Lower crustal earthquakes in the March 2018 sequence along the Western Margin of Afar

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Key Points

- We studied fault activity and kinematics at the Western Afar Margin using seismicity and InSAR.
- We observed a seismic sequence occurring in the lower crust along both west- and east-dipping faults.
- Deep seismicity could be caused by fluid migration in the lower crust.

Abstract

During the evolution of continental rift systems, extension is thought to progressively focus in-rift to the future break-up boundary while faults along the rift margins progressively deactivate. However, observational constraints on how strain is partitioned between rift axis and rift margins is still lacking. The Afar Rift records the latest stages of rifting and incipient continental break-up. Here we analyzed the recent M_W 5.2 earthquake on the Western Afar Margin on 24 March 2018 and the associated seismic sequence of more than 500 earthquakes using twenty-four temporary seismic stations deployed during 2017-2018. We show seismicity occurring lower crustal depths, from ~15 km to ~30 km, with focal mechanisms and relocated earthquakes highlighting both west- and east-dipping normal faults. We tested earthquake depth using InSAR by processing six independent interferograms using Sentinel-1 data acquired from both ascending and descending tracks. None of them shows evidence of surface deformation. We tested possible ranges of depth by producing forward models for a fault located at progressively increasing depths. Models show that surface deformation is not significant for fault slip at depths greater than 15 km, in agreement with the hypocentral depth of 19 km derived from seismic data for the largest earthquake. Due to the localized

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nature of deep earthquakes near hot springs coupled with subsurface evidence for magmatism, we favor an interpretation of seismicity induced by migrating fluids such as magma or CO_2. We suggest that deep fluid migration can occur at the rifted-margin influencing seismicity during incipient continental rupture.

Plain Language Summary

The Earth's continents are thinned and broken by extensional forces along rift valleys. Rift valleys are bounded by big fractures (called border faults) that form at the inception of extension and that slip causing earthquakes. As thinning proceeds, molten rock (magma) can rise making its way through the crust. It is not well understood where and how the molten rocks migrates through the crust, and whether, for example, the large border faults are exploited as pathways. The migration of magma, and the gasses and fluids it releases can fracture rock causing earthquakes. In this study, we analyzed earthquakes occurring along border faults of the Afar rift of Ethiopia. We found that they occur deep in the crust where previous studies indicate the presence of magma. Our results could suggest that border faults could keep slipping and causing earthquakes as a result of the migration of magma into the deep parts of the crust.

1. Introduction

During the early stages of continental rifting, extension generally focuses at the rift margin along large offset border faults. As rifting proceeds, extension is thought to migrate to a narrow zone in the rift valley floor (Manighetti et al., 2001; Wolfenden et al., 2005; Corti, 2009; Stab et al. 2016). In magma-rich settings the narrow zone of extension occurs in a series of ~70-km-long, ~20-km-wide *en-echelon* magmatic segments which host active volcanoes producing significant eruptions and intrusions (Hayward & Ebinger, 1996; Wright et al., 2012). The magmatic segments are interpreted to be the initiation of the future break-up plate boundary where seafloor spreading initiates (Keranen et al., 2004; Wright et al., 2006), while the border faults progressively deactivate and eventually become passive margins after seafloor spreading starts (Hayward & Ebinger, 1996; Pagli et al., 2014). However, recent seismic observations at mature continental rifts show both intense fault-related seismicity (e.g. Ayele et al., 2007; Illsley-Kemp et al., 2018), and magmatic intrusion (e.g. Ebinger & Belachew, 2010; Pallister et al., 2010) characterizing the incipient passive margins of the Aden, Red Sea and Afar rifts. This posed several questions regarding the dynamics of faulting, the causes of seismicity and the related seismic hazard along mature rift margins.

The Afar rift is the locus of separation between the Nubian, Arabian and Somalian Plates. A wide body of geological and geophysical observations (e.g. Barberi et al., 1972b; Makris & Ginzburg, 1987; Keir et al., 2013) indicates that continental break-up is imminent in Afar. 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. Here, the interplay between synthetic (east-dipping) and antithetic (west-dipping) faults shape a series of seismically active marginal grabens which can be observed along the entire margin (Figure 1) (Mohr & Gouin, 1976; Chorowicz et al., 1999; Stab et al., 2016; Zwaan et al., 2020a).

The Northern WAM (NWAM), east of the Tigray capital city of Mekele (at latitudes of N13°-N14°), displays the highest seismic activity along the entire WAM. Decades of recording from global seismic networks have shown the margin is seismically active with several $M_W > 5$ earthquakes occurring within the systems of marginal grabens (Figure 2, USGS National Earthquake Information Centre). Intermittent temporary local seismic deployments show micro-seismicity in the upper crust (<15 km deep) is common (Figure 2) with lower crustal seismicity (15-30 km) being less common (Ayele et al., 2007; Belachew et al. 2011; Illsley-Kemp et al., 2018).

