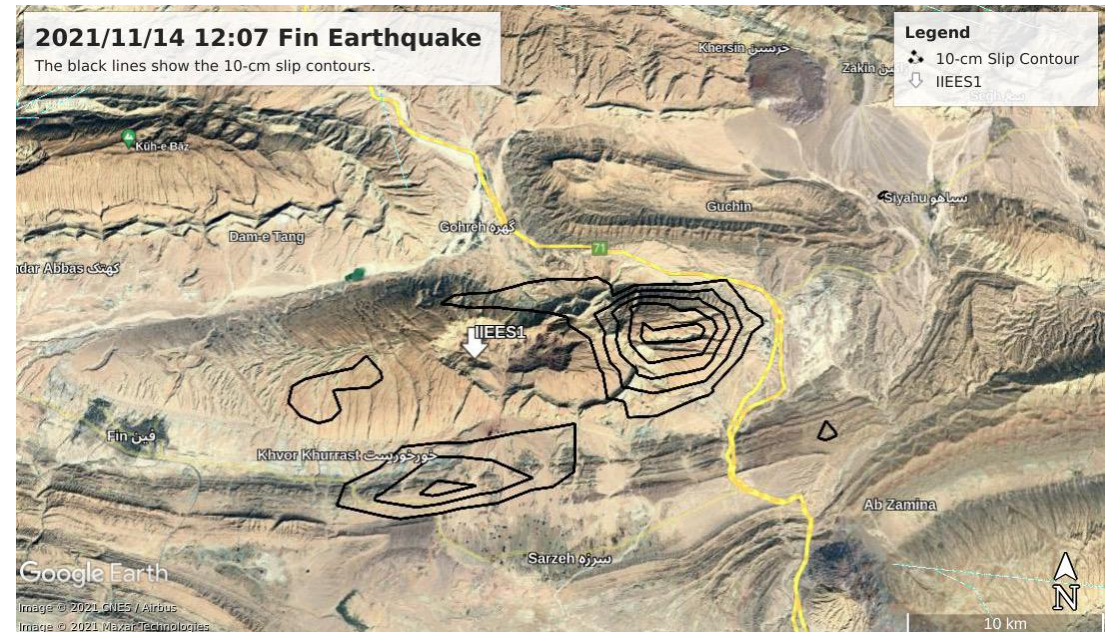
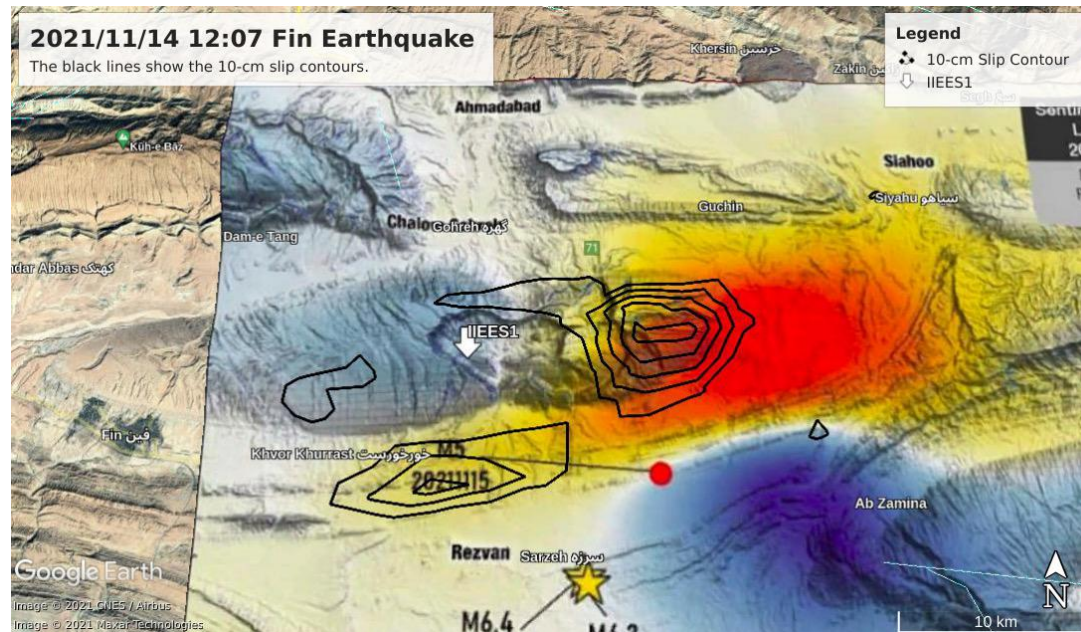
The 10-cm slip contours of the first earthquake shows the **eastern half of the anticline** and an area immediately to its south were involved.



Slip distribution of the 2021/11/14 12:07 earthquake

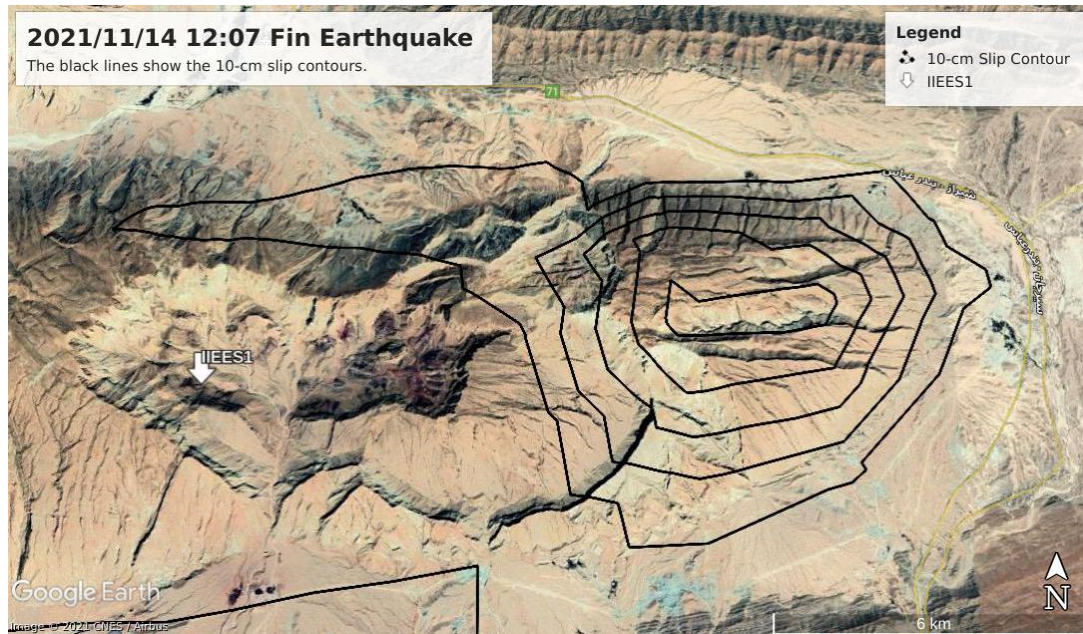
The descending LOS Displacement map is draped carefully on Google Earth image.

The slip contours are in 10 cm intervals.



LOS Displacement, prepared by Dr. S. Vakaniotis, Processed with DIAPASON at Geohazards TEP

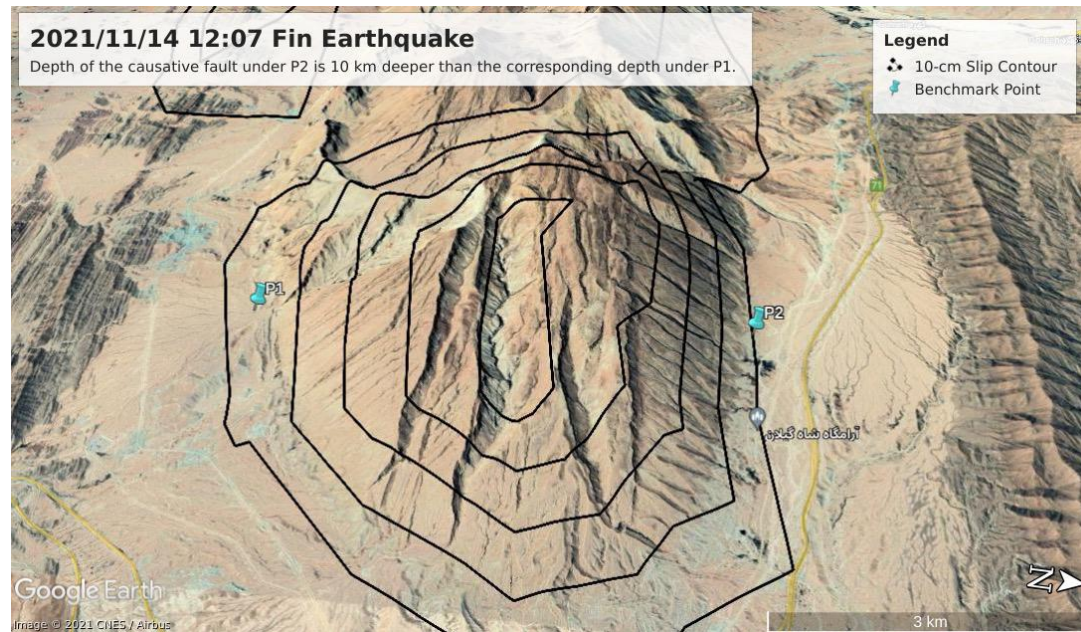
Slip distribution of the 2021/11/14 12:07 earthquake



