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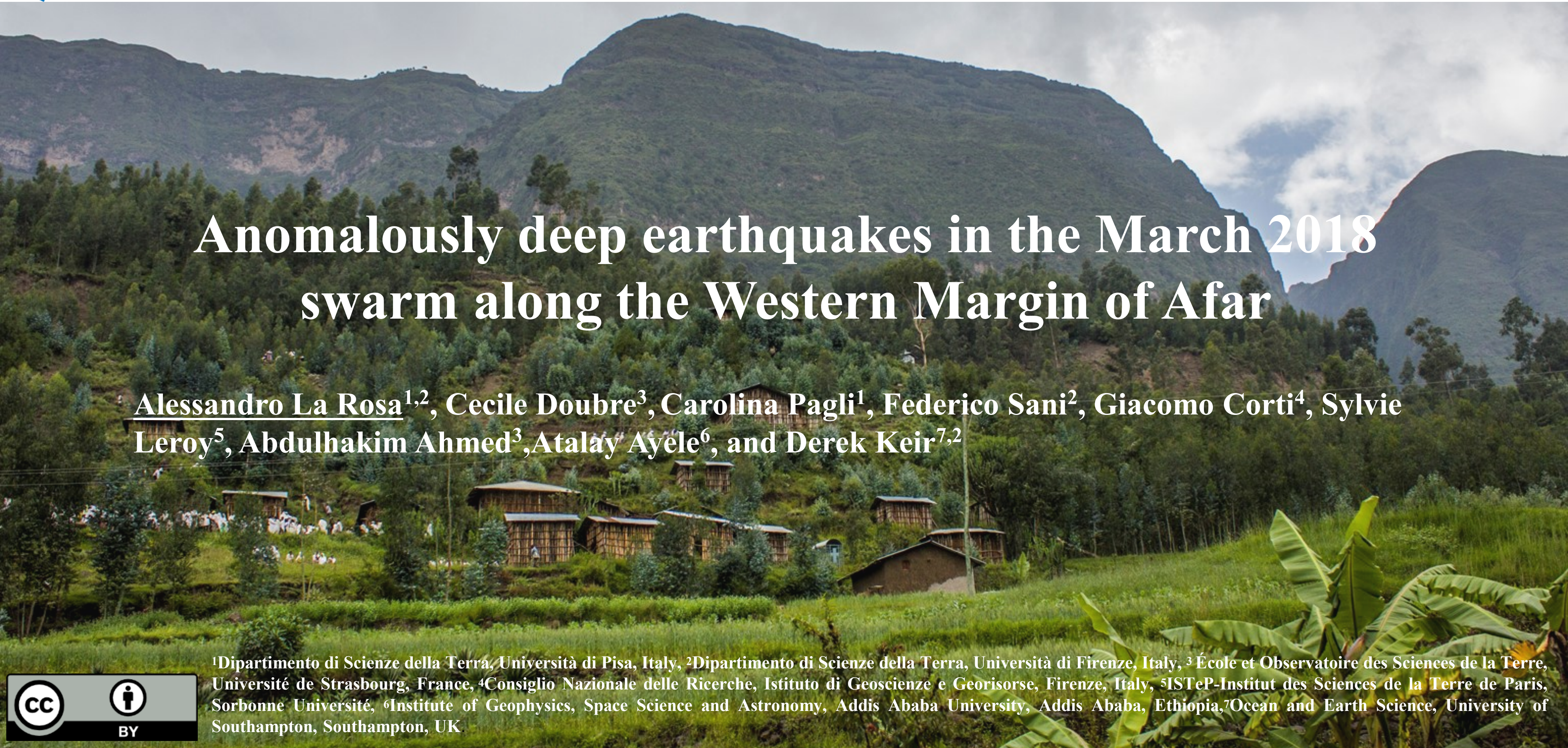

Anomalously deep earthquakes in the March 2018 swarm along the Western Margin of Afar