Recently, a M_W 5.2 earthquake struck the NWAM on 24 March 2018. Here we analyzed the associated seismic sequence by using continuous recordings from the more recent temporary and high-density seismic network in Afar (Doubre et al., 2017; Keir et al., 2017) to investigate the fault activity and kinematics along the NWAM. Earthquakes were located at mid-to-low crustal depths (15-30 km) and the accuracy of hypocentral distribution has been evaluated through a series of simulated interferograms. A series of focal mechanisms were produced to analyze the kinematics of faulting during the seismic sequence. Our observations show that low crustal earthquakes occur at the NWAM during incipient continental break-up. In the same area, previous independent geophysical observations suggest the presence of melt emplaced in the lower crust (Hammond et al., 2011; Korostelev et al., 2015). Fluid migration from such emplaced melt is interpreted to influence seismicity and fault activity in the area.

2. Tectonic Setting

The Afar depression is bounded to the west by systems of tens of km-long, ~NS-trending normal faults which define the margin from latitude N9.5° to N15° (Beyene &

Abdelsalam, 2005). Steep, synthetic east-dipping fault scarps with ~1000 m-high throws mark the sharpest decrease in elevation from the plateau to the Danakil Depression (Beyene & Abdelsalam, 2005; Sembroni et al., 2017; Zwaan et al., 2020a). However, antithetic west-dipping normal faults dominate the architecture of several parts of the WAM producing eastward tilted blocks and a series of *en-echelon* right-stepping marginal grabens (Baker et al., 1972; Beyene & Abdelsalam, 2005; Stab et al., 2016; Zwaan et al., 2020a). The tilted blocks are evident south of N12.5° showing a dip angle increasing rift-ward from 10° to 45° and are controlled by west-dipping faults with dip angles up to 70° (Zwaan et al., 2020a, 2020b). The marginal grabens are generally 10-30 km long, strike in a NNW-SSE direction, oblique with respect to the general NS orientation of the WAM (Figure 1), and are connected by complex transfer zones which result in a right-stepping geometry (Chorowicz et al. 1999; Beyene & Abdelsalam, 2005; Zwaan et al., 2020a, 2020b). Dense drainage networks crosscut the WAM from west to east eroding the faulted blocks and depositing sediments within the adjacent basins. Geochronological data suggest that fault activity at the WAM began in the Oligocene (Wolfenden et al., 2005; Ayalew et al., 2006), but the inception of marginal grabens formation at the WAM is still debated. Dating of alluvial deposits filling some of the marginal grabens in the northern sector of the WAM suggests that they started forming during the Pliocene (e.g. Chorowicz et al. 1999; Beyene & Abdelsalam, 2005). However, in most cases, dating at the base of alluvial deposits is not available and the age of marginal grabens is poorly constrained (e.g. Tesfaye & Ghebreab, 2013; Zwaan et al., 2020b).

On the Plateau, east of the Mekele city, between N12.5° and N14.0°, a 2000 m-elevated region of Mesozoic marine sediment outcrops and overlays the Precambrian metamorphic basement. The entire sequence is intruded by Miocene dykes (Figure 1) and sills (Sembroni et al., 2017; Zwaan et al., 2020b). Systems of east-dipping and west-dipping normal faults form a series of marginal grabens of which some are the Berhale, Abala (Zwaan et al., 2020a) and Dergaha grabens (Gouin, 1979) (Figure 1b). The marginal grabens have the same NNE-SSW trend observed elsewhere along the WAM, south of N12°. However, unlike other sectors of the WAM where the marginal grabens are well developed and have sharp margins and clear fault surfaces, smaller and less developed basins have been observed between N13° and N14° (e.g. Dergaha, Figure 1) (Zwaan et al. 2020a, 2020b). Structural field measurements in the Abala graben report an extension direction of ~N80°E (Zwaan et al., 2020b) while in the other adjacent grabens no measurements have been made.

Finally, hydrothermal activity with hot springs is also reported 20 km south of Dergaha (Figure 1) (Keir et al., 2009).

The decrease in topographic elevation caused by the activity of the border fault systems at the WAM is mirrored by a progressive crustal thinning toward the rift valley. Several seismic studies (Makris & Ginzburg,1987; Maguire et al., 2006; Hammond et al., 2011) showed that the variation in topographic elevations across the WAM is accompanied by strong variations in crustal thickness and Vp/Vs ratios. In Northern Afar, the crust thins eastward from ~38 km below the Ethiopian plateau to ~16 km beneath the Danakil Depression, with most of the thinning occurring across the WAM. Progressive crustal thinning and decreasing elevation toward the rift axis also characterize the rift floor which reaches minimum elevations between 50-100 m below sea level at the Danakil Depression (Hammond et al., 2011). South of ~N11°, the crust below the plateau is thicker (~40 km) and thins eastward to ~20 km into the rift. Low Vp/Vs ratios (1.7-1.8) characterize the thick felsic crust at the plateau, yet anomalously high Vp/Vs values (1.9-2.0) have been measured beneath the Dergaha graben (Hammond et al., 2011). Similar values characterize the mafic crust of the rift valley. Additionally, Korostelev et al. (2015) and Chambers et al. (2019) used ambient noise tomography and imaged a pattern of slow seismic wave-speeds focused right beneath our study area, between the lower crust and upper mantle. Both high Vp/Vs and slow seismic velocities have been interpreted as related to the presence of melt and fluids (Hammond et al., 2011; Korostelev et al., 2015; Chambers et al., 2019).