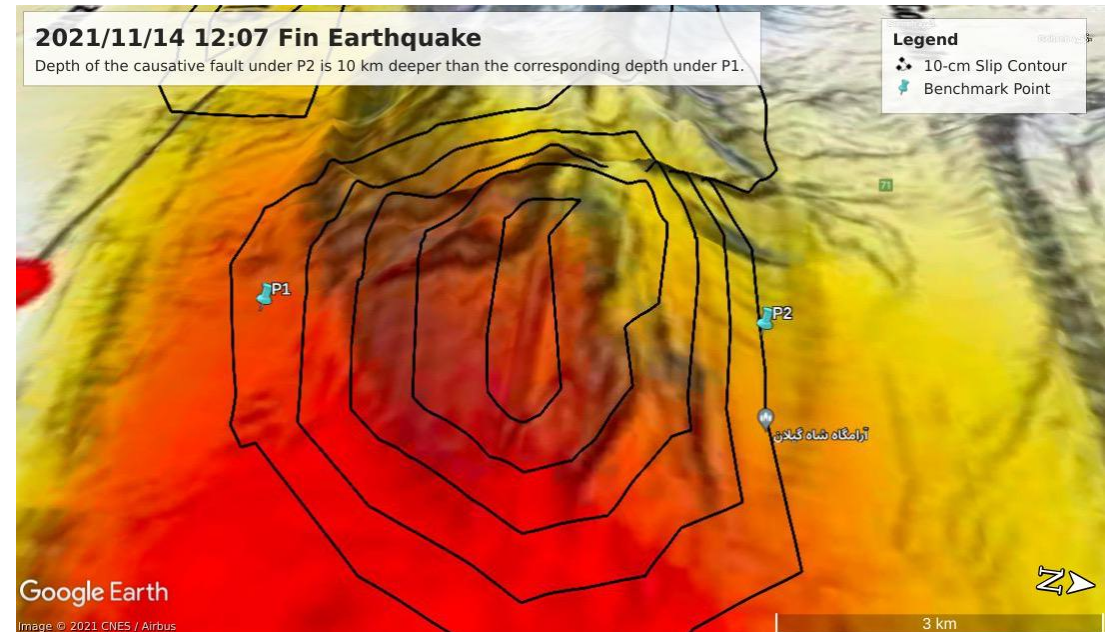
- The eastern part of the anticline coincides with the main part of the energy released during the first event.
- Although the event initiated from a point inside the **diapir**, the diapir did not contribute in seismic energy release.

Slip distribution of the 2021/11/14 12:07 earthquake

The eastern half of the anticline with 10-cm slip contours. There is a remarkable **correlation** between the topography and the slip contours. The fault plane under point P2 is **10 km** deeper than the corresponding point under P1.



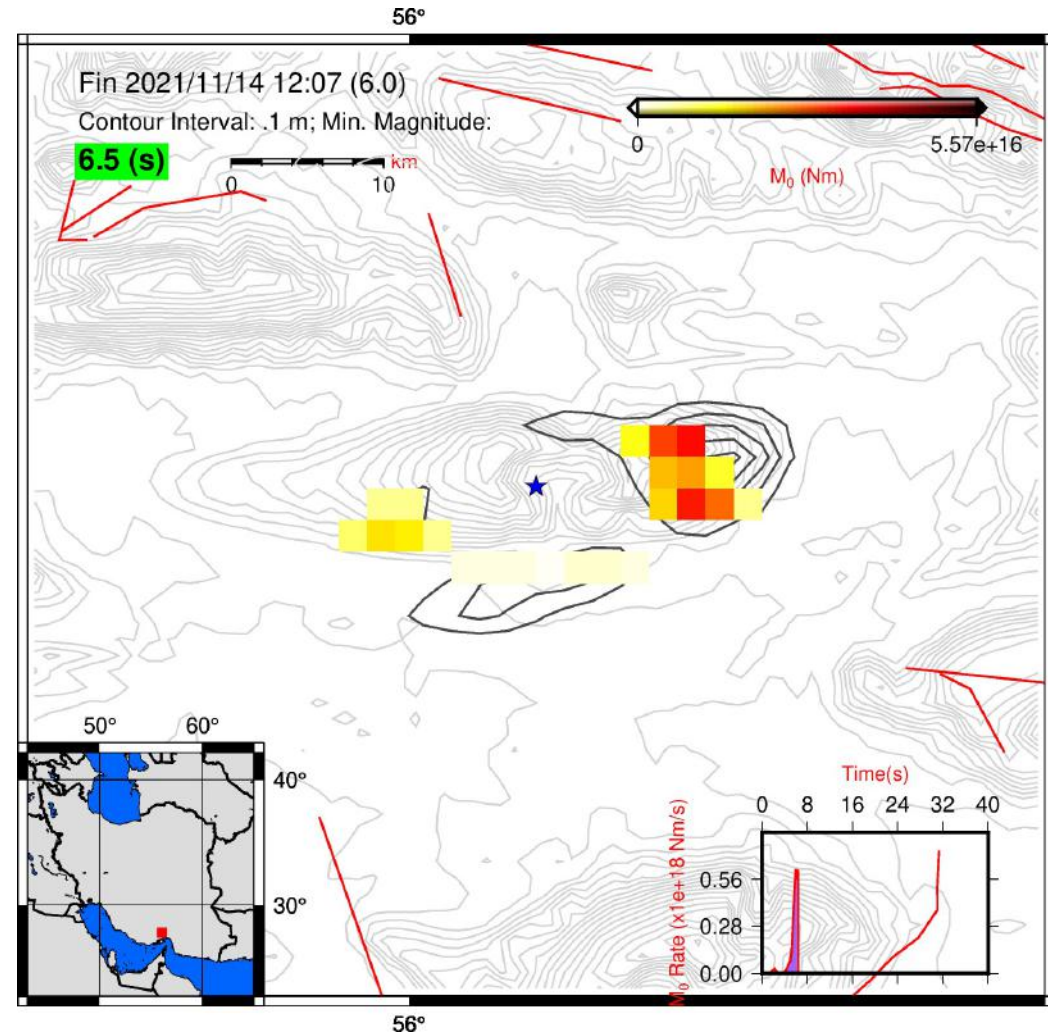
The same as the left image, except for drapping the LOS displacement map. The **asymetry** of the anomaly at points P1 and P2 may indicate a north-dipping fault.



LOS Displacement, prepared by Dr. S. Vakaniotis, Processed with DIAPASON at Geohazards TEP

Slip distribution of the 2021/11/14 12:07 earthquake

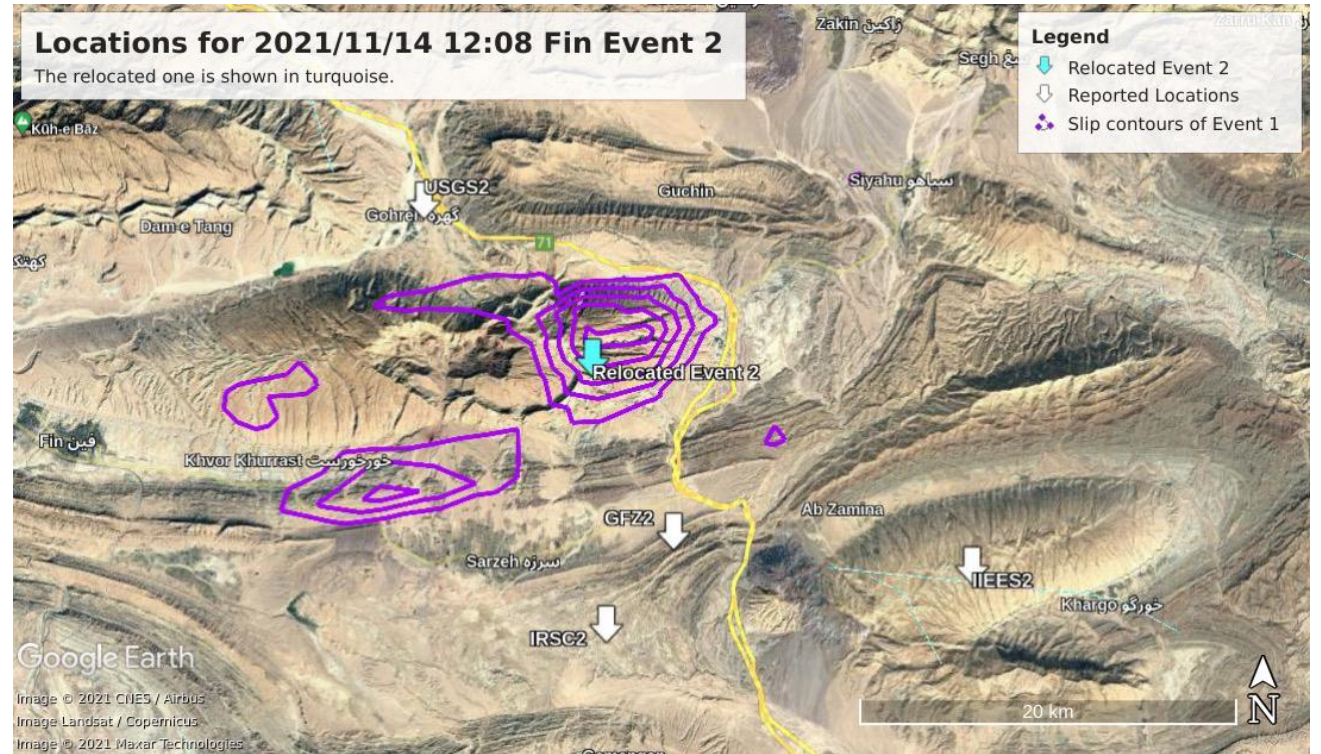
- The **green label** shows the seconds after rupture initiation.
- The source time function at the **bottom-right** corner shows the moment rate from the beginning of the rupture until the current moment, the green label.
- The colored patches show the location of the moment release. Its color shows the moment in Nm according the color bar on the **top-right**.



Relocation of the 2021/11/14 12:08 Fin earthquake

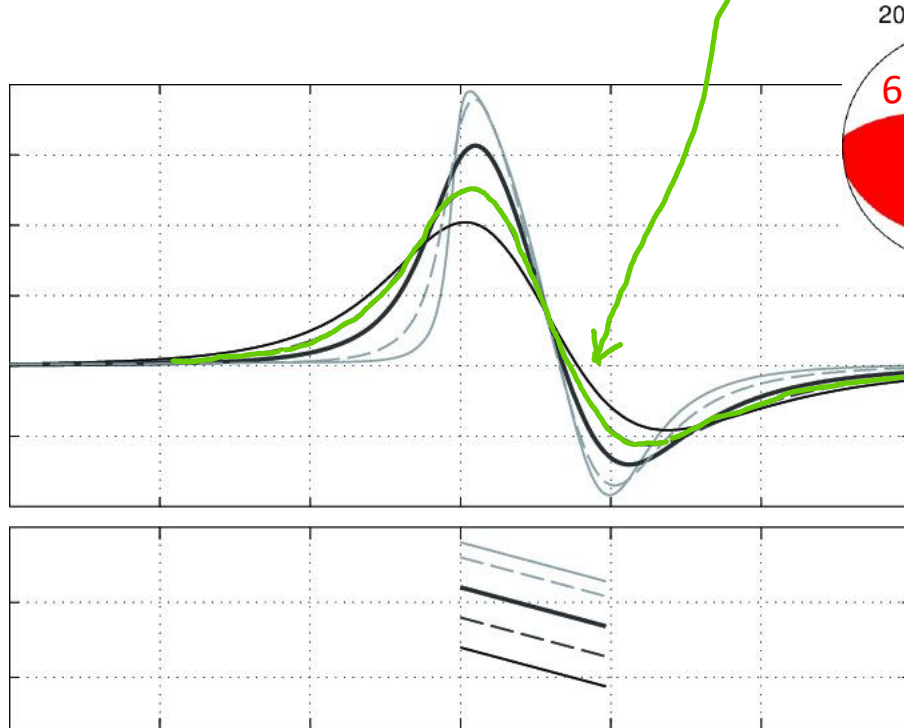
Readings of 174 seismic stations from IRSC and EMSC were used to relocate the event.