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Overview and Aims

- The Afar rift is the locus of separation of the Nubian, Arabian and Somalian Plates. Large-scale systems of extensional faults (referred to as “Western Afar Margin”, WAM) bound Afar to the west separating the rift floor from the uplifted Ethiopian Plateau.
- The interplay between synthetic (east-dipping) and antithetic (west-dipping) faults shaped a series of seismically active marginal grabens which can be observed along the entire margin.
- The Northern WAM (NWAM), east of Mekele (at latitudes of N13°-N14°), displays the highest seismic activity. Shallow seismicity (< 20 km) commonly occurs but mid-to-low crustal earthquakes (15-35 km) have also been documented (*Ayele et al., 2007; Illsley-Kemp et al., 2018*). However, the origin of such seismicity is still poorly understood.

- Here **we investigated the seismic activity and the fault kinematics along the NWAM** by analyzing the seismic swarm associated with the **M_w 5.2 earthquake of 24 March 2018** with a local dense seismic network.
- We located earthquakes and calculated their magnitude using a local magnitude scale from *Illsley-Kemp et al.* (2017).
- We relocated the events with a Double-Difference approach (*Waldauser and Ellsworth, 2000)* to image the subsurface shape of active faults.
- We processed twenty **focal mechanisms** related to the major earthquakes to constrains the orientation and kinematics of faults that activated during the seismic sequence.
- We further tested our estimated hypocentral depths through a series of **simulated interferogram** obtained from Sentinel-1 Line-Of-Sight (LOS) incidence angles.

Seismicity in Afar and along the Western Afar Margin (WAM)