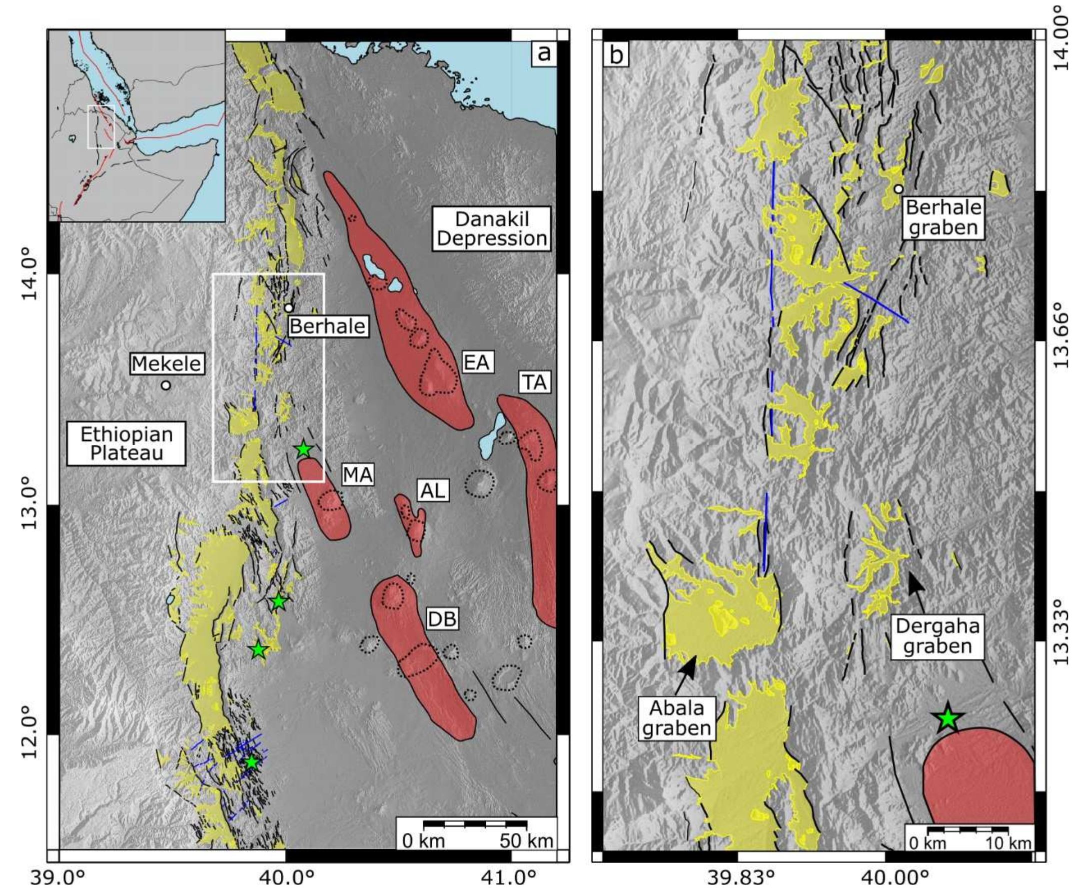

Figure 1- a) Tectonic map of North-Western Afar showing the magmatic segments (red polygons) and associated volcanoes (black dashed lines), the marginal grabens (yellow polygons) along with major faults (black solid lines) and Miocene dikes (blue lines) identified in the area by Zwaan et al. (2020b, 2020c). The map also shows the hydrothermal springs (green stars) reported along the WAM by Keir et al. (2009) and the main active magmatic segments (red polygons) accommodating extension at the rift axis. EA =Erta Ale, TA = Tat Ali, AL =Alayta, DB = Dabbahu, MA = Ma'Alalta **b)** Close up on the study area showing the main marginal grabens and structures, as represented in **a).**