- OT: 2021/11/14 12:08:37.8
- Longitude: 56.167 ± 4.4 km
- Latitude: 27.662 ± 5.1 km
- Depth: 6.6 ± 10.5 km

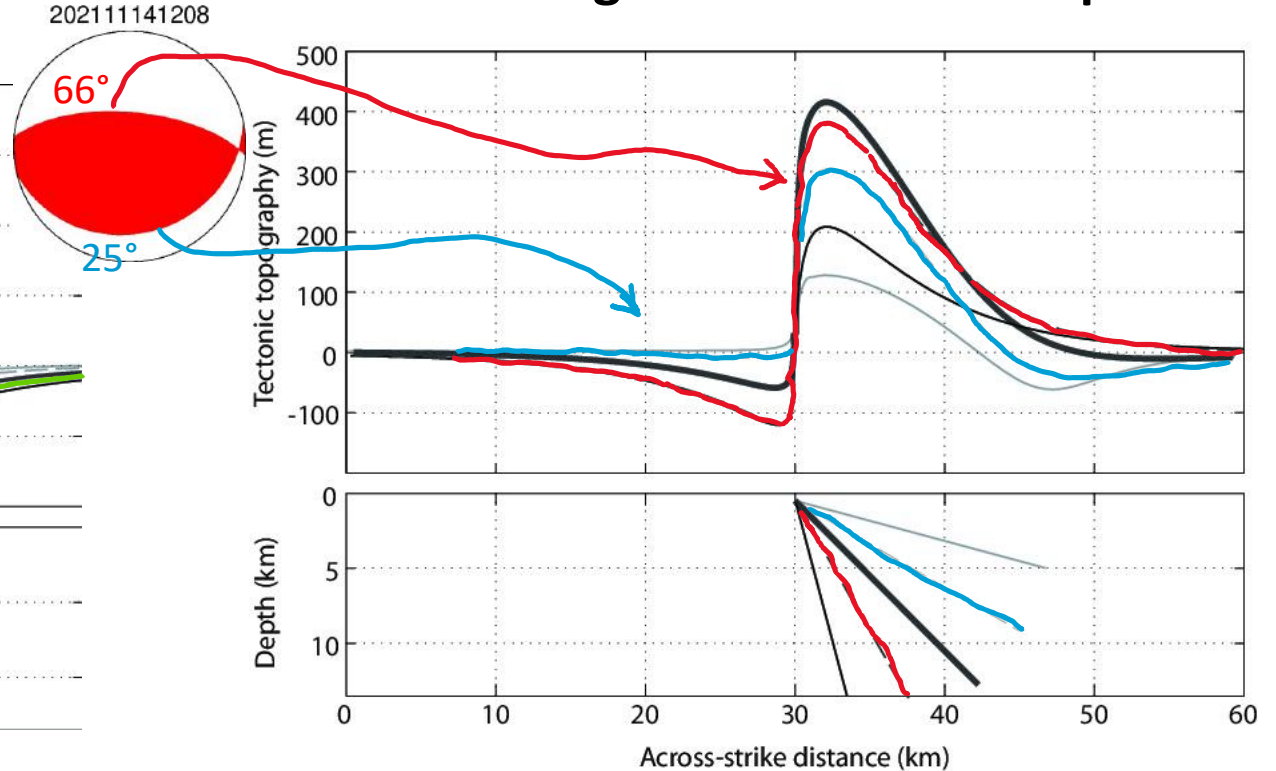


Surface displacement for blind thrusting

Surface displacement due to a 15°-dipping blind thrust at depths of 1, 2, 4, 6, and 8 km.



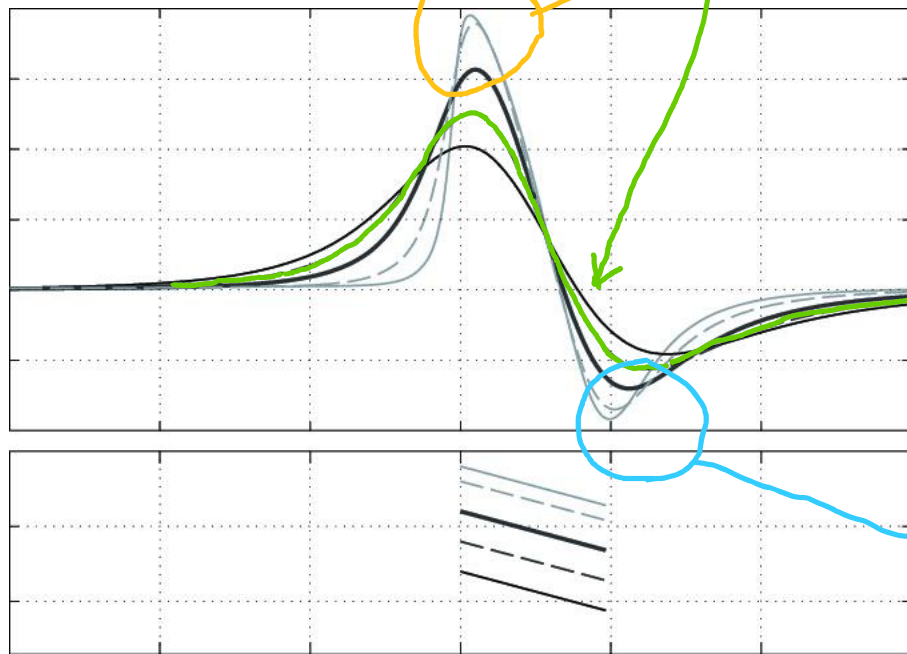
Surface displacement for blind thrust faults dipping 15°, 30°, 45°, 60°, and 75°. The shallow edges are at 0.5 km depth.



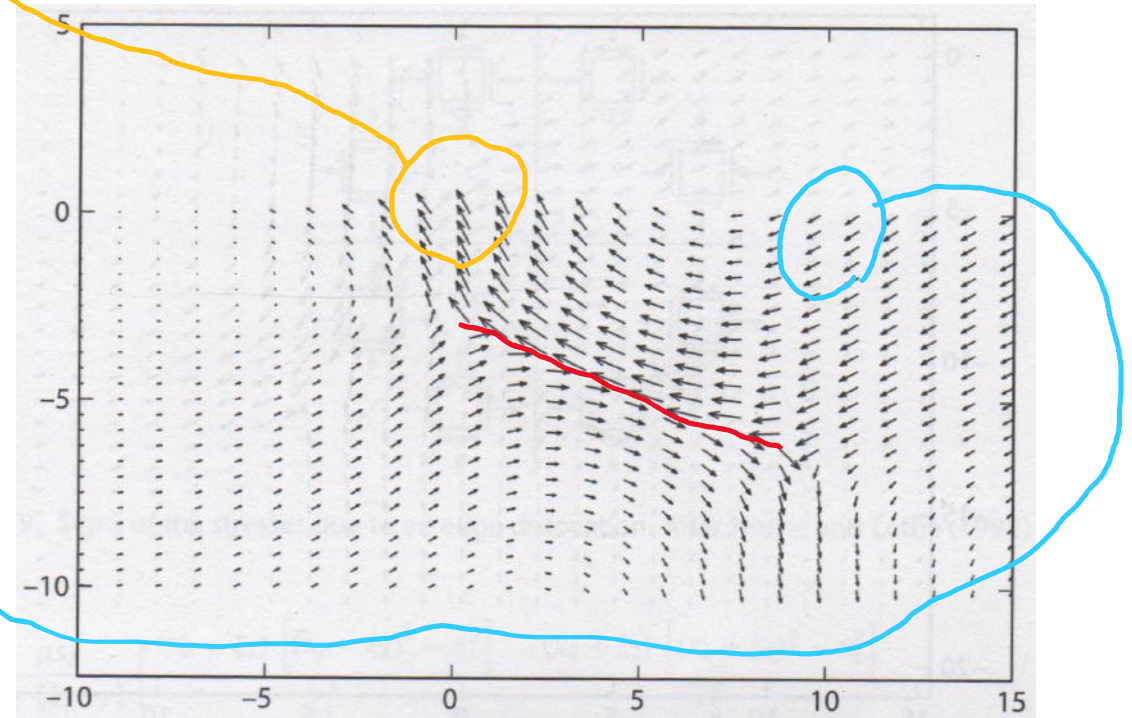
Ellis, M. A., & Densmore, A. L. (2006). First-order topography over blind thrusts. *Special Papers-Geological Society of America*, 398, 251.

Surface displacement for blind thrusting

Surface displacement due to a 15°-dipping blind thrust at depths of 1, 2, 4, 6, and 8 km.



Displacement within the half-space from a 20°-dipping thrust fault.