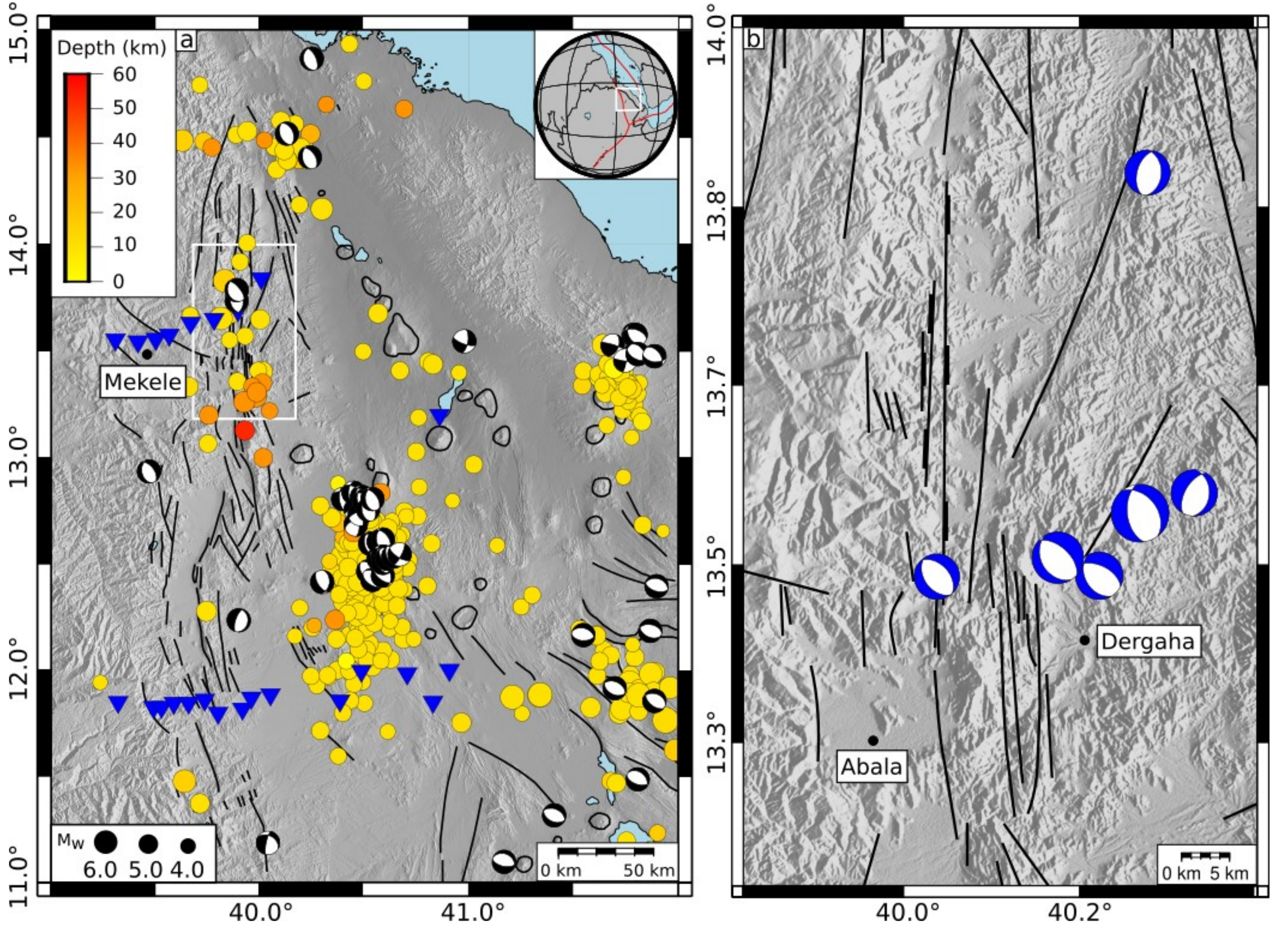


Figure 1 – a) Seismicity in Afar between 1973-2019 (NEIC). Black focal mechanisms in **a)** are from gCMT catalog while the blue ones in **b)** are related to the sequence of 2002 (*Ayele et al., 2007*). The blue triangles are the seismic stations used in this study. Black lines are faults from *Sembroni et al. (2017)* and *Stab et al. (2016)*.

- Persistent low-to-moderate seismicity characterizes the NWAM.
- The first seismic swarm instrumentally recorded in the NWAM occurred in April 1989 (NEIC). Two earthquakes with Mw > 5.0 and several Mw > 4.0 occurred along the southern tip of the Dergaha graben at depths between 10 km and 33 km (Fig. 1).
- In August 2002, 75 earthquakes accompanied a main shock with Mw 5.0. Focal mechanisms from six major events showed normal faulting along NNW-striking, NNE-dipping planes (Fig.1b, Ayele et al., 2007). The estimated depths range between 5-7 km.
- Seismicity recorded during 2011-2013 highlighted west-dipping faults with seismicity mainly clustered at depth < 5 km but also getting deeper than 20 km (*Illsley-Kemp et al., 2018*).