2.1. Seismicity at North-Western Afar Margin (NWAM)

Figure 2 shows the seismicity recorded by both global (Figure 2a) and local (temporary) (Figure 2b) networks in the study area. Seismic activity in the NWAM is characterized by several $M_W > 5.0$ earthquakes that occurred during the last few decades. In general, seismicity located by both local and global catalogs at the margin is located in the upper crust (<15 km), with deeper seismicity focused in the lower crust (> 15 km) being much less common (Illsley-Kemp et al., 2018; USGS National Earthquake Information Centre - NEIC). The first seismic sequence instrumentally recorded in the area is that of April 1989 (USGS NEIC). The episode includes two earthquakes with $M_W > 5.0$ and several $M_W > 4.0$ earthquakes at the southern tip of the Dergaha and Abala grabens, between N13.2° and N13.4° (Figure 2a). Relatively deep hypocenters, between 10 km to 33 km, are reported in global catalogs for these episodes, though due to the large error bars in the NEIC catalog the depths are in reality poorly constrained (Figure 2a). Further north, between N13.5° and N13.8°, a sequence of 75 aftershocks ($M_W \leq 5.0$) accompanied a main shock with M_W 5.6 in August 2002 (Ayele et al., 2007). Moment tensor inversion of locally recorded waveforms provided focal mechanisms for six of these events, all consistent with normal faulting along NNW-striking and NE-dipping planes (Figure 2b) (Ayele et al., 2007). The source depth of the main events deduced from moment tensor inversion of local broadband waveform data is estimated at 5-7 km (Ayele et al., 2007). Re-computation of moment tensors of the larger earthquakes along the WAM from regional and global waveforms also yields similarly shallow depths (<10 km) (Craig et al., 2011).

More recently, the temporary seismic networks implemented between 2005-2009 (Belachew et al., 2011; Ebinger et al., 2008) and 2011-2013 (Illsley-Kemp et al., 2018) recorded more than 1900 low-magnitude earthquakes ($0.3 < M_L > 4.5$) north of the Dergaha graben (Figure 2b) suggesting that seismicity along the NWAM is persistent. Furthermore, several indications, such as the b-value, the double-couple mechanisms and the high-frequencies of the earthquake waveforms were interpreted to indicate that the origin of this seismicity is mainly tectonic (Illsley-Kemp et al., 2018). The hypocentral distribution during the 2011-2013 period highlights ~NS-striking, west-dipping faults with seismicity mainly clustered at depths < 15 km but with some located deeper than 20 km near to the Abala graben (Illsley-Kemp et al., 2018; Zwaan et al., 2020b). The focal solutions indicate oblique faulting characterized by both normal and strike-slip component and (Figure 2b) accommodating a N82°E-trending extension, suggesting that extension along the NWAM occurs mainly along west-dipping normal faults. Similar structural architecture has been also observed in other parts of the WAM, south of latitude N12° (e.g. Stab et al., 2016).