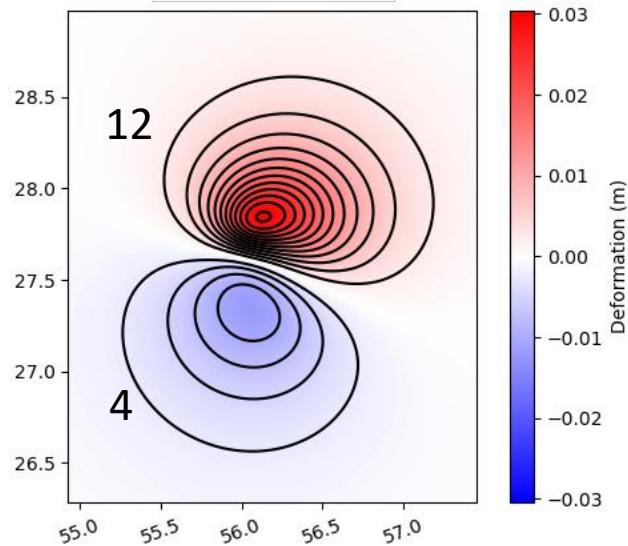


Ellis, M. A., & Densmore, A. L. (2006). First-order topography over blind thrusts. *Special Papers-Geological Society of America*, 398, 251.

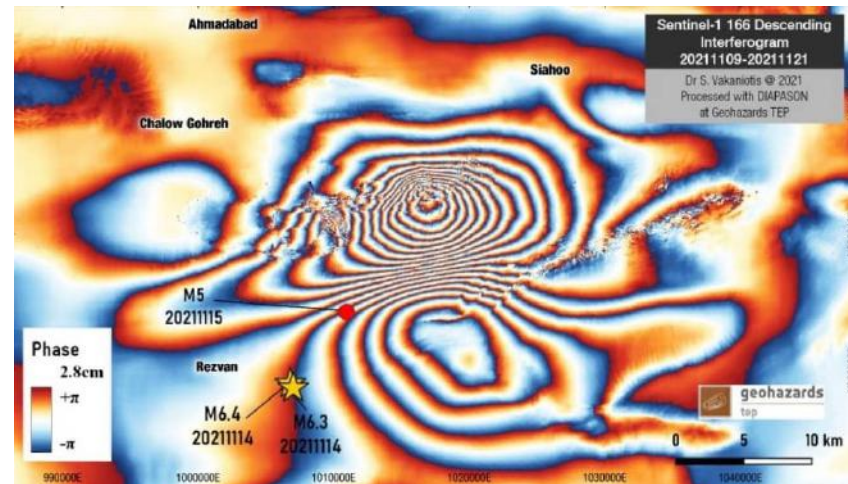
Segall, P. (2010). *Earthquake and volcano deformation*. Princeton University Press.

Observed and synthetic surface deformation

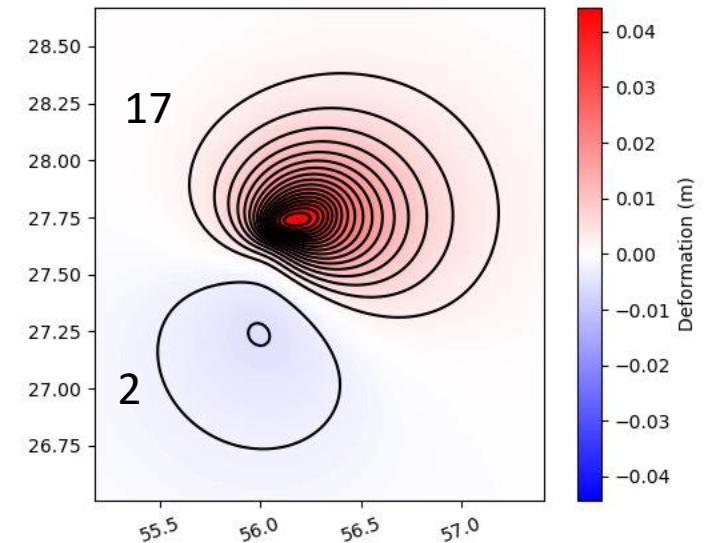
**Thrust fault, 14°
dipping South**



**Sentinel-1 166 Descending
interferogram for the
2021/11/14 Fin earthquakes.**



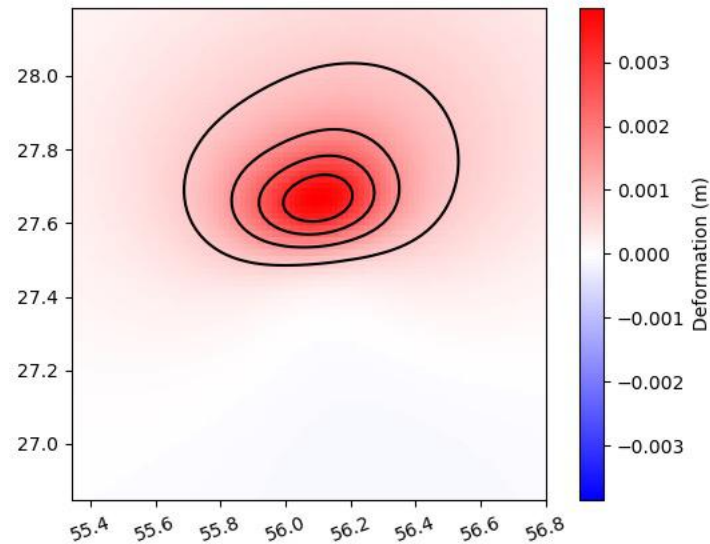
**Thrust fault, 30°
dipping south**



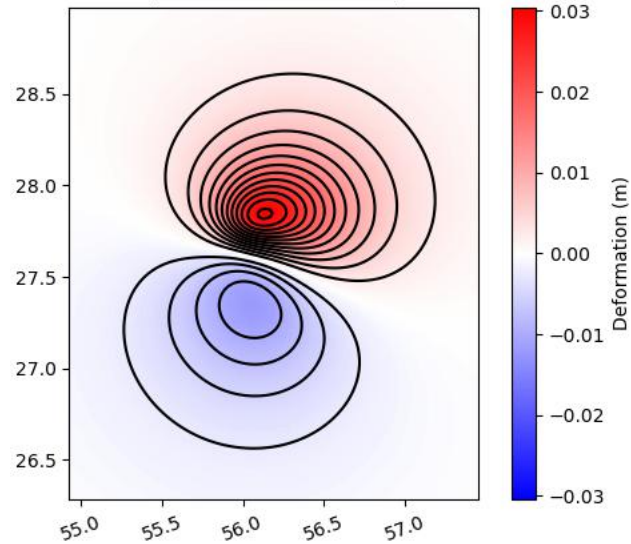
Descending interferogram, prepared by Dr. S. Vakaniotis, Processed with DIAPASON at Geohazards TEP

Relative surface deformation due to reverse faulting

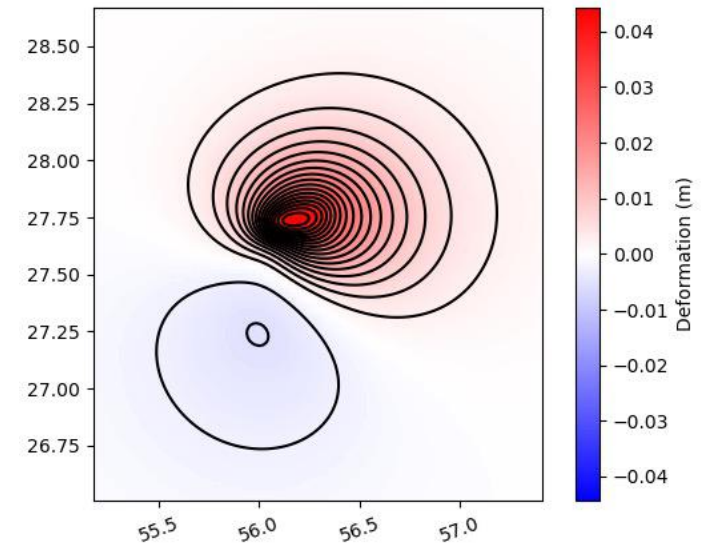
Reverse fault, 56° dipping north



Thrust fault, 14° dipping South

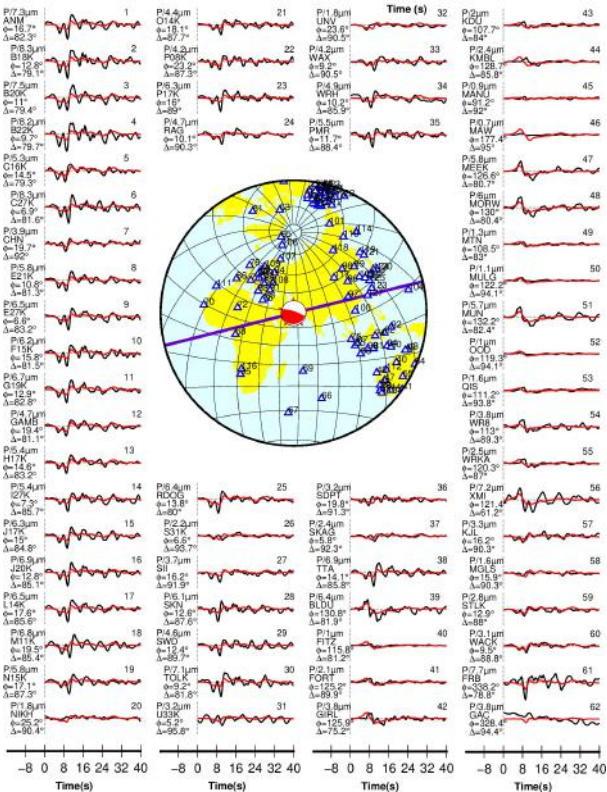
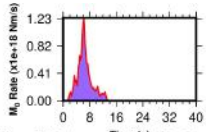