Seismic analysis – Earthquake location and local magnitude calculation

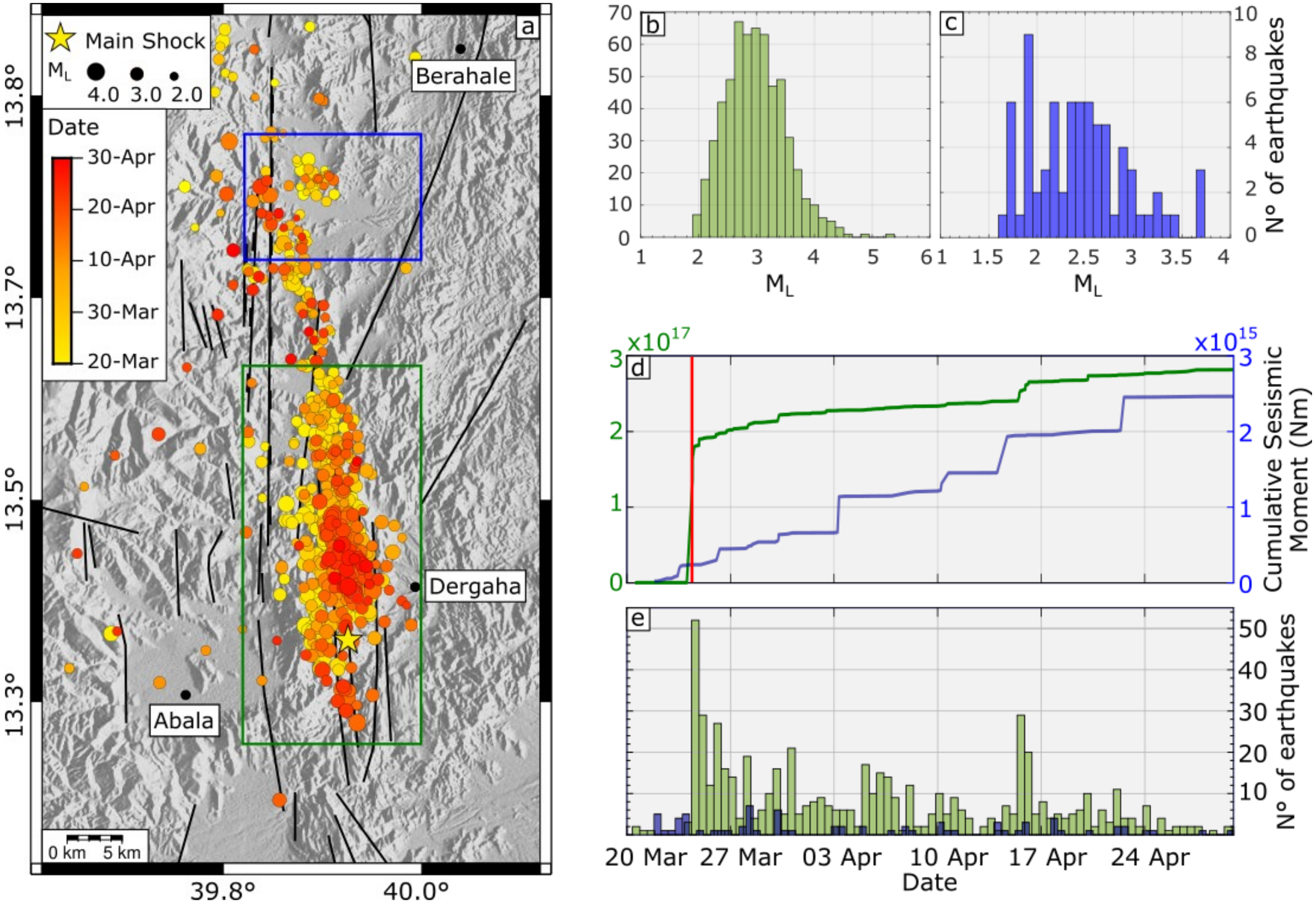
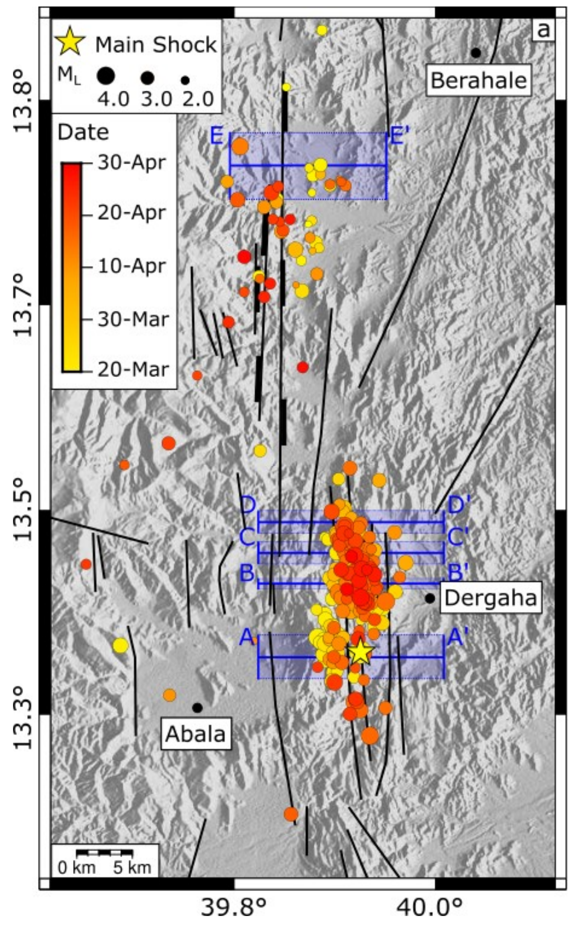