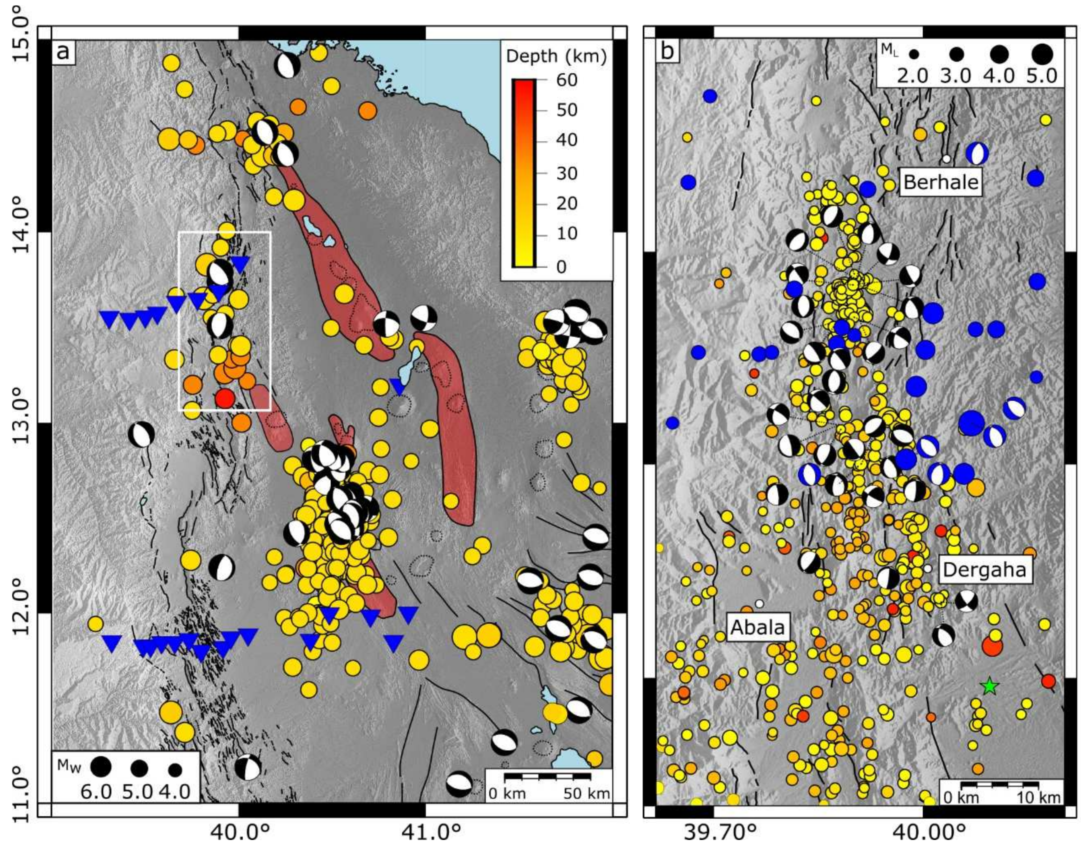

Figure 2 – a) Seismicity in Afar between 1973-2020 from USGS NEIC and focal mechanisms from the GCMT catalog. The blue reversed triangles are the seismic stations used in this study (Keir et al., 2017; Doubre et al., 2017). The white box marks the area shown in **b)**. **b)** Local seismicity between 2005-2013 (Ayele et al., 2007; Zwaan et al., 2020b). The blue circles and focal mechanisms refer to the sequence of August 2002 (Ayele et al., 2007) (the depth information is not available). Black focal mechanisms are from the 2011-2013 period (Illsley-Kemp et al., 2018; Zwaan et al., 2020c).

3. Earthquake location and magnitude estimation

Twenty-four stations from two recent temporary seismic networks installed in Afar (Figure 2a) (Keir et al., 2017; Doubre et al., 2017) were operational on 24 March 2018 when the M_W 5.2 earthquake struck the NWAM, east of Mekele. We visually inspected 41 days of continuous seismic recordings, from 20 March to 30 April 2018 and manually picked both P and S waves for earthquakes recorded by four or more stations (Text S1). We located the events using the Oct-Tree search algorithm implemented into the NLLoc software (Lomax et al., 2000).

For the location, we used a 2.5D seismic velocity model reproducing the large-scale crustal structure of the WAM (Text S2). A correct velocity model and an accurate Vp/Vs ratio is crucial for a precise earthquake location. However, this is challenging to obtain, especially for complex crustal structures and variable Vp/Vs values as it has been observed at the WAM by Makris & Ginzburg (1987), Maguire et al. (2006) and Hammond et al. (2011). Starting from these observations, we created a 2D velocity profile cross-cutting both the Afar margin and axis in an EW direction, along a distance of 250 km (Text S2 and Figure S1a). The profile has been then extended to 250 km along the third dimension (NS in this case) to create a 2.5D grid. We made a model characterized by crustal features intermediate between Northern and the Central Afar, where the seismic stations and the study areas are located (Figure 2a and S1a). The velocity model has a crustal thickness of 35 km below the Ethiopian plateau which gradually decreases to 18 km at the rift axis (Text S2 and Figure S1a). The topography has been also reproduced with elevations varying from 2 km at the plateau to 0.5 km at the axis. The crustal structure is made of 4 layers encompassing the cover rocks, the basalts, the upper and lower crust, with velocities gradually increasing from 4.4 km/s of the cover rocks to 6.8 km/s at the base of the lower crust. An additional shallow low velocity layer (3.3 km/s) was introduced in the rift zone to reproduce the recent sediments. Finally, an upper mantle with uniform velocity of 7.4 km/s completes the model (Text S2 and Figure S1a).

Since high variability in Vp/Vs characterizes the margins where our network was located, we tested several Vp/Vs and produced Wadati diagrams in order to find a value corresponding to an average through the model (Figure S1b). We found minimum residuals for Vp/Vs of 1.74 which average those measured by Hammond et al. (2011) at the stations along WAM (Figure S1b). However, our Wadati diagram does show that the stations within the rift on the southern profile show a distinctively higher Vp/Vs of 1.85, but these contribute only ~36% of total arrivals.

The local magnitude (M_L) for each earthquake has been calculated by measuring the zero-to-peak amplitude on simulated Wood Anderson seismometers, and using the distance correction for the Danakil Depression from Illsley-Kemp et al. (2017).

We located 673 events on the NWAM (Figure 3a and Table S1) with average vertical and horizontal errors of ±4.8 km and ±6.6 km, respectively. Hypocentral depths and related uncertainties are reported in Figure S2, where we report just earthquakes with both horizontal and vertical errors lower than 6 km. Further details on the error calculation are also provided in the supporting material. The seismic catalog encompasses events with $M_L \geq 1.6$ with a mean magnitude uncertainty estimated as ±0.3 (Figure 3b and c). The local magnitude of the largest earthquake has been calculated as M_L 5.3 ± 0.4, close to the value of M_W 5.2 reported by the USGS NEIC. The largest earthquake occurred at a depth of ~19 ± 4 km, where most of the hypocenters also focused. We identified two areas of clustered seismicity characterized by distinct spatial and temporal distributions (Figure 3). The main seismic sequence of March-April 2018 occurred within the Dergaha graben with 514 earthquakes located along a system of ~NS-striking faults bounding the graben to the west (green box in Figure 3a). Hypocentral depths range between ~1 km and ~30 km indicating that seismicity in this part of NWAM occurs throughout the entire crust.