Thrust fault, 30° dipping south

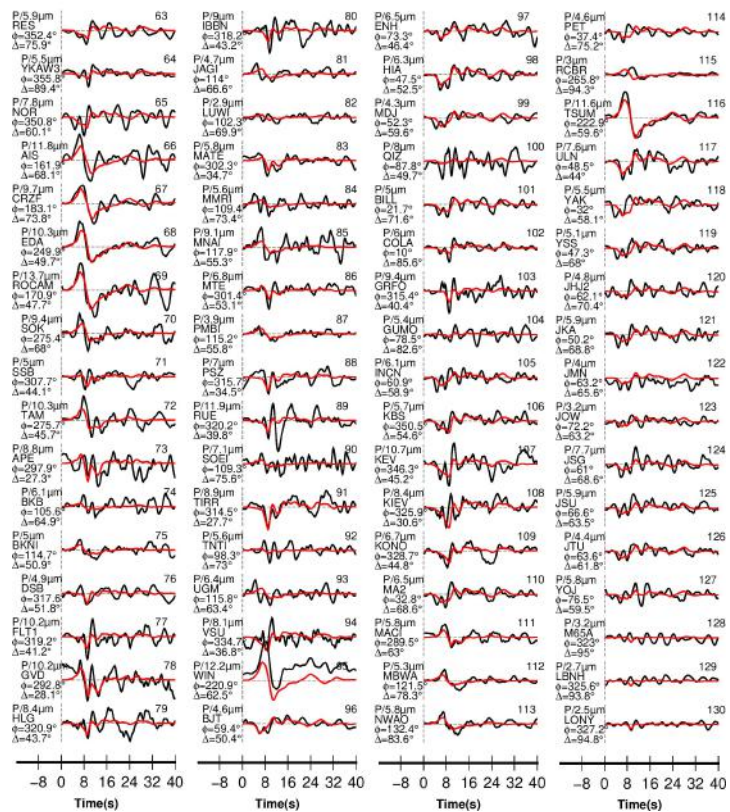


Body-waveform slip inversion of the 2021/11/14 12:08, the **second** Fin earthquake

Fin 2021/11/14 12:08
 $M_0=0.003E+21Nm$ $M_w=6.27$
 Lat.=27.662° Lon.=56.167° Depth=6.6 km.
 Strike=76° Dip=14° Rake=59.1°
 Variance=0.718

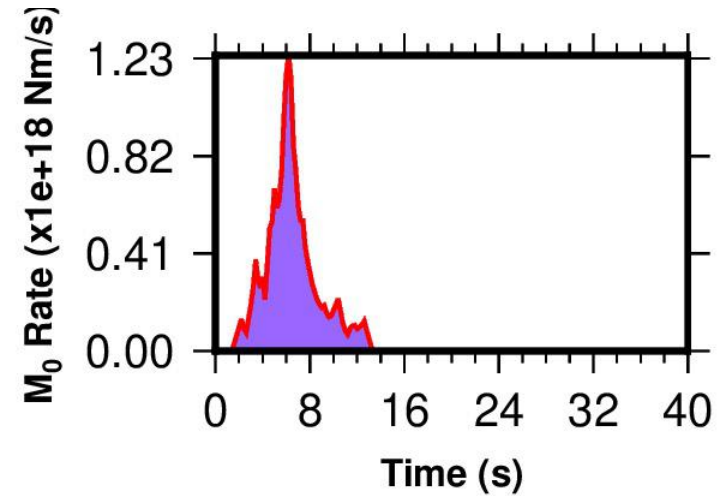
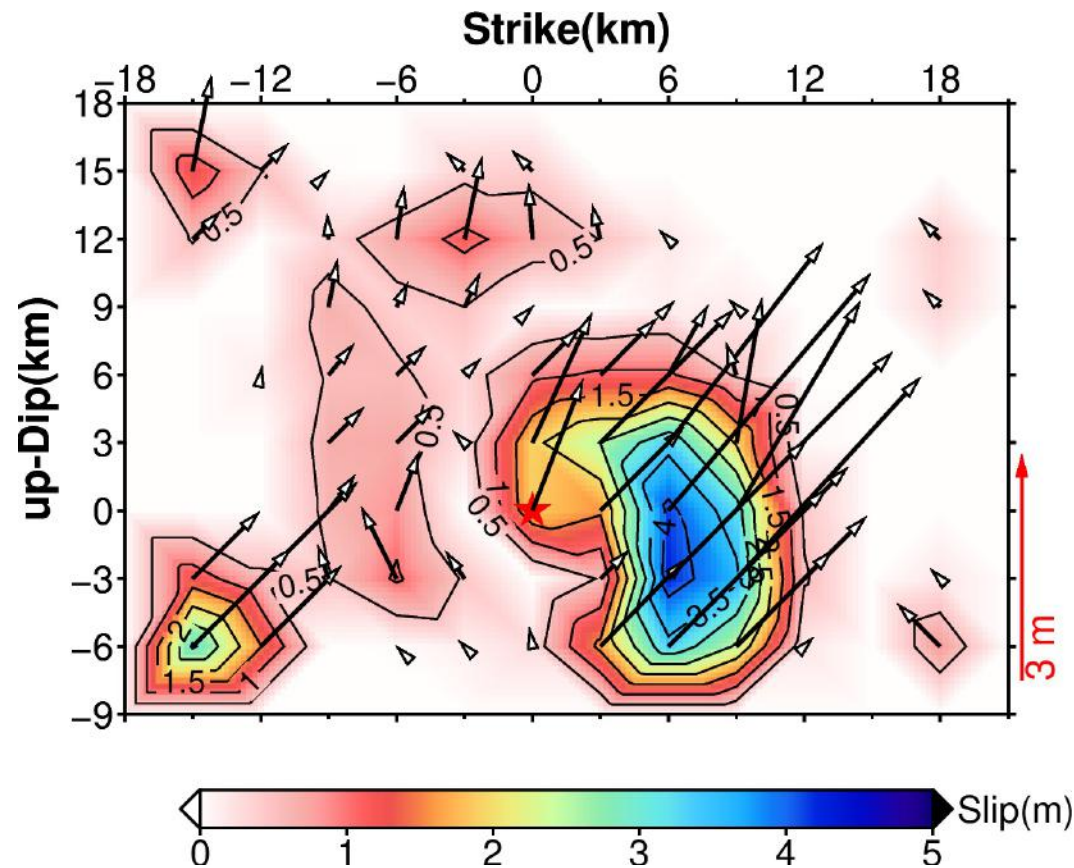


Fin 2021/11/14 12:08



- The waveforms of this event are combined with the trailing waveforms of the first event; therefore, the slip inversion processing of this event is very difficult.
- The black lines are the recorded waveforms while the red lines show the synthetic ones.
- 131 P-wave recordings in the epicentral distances of 24° to 96° are used.
- The source time function indicates a rupture process of about 13 s.

Body-waveform slip inversion of the 2021/11/14 12:08, the **second** Fin earthquake



Fin 2021/11/14 12:08

$M_0=0.003E+21\text{Nm}$ $M_w=6.27$

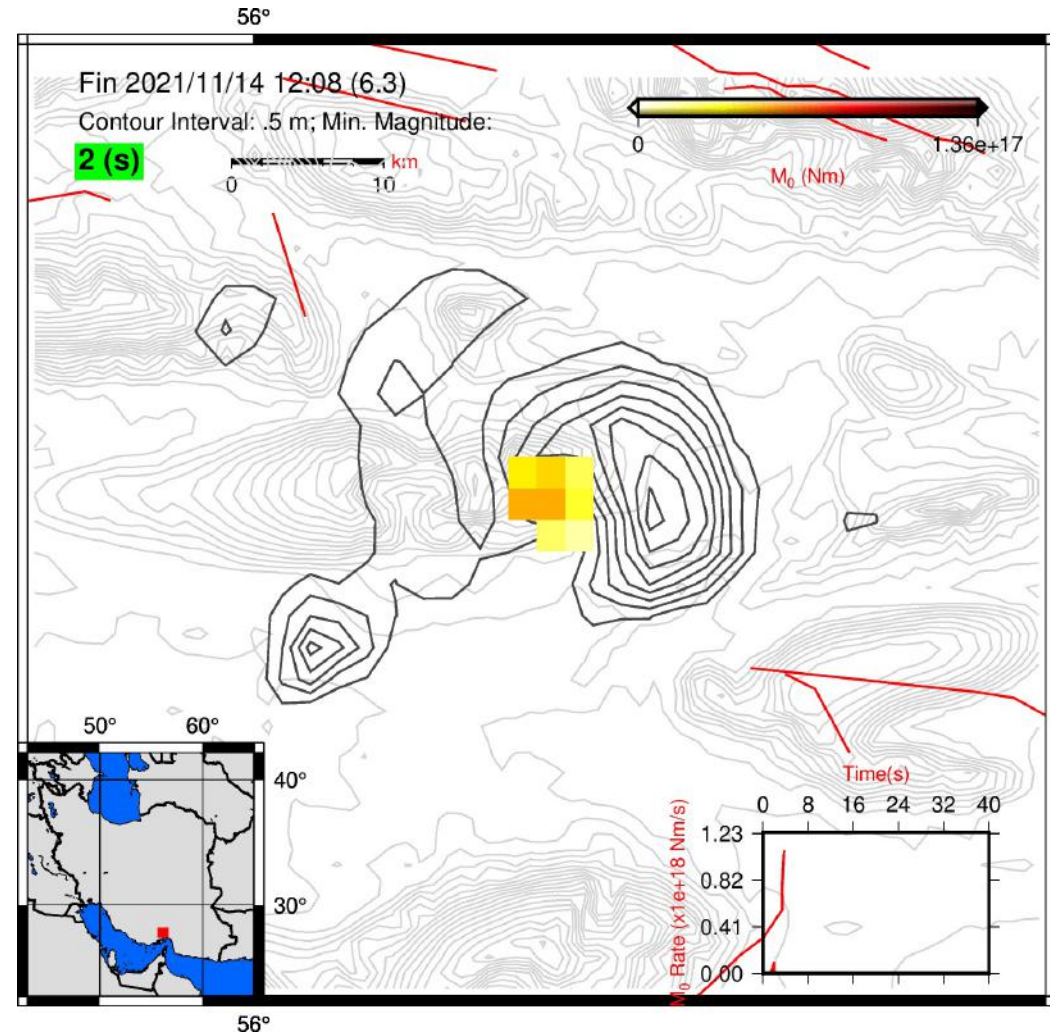
Lat.=27.662° Lon.=56.167° Depth=6.6 km.