Figure 2 – a) Epicentral distribution of earthquakes during the seismic swarm. The blue and green boxes highlight two different marginal grabens along the NWAM. **b), c)** Histograms of magnitudes for the two areas highlighted in **a)**. **d), e)** cumulative seismic moment curves and histograms of number of earthquakes for the two areas in **a)**.

- We used NonLinLoc to locate **743 events** during 20 March to end of April 2018 along the WAM (Fig. 2a) with average vertical and horizontal errors of 5.1 km and 7.7 km, respectively.
- We identified two areas of clustered seismicity characterized by different spatial and temporal distribution. The main cluster associated with the 24 March M5.2 earthquake occurred within the Dergaha graben while a smaller cluster has been located in a graben SW of Berahale.
- Seismicity is continuous during the time period of our analysis. Near the Dergaha graben, activity occurs in bursts (esp. 24/03 and 16/04) (Fig. 2d and e). In contrast, earthquakes in the northern graben occurred scattered in time (Fig. 2d and e). Furthermore, the occurrence of the earthquakes in this sector seems to be temporally independent from the main seismic swarm.

Seismic analysis – Hypocentral distribution



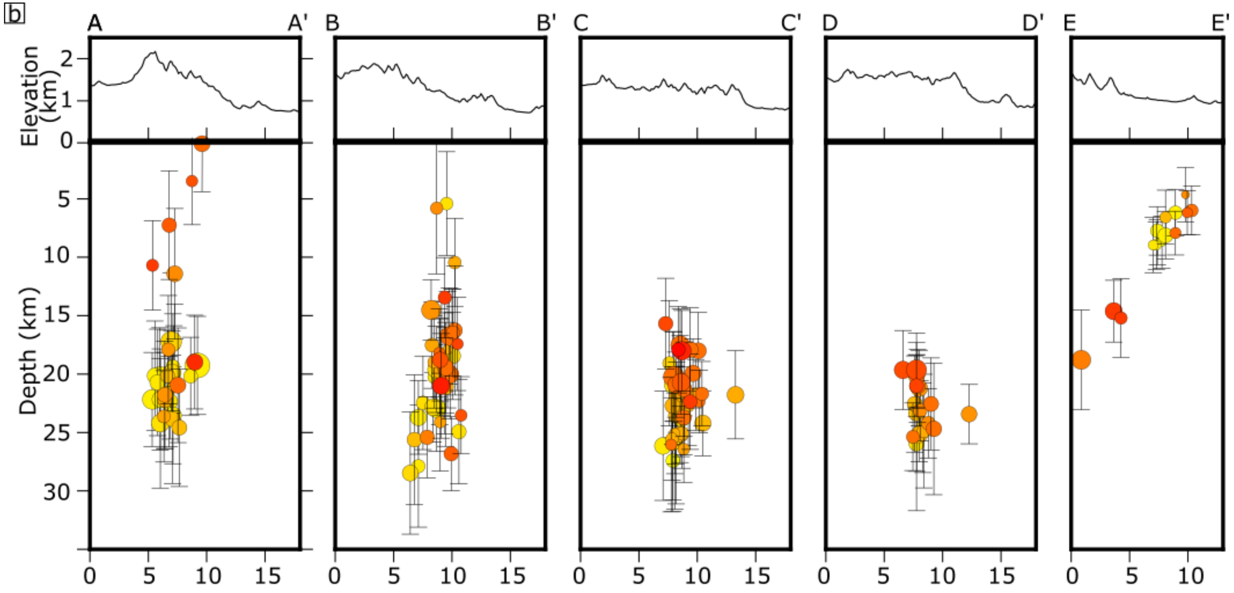
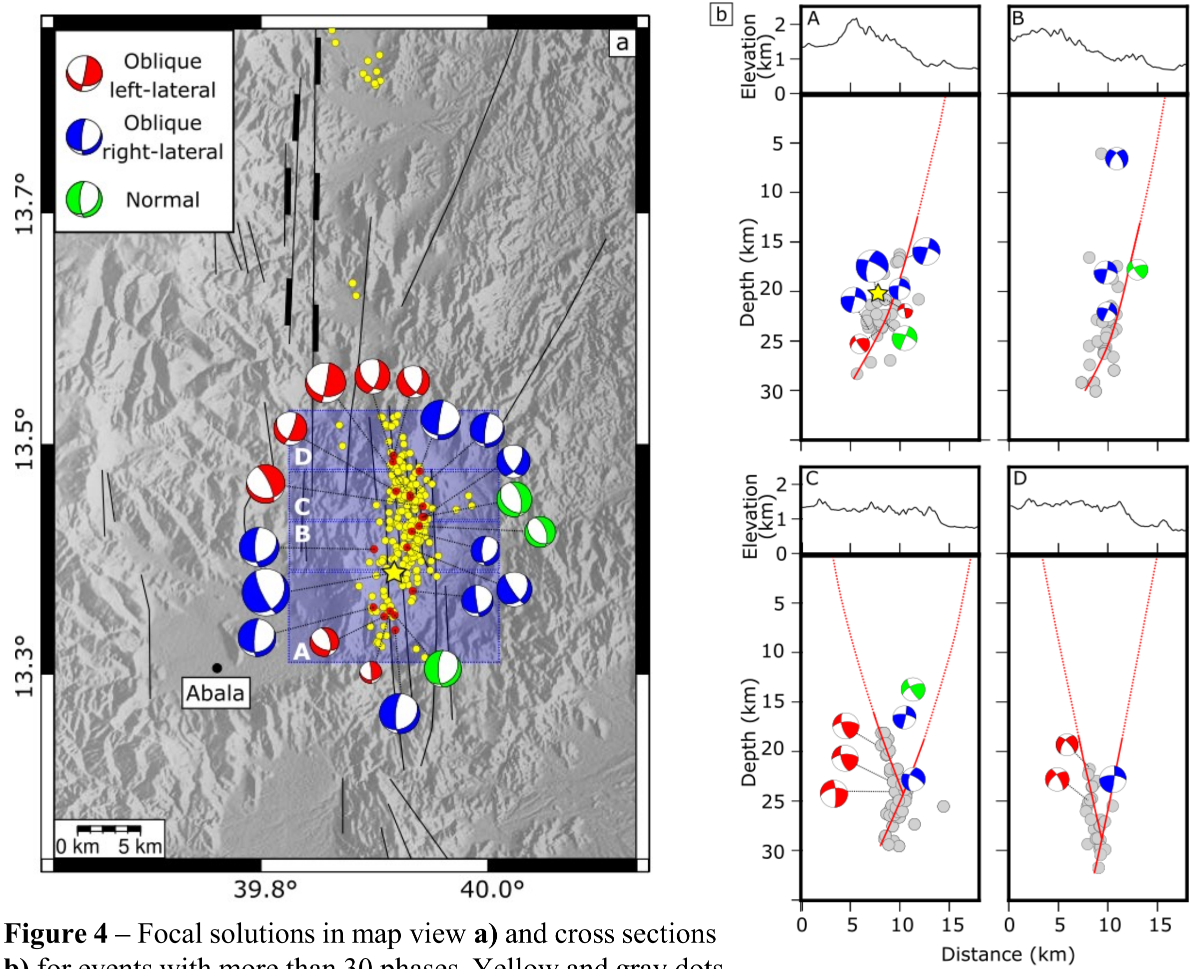