Most of the seismic sequence (309 of the 514 events) occurred between 24 March 2018 (day of the main event) and 31 March 2018 with an average of 39 earthquakes per day. The seismicity rate progressively decays to a minimum of ~3 earthquakes per day by the 30 April 2018, comparable to the number of earthquakes that occurred in the days before the onset the seismic sequence (Figure 3d and e). However, another burst of activity is also observed on 16 April 2018, with the occurrence of 30 located earthquakes (Figure 3d and e).

Minor seismic activity is also observed within a small graben, south-west of Berhale, during the analyzed time-period (blue box in Figure 3a). Seismicity is shallow, between 5 km and 15 km (Figure S2) with 75 earthquakes scattered in time rather than clustered in seismic sequences, as observed in the Dergaha graben. Furthermore, the occurrence of the earthquakes in this area seems to be temporally independent from the main seismic sequence (Figure 3d and e). Interestingly, a pattern in the spatio-temporal distribution of earthquakes with low error in the hypocentral location can be inferred from the profiles in Figure S2. The main sequence takes place close to the southern tip of Dergaha at depth of 19-25 km, where the largest earthquake occurred. After that, earthquakes show a progression to shallower crustal levels and toward the northern tip of Dergaha which could indicate a migration of seismicity.

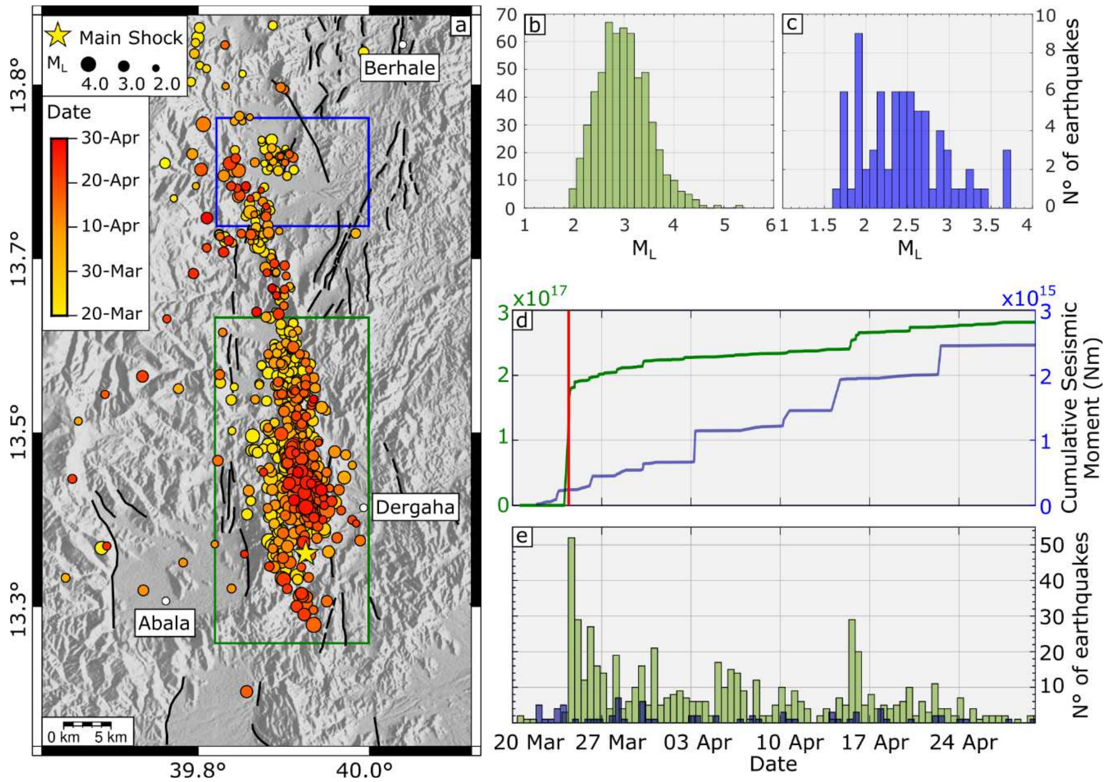

Figure 3 – a) Epicentral distribution of the 673 earthquakes located with NLLoc (Lomax, 2000) and occurred between 20 March 2018 and 30 April 2018. The earthquakes are color-coded by time. The blue and green boxes highlight the two marginal grabens along the NWAM. **b)** and **c)** Histograms of magnitudes for the two areas highlighted in **a). d)** and **e)** cumulative seismic moment curves and histograms of number of earthquakes for the two areas in **a)**.

To improve the resolution of hypocenter locations and highlight active fault planes, we relocated 262 earthquakes using the double-difference method implemented in the HypoDD software and a minimum of 10 observations per event pair (Waldhauser & Ellsworth, 2000; Waldhauser, 2001). The relocated seismicity highlights both east and west-dipping active fault planes bounding the western side of the Dergaha graben (Figure 4a and b). We interpret the sharp alignments of seismicity as illuminating the fault planes between 15-30 km (Figure 4b). In addition, the projection of the west-dipping plane to the surface clearly matches the topographic expression of a fault represented by a scarp separating the Dergaha graben from the adjacent horst (Figure 4b). The distribution of seismicity also shows a main fault plane dipping to the west while a conjugate east-dipping fault is just observed at the northern tip of the Dergaha graben.