Strike=76° Dip=14° Rake=59.1°

Variance=0.718

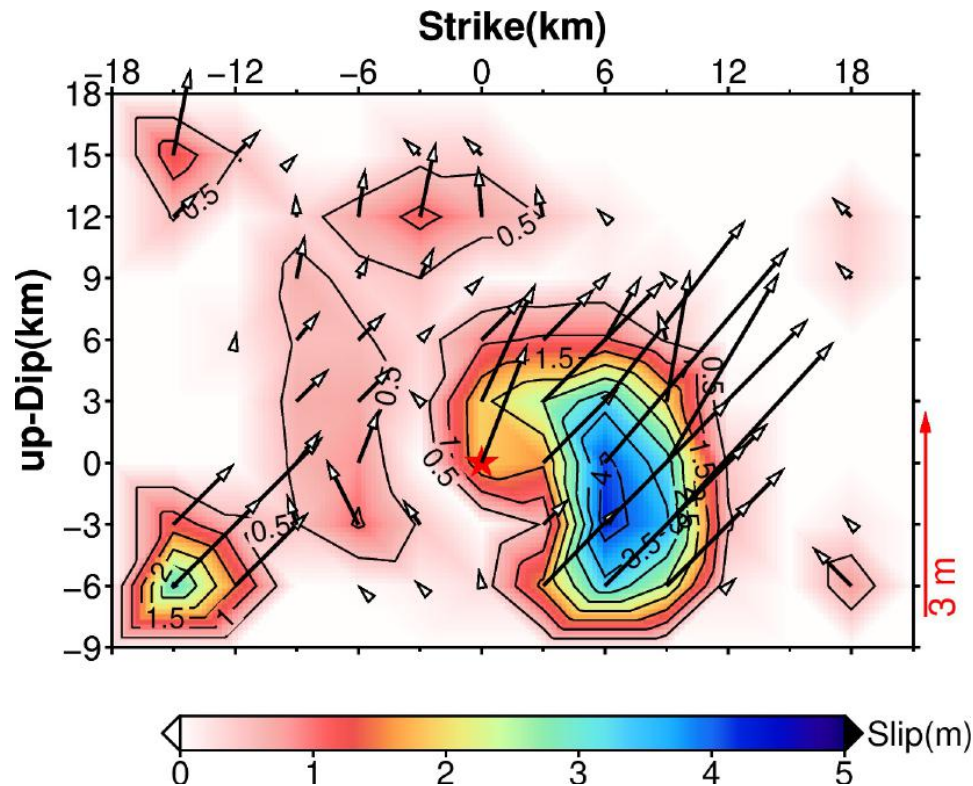
Slip distribution of the 2021/11/14 12:08 earthquake

- The **green label** shows the seconds after rupture initiation.
- The source time function at the **bottom-right** corner shows the moment rate from the beginning of the rupture until the current moment, the green label.
- The colored patches show the location of the moment release. Its color show the moment in Nm according the color bar on **top-right**.

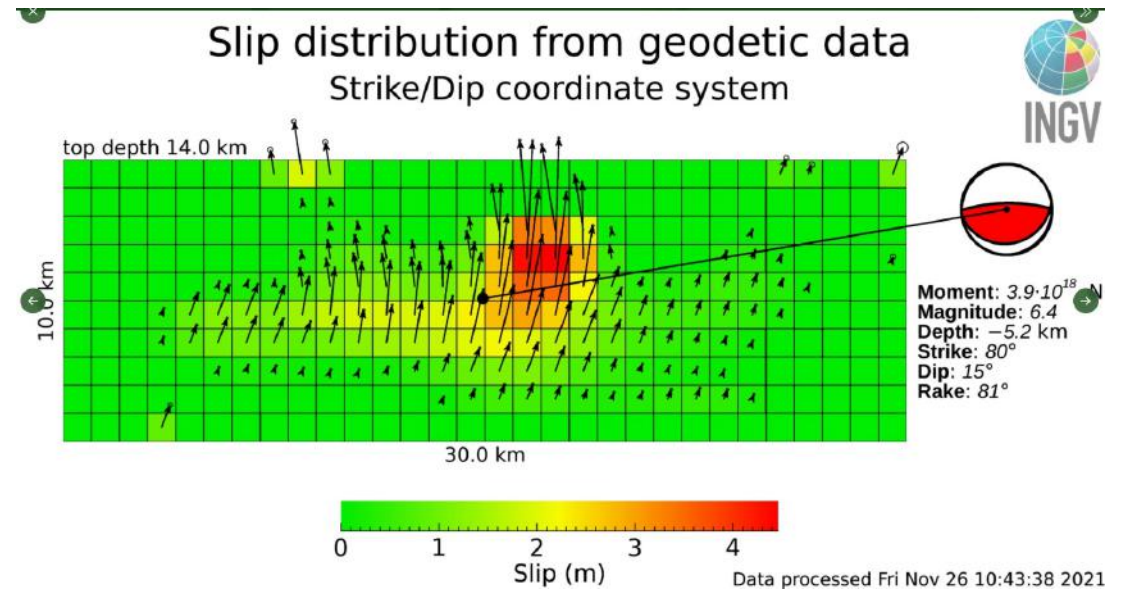


Comparison of the body-waveform slip and geodetic inversions

The slip contours are 0.5 m apart and the maximum slip exceeds **4 m**. This **increases** if the real shear modulus is less than **6 GPa** used in the computations.

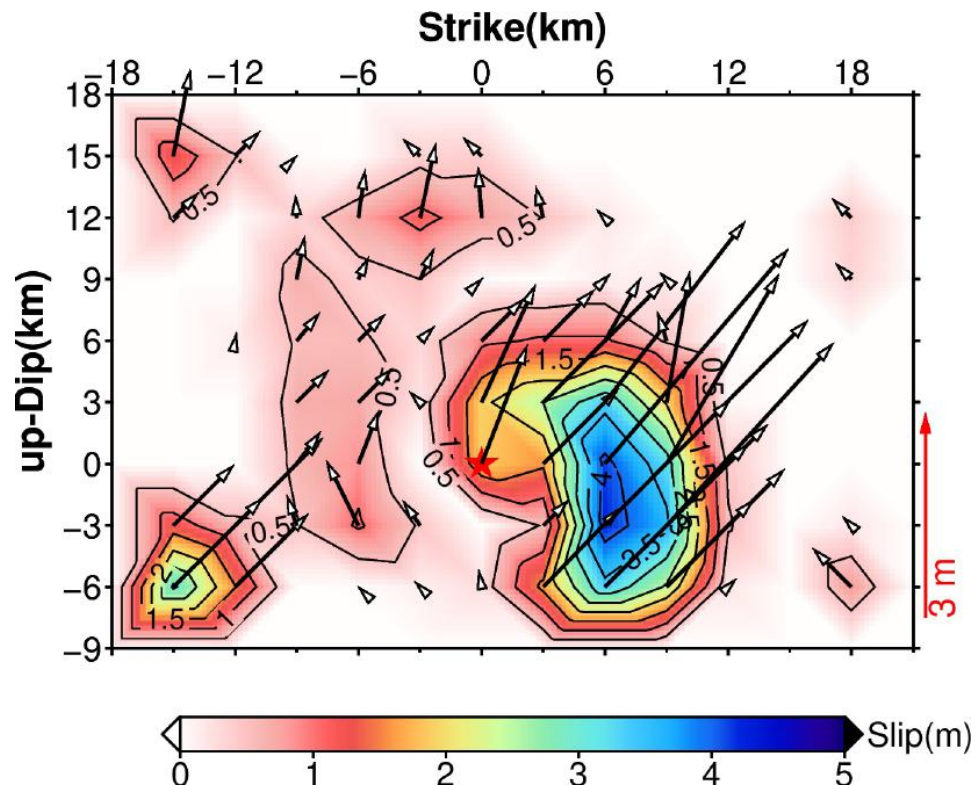


The main difference of the two inversions is the **20°** difference in average slip direction.

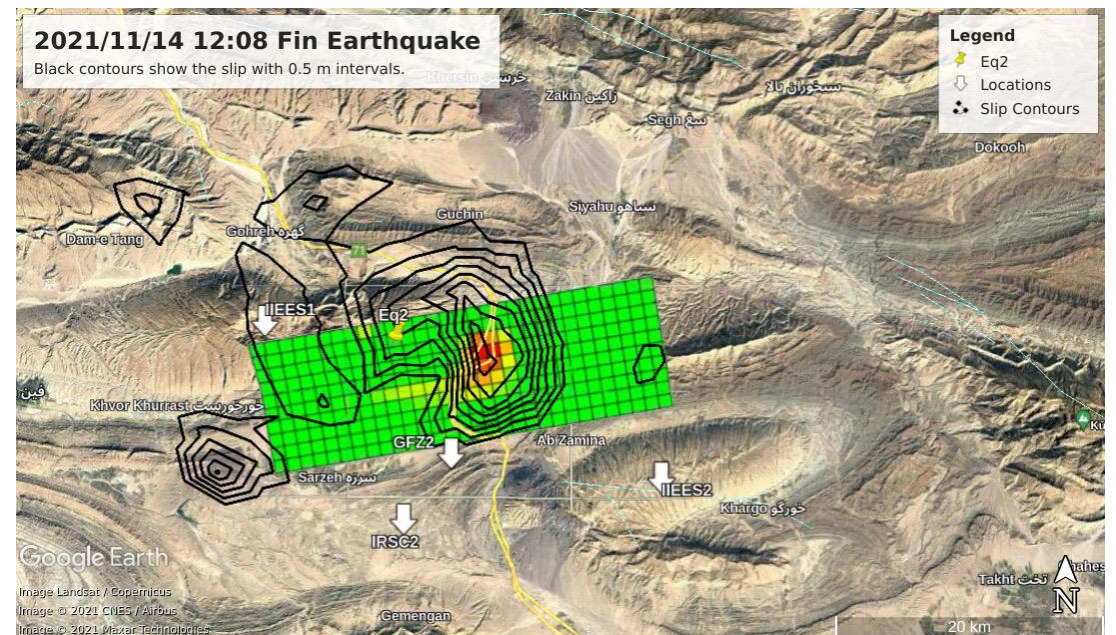


Comparison of the body-waveform slip and geodetic inversions

The body-waveform slip inversion covers the **initial 40 s** of the second event.