Figure 3 - Hypocentral distribution of the events with lowest errors in map view **a)** and in cross section **b)**. Swath profiles have width varying from 1 km (profile BB') to 6 km (profile EE').

- We filtered the catalog by keeping just 290 well-located events with average vertical and horizontal errors of less than 3.8 km and 3.1 km, respectively.
- Seismicity in the Dergaha graben is anomalously deep and involves the entire crust with hypocenters ranging between ~1 km and ~35 km. The main-shock occurred at a depth of ~19 ± 4 km, where also most of the seismicity is focused.
- Conversely, the northern graben shows shallower seismicity between 5 km and 10 km.

Seismic analysis – Focal mechanisms



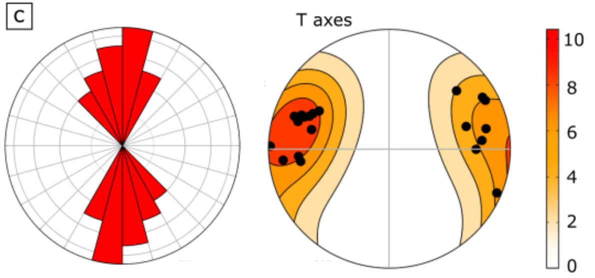


Figure 4 – Focal solutions in map view **a)** and cross sections **b)** for events with more than 30 phases. Yellow and gray dots in **a)** and **b)** are the relocated seismicity. Red lines in **b)** represents possible faults highlighted by the relocated seismicity. **c)** Stereographic plots showing the strikes and T axes of the main nodal planes.

- The focal solutions and the relocated seismicity (fig. 4a and b) show **dominant normal faulting along ~NS-striking faults** associated with a minor lateral component. The **major events** show **oblique right-lateral slip** on steep (57°-84°), west-dipping planes.
- **Minor earthquakes with oblique left-lateral slip** along east-dipping planes mainly focus along the northern tip of the Dergaha graben.
- T axes indicate average **extension** directed **N92°E** (fig. 4c), nearly orthogonal to the average faults strike in this sector of the NWAM.

InSAR analysis

- **No significant co-seismic deformation** is identified near the 2018 earthquake epicenter by InSAR. Two Sentinel-1 independent interferograms are shown in fig. 6a and b. Lack of significant focused surface deformation is consistent with the main-shock occurring at high depths.
- We put bounds on the depth of the fault that moved during the 2018 earthquake by producing a series of forward models.
- The modeling assumed a 10 km-long and 10 km-wide fault, striking north-south and dipping 70° to the west. We assumed that the fault has a normal slip of 24.5 cm corresponding to a M_w 5.2.
- We produced simulated interferograms assuming varying depths of the normal fault, between 1 km and 15 km (Fig. 6 c, d, e, f).
- Our models show that surface deformations are ≤ **0.6 cm** when the fault depth is ≥ **15 km**, supporting our estimated depth of ~19 km.