4. Focal Mechanisms

We computed focal mechanisms based on the polarities of the P-wave arrivals at both northern and southern stations. P-wave arrival polarities of events recorded by more than 15 stations have been processed using FOCMEC software (Snoke, 2003). Focal solutions have been attempted only for earthquakes with unambiguous first arrivals and no polarity errors have been allowed. This resulted in well resolved focal mechanisms with maximum standard deviations (σ) in strike and dip angles of the possible solutions equal to 7.5° and 11°, respectively (Table 1). We considered the nodal planes subparallel to the faults reported in literature (i.e. ~NS) as the main ones and classified their kinematics on the basis of the rake value. P and T axes of each solution have been used to retrieve the average extensional direction along the NWAM.

Twenty well-constrained focal mechanisms were obtained for earthquakes within the Dergaha graben. All the solutions have main nodal planes oriented ~NS (Figure 4 and Table 1). The focal solutions are characterized by dominant normal faulting along ~NS-striking faults, associated with a minor lateral component (Figure 4a and b). Ten focal mechanisms related to the major events can be observed along the central and southern part of the Dergaha graben and show normal faulting with minor oblique right-lateral slip on steep (57°-84°), west-dipping planes (Figure 4a and c, Table 1). Conversely, normal faulting earthquakes with minor oblique left-lateral slip along east-dipping planes mainly focus along the northern tip of the Dergaha graben (Figure 4a and c, Table 1). Three pure dip-slip focal mechanisms are also present in the central part of the graben, with both east- and west-dipping planes (Figure 4a and c, Table 1). P and T axes computed from all the solutions indicate an average N092°E-trending extension, nearly orthogonal to the average strike of the faults observed in this area of the NWAM. The main nodal planes match very well with the structures observed in the field by Zwaan et al. (2020b) as well as the fault planes deduced from the relocated seismicity (Figure 4).