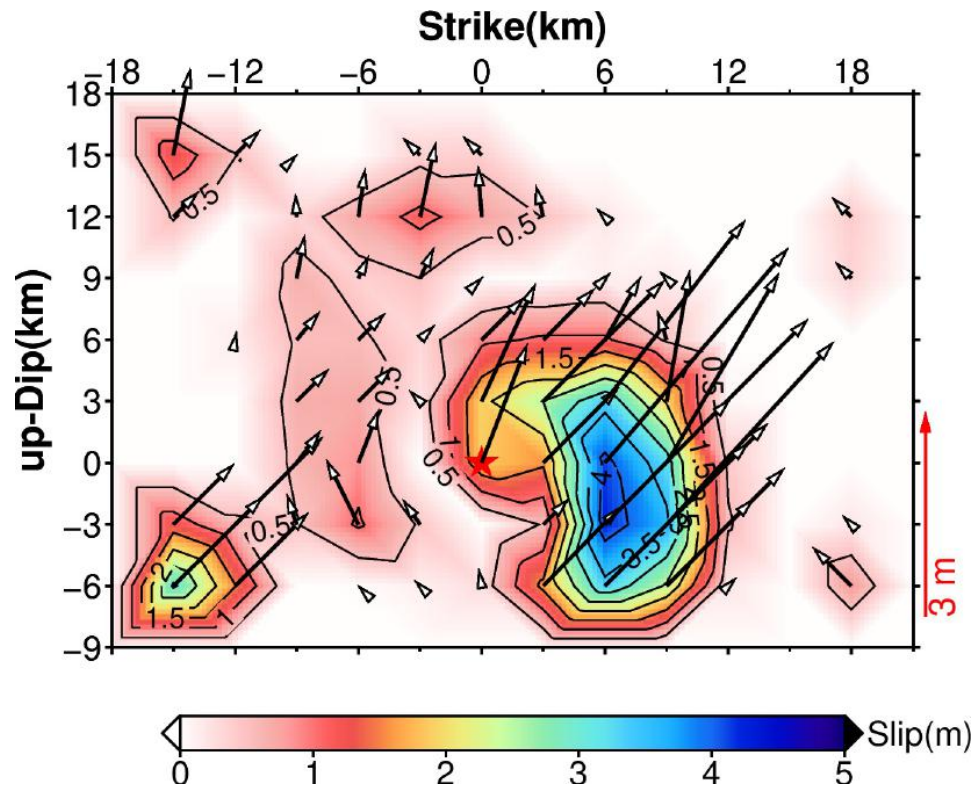


The geodetic slip inversion covers **Event 1, Event 2** and **Post seismic** deformations.

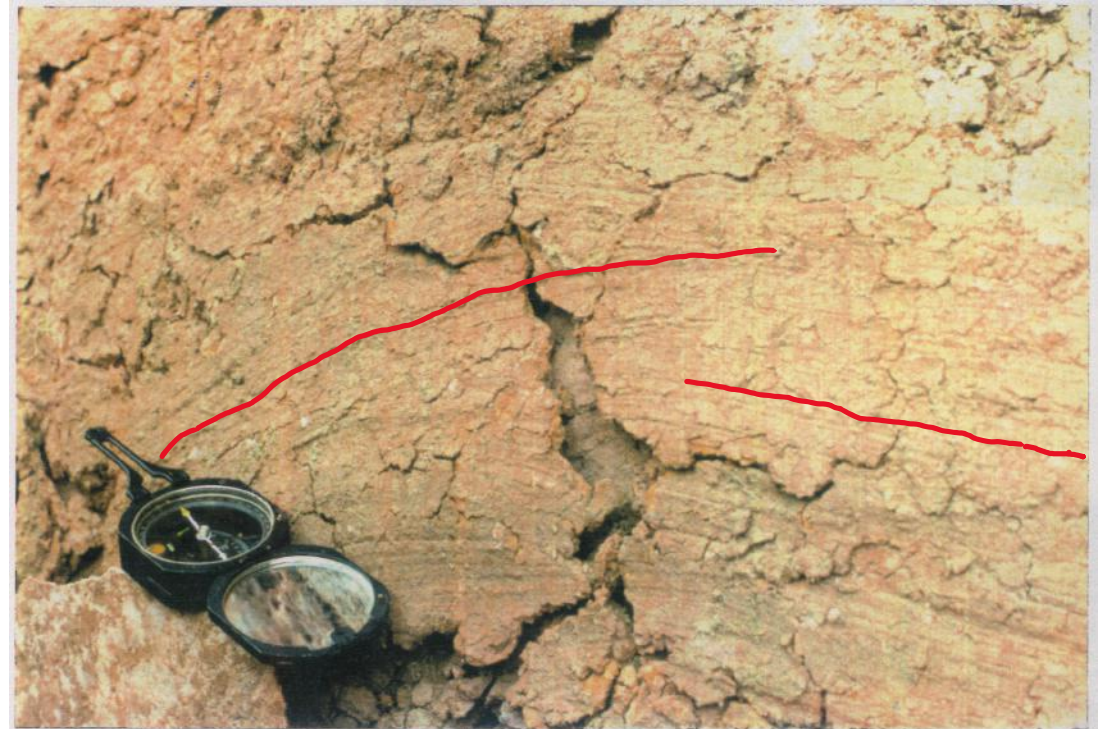


Slip change along the same fault segment

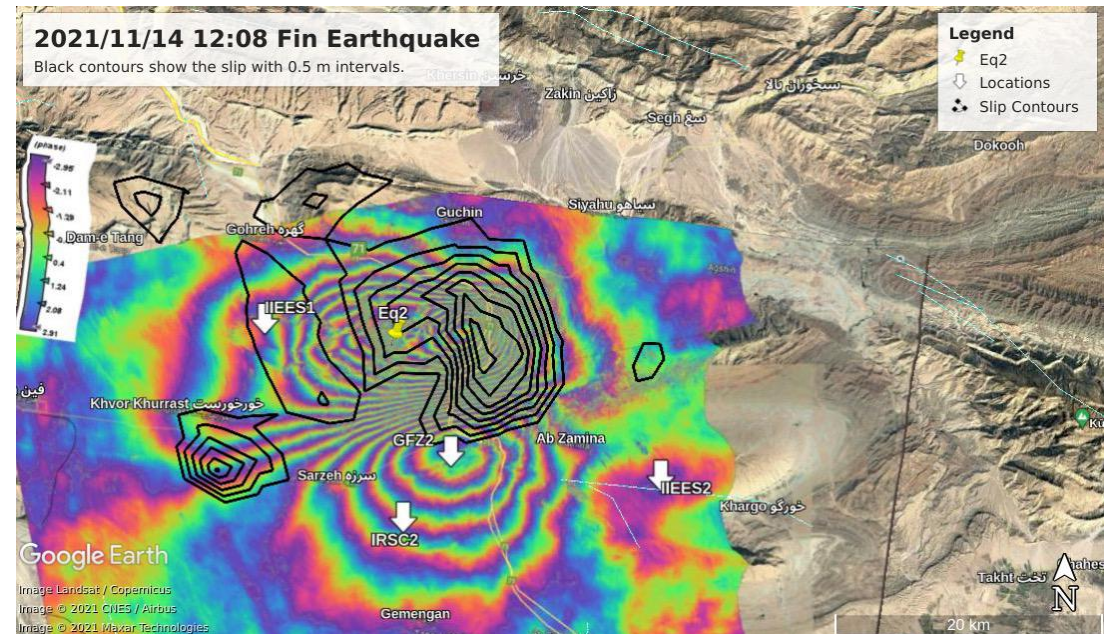
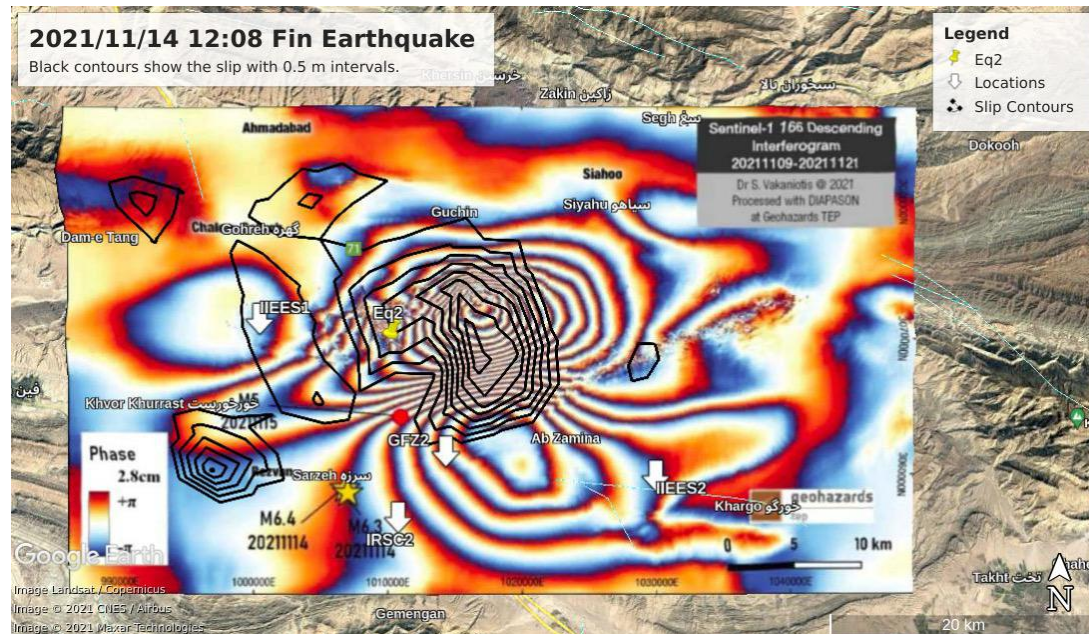
The body-waveform slip inversion covers the **initial 40 s** of the second event.



The slip direction change on a portion of the causative fault of the 1990/05/10 (Mw 7.2) Ghaen earthquake.