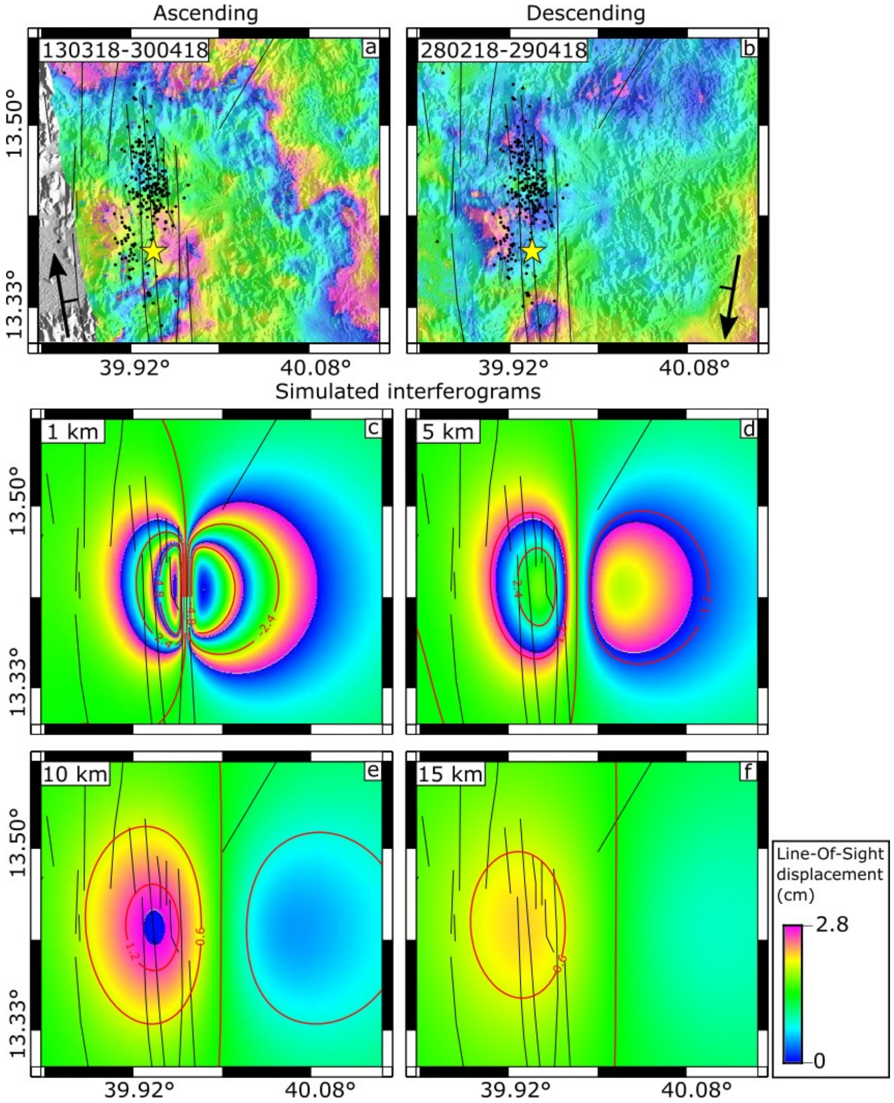


Figure 6 – a), b) Measured wrapped co-seismic interferograms from Sentinel-1 acquisitions. **c), d), e), f)** Simulated wrapped interferograms assuming Okada shear dislocation model located at increasing depth. The red contour lines display the deformation in cm.

Conclusion

- The seismic swarm of 24 March 2018 is characterized by **anomalously deep earthquakes**, mainly focused in the Dergaha graben.

- Both the relocated events and the focal solutions highlighted **a main systems of west-dipping** faults associated with conjugate **east-dipping faults**. The latter seem to be mainly active in the northern tip of the Dergaha graben. Dominant west-dipping faulting has been also observed in other portions of the WAM (e.g. *Stab et al., 2016*).

- Deep seismicity is observed elsewhere along active rift systems. In some case, it has been related to the presence of a strong lower crust (e.g. *Déverchère et al. 2001*). In other cases, deep seismicity has been related to deep fluids (e.g. magmatic fluids) migrating into the lower crust (e.g. *Keir et al., 2009; Lavayssière et al., 2019*). Since the deep earthquakes appear spatially localized in our local, and independent global earthquakes catalogs, we favor the hypothesis that they are fluid induced.

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