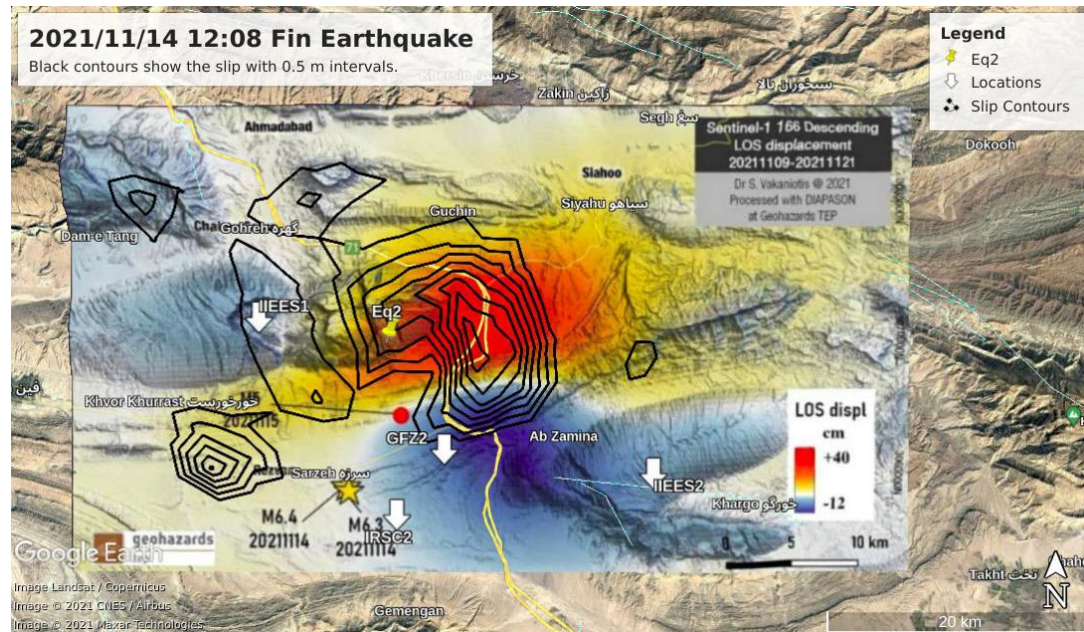
Comparison of the slip contours of the second event with the descending (left) and ascending (right) interferograms



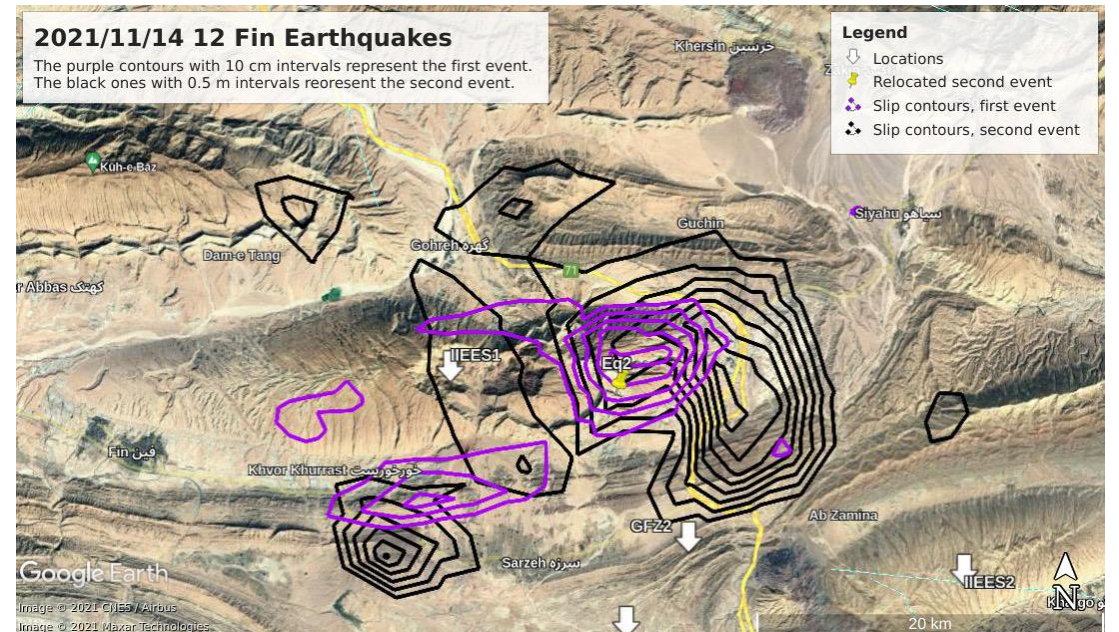
Descending interferogram, prepared by Dr. S. Vakaniotis, Processed with DIAPASON at Geohazards TEP

Comparison of the slip contours of the second event with the descending LOS displacement (left) and for both events and topography (right)

The slip contours of the second event on the background of LOS displacement.



The purple contours, 10 cm apart, represent the first event. The 50 cm apart black contours show the second event.



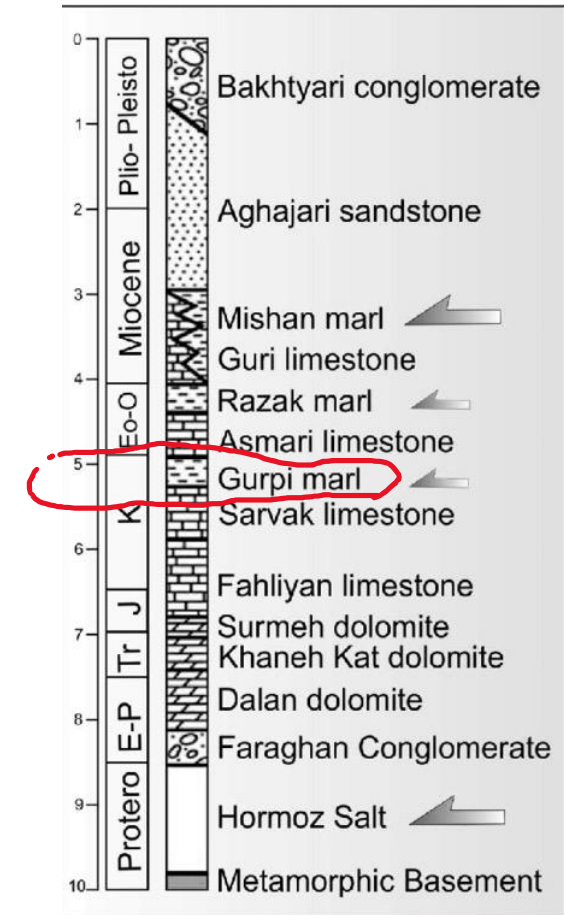
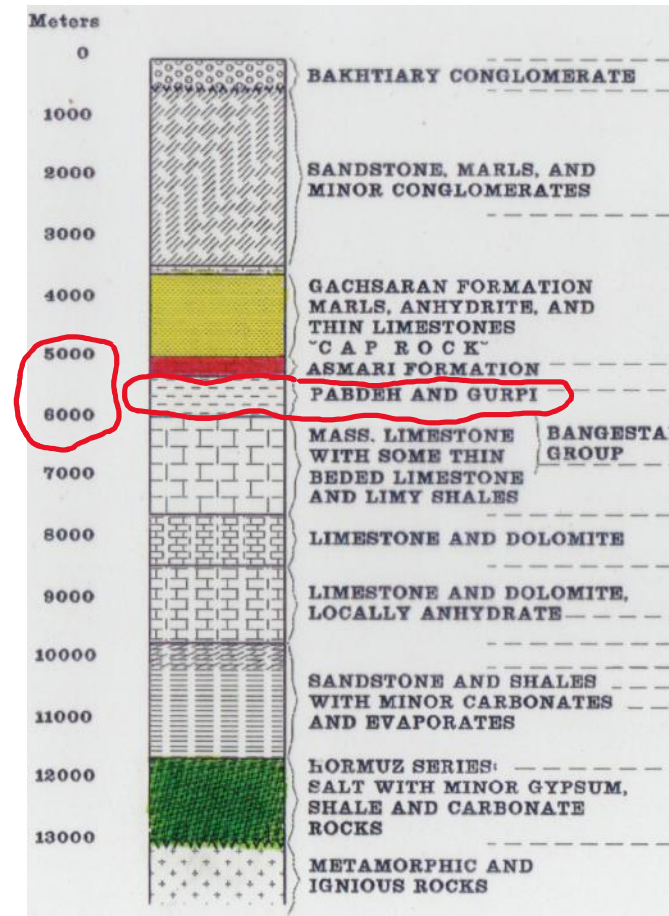
LOS Displacement, prepared by Dr. S. Vakaniotis, Processed with DIAPASON at Geohazards TEP

The second event requires a very small shear modulus, μ , according to the seismic moment equation

$$M_0 = \mu AD$$

A is the fault area, and D is dislocation.

- The low angle of 14° requires very low shear modulus in order to obtain the observed surface deformation.
- The depth of 6.6 km (seismic) and 5.2 km (geodetic) confirms that the sedimentary cover of Zagros was involved.
- The main candidate for such low shear modulus is the **GURPI** formation, which consists of marl and shale.
- In the calculations, shear Moduli of 23.3 and 6.0 GPa were used for the two earthquakes respectively.
- Through a personal communication, the shear modulus for **Pabdeh** formation was reported as 5.49 GPa, while 4.03 GPa was mentioned for **Gurpi** formation.
- In both sedimentary columns for Zagros (left), and Zagros in Bandar Abbas area (right) the depth of Gurpi formation is between 5000 to 6000 meters.



- Colman-Sadd, S. P. (1978). Fold development in Zagros simply folded belt, Southwest Iran. *AAPG Bulletin*, 62(6), 984-1003.
- Nissen, E., Yamini-Fard, F., Tatar, M., Gholamzadeh, A., Bergman, E., Elliott, J. R., ... & Parsons, B. (2010). The vertical separation of mainshock rupture and microseismicity at Qeshm island in the Zagros fold-and-thrust belt, Iran. *Earth and Planetary Science Letters*, 296(3-4), 181-194.

Conclusions

1. The 2021/11/14 12:07 (Mw 6.0) earthquake took place on a **57° north-dipping** fault.
2. The rupture **did not release** substantial seismic energy in the nearby **salt dome**.
3. The main energy release in the first event took place in the **eastern part** of the involved **anticline**.
4. The area immediately to the south of the salt diapir was ruptured in the first earthquake.
5. The first event is a vivid example of **mountain building** processes.
6. Most likely the second event was initiated where the fault of the first event crossed the Gurpi formation.
7. The 2021/11/14 12:08 (Mw 6.3) took place on a **14° south-dipping** fault.
8. The **Gurpi** formation is the prime candidate for the huge dislocation of more than 4 meters.
9. The 2021/11/14 12:08 is a **UNIQUE** earthquake in Zagros; therefore, every aspect of the event should be studied carefully.
10. The rupture trend for both earthquakes were **eastward**, this might be the trend for the future earthquakes in the nearby region.