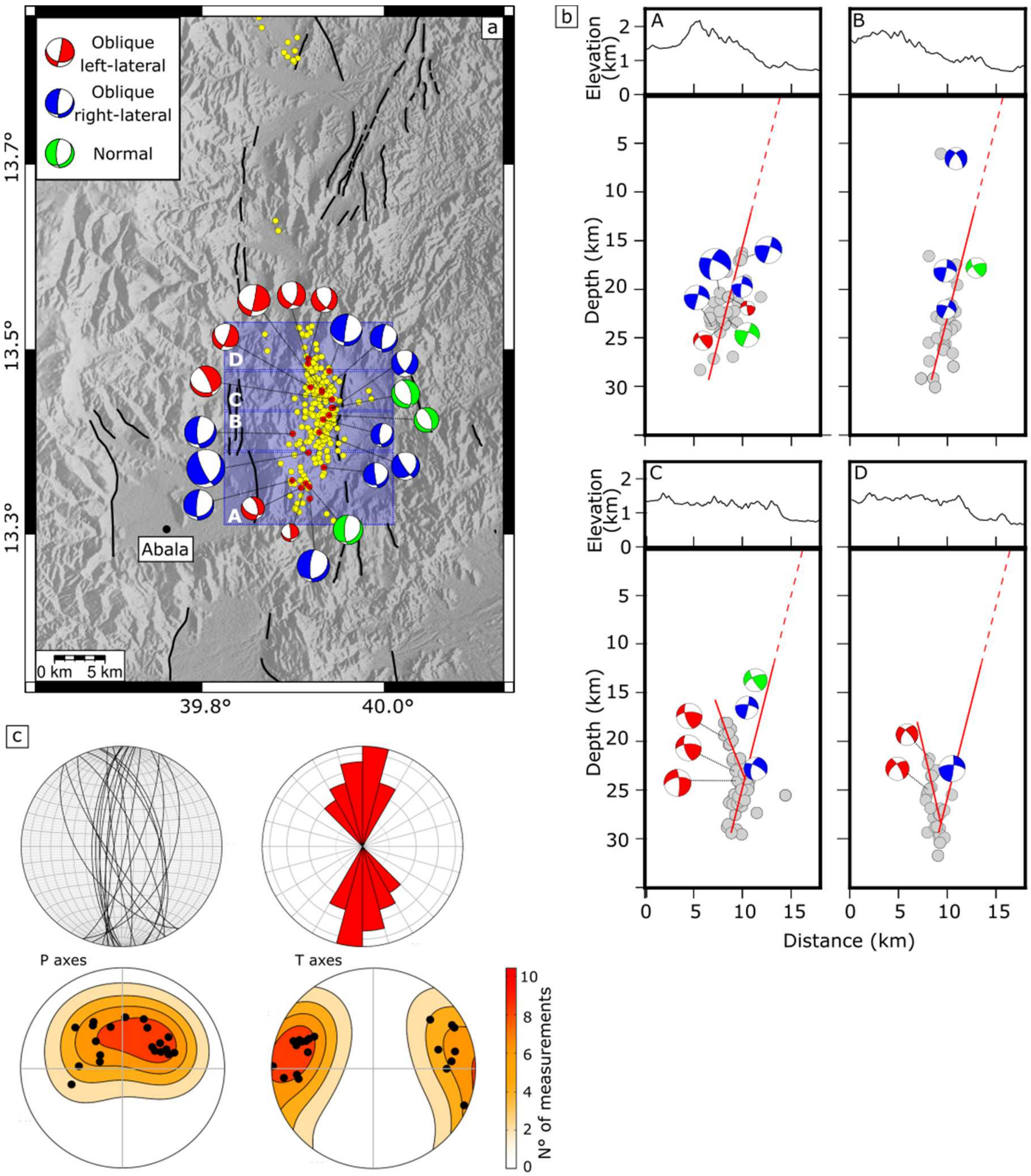

Figure 4 - Focal mechanism solutions in map view **a)** and cross sections **b)** for events located with more than 15 stations. Yellow dots in a) and gray dots in **b)** are the relocated seismicity. Red lines in b) represents possible faults highlighted by the relocated seismicity. **c)** The plots show the stereographic projection of the strike and dip (top left), the rose diagram of the strikes (top right), and the P and T axes of the main nodal planes with contour of number of measurements (bottom).

Date and Time	M_L	Strike	σ Strike	Dip	σ Dip	Rake	σ Rake

2018/03/24 10:27	5.3	154	3.9	76	6.9	-117	0.9
2018/03/24 10:56	4.3	184	0.8	78	0	-113	0
2018/03/24 11:23	4.0	146	0	79	0	-122	0
2018/03/24 21:02	4.5	180	3.2	72	1.0	-117	3.1
2018/03/25 01:48	3.3	348	3.6	56	4.0	-53	2.0
2018/03/26 00:25	2.5	355	1.5	84	0.8	-61	0.5
2018/03/26 00:29	4.2	181	4.6	69	7.6	-109	2.2
2018/03/29 18:37	3.8	145	4.9	57	4.4	-141	6.2
2018/03/30 06:31	4.6	184	1.3	73	3.3	-111	0.4
2018/03/31 00:56	3.5	340	2.8	59	3.9	-74.5	0.9
2018/04/02 11:02	3.8	22	1.7	78	4.0	-55	0.6
2018/04/02 11:50	4.0	17	7.0	61	11.0	-50	9.0
2018/04/07 19:49	3.9	187	2.3	79	3.4	-111	2.4
2018/04/11 20:59	3.6	172	1.7	84	1.7	-116	0.4
2018/04/15 12:11	4.6	11	0.8	87	1.7	-56	1.4
2018/04/15 12:34	4.4	335	1.4	75	1.4	-68	0.7
2018/04/15 13:23	4.0	347	4.7	59	6.4	-71	2.0
2018/04/15 22:37	4.5	188	0.7	84	0	-114	0
2018/04/20 03:34	3.7	23	7.5	48.5	7.8	-41	5.8
2018/04/23 01:25	3.4	181	1.8	66.5	3.1	-114	0.7

Table 1 - Parameters of the focal solutions computed for 20 major earthquakes occurred at Dergaha and showed in Figure 4. Sigma (σ) is the standard deviation calculated from the range of solutions provided by FOCMEC for each main nodal plane.

5. Interferometric Synthetic Aperture Radar (InSAR)

InSAR is widely used to identify co-seismic surface displacements and investigate the earthquake source parameters. However, the ability of InSAR to detect co-seismic surface deformation strongly depends on the noise level affecting the interferometric phase (e.g. spatial and temporal decorrelations or atmospheric noise) along with the earthquake magnitude and the depth of the source (e.g. Dawson & Tregoning, 2007; Funning & Garcia, 2019).

In order to investigate the surface deformation related to the M_L 5.3 event of 24 March 2018, we processed six independent interferograms from C-band SAR images acquired by the Sentinel-1 satellite on both ascending (014) and descending (079) tracks (Figure 5a, b and S2). Six independent co-seismic interferograms with temporal baselines ranging from 36 to 144 days were processed using the InSAR Scientific Computing Environment (ISCE) software developed by the Jet Propulsion Laboratory, Caltech and Stanford University (Rosen et al., 2012). The interferograms were co-registered and corrected from topography-correlated noise using a standard 1 arc-sec SRTM Digital Elevation Model (DEM) (Farr et al., 2007). We then applied a standard power spectrum filter

(Goldstein & Werner, 1998) of 0.5 and unwrapped the interferograms using the branch cut method (Goldstein et al., 1988). The interferograms were finally geocoded at a final pixel spacing of 30 m using the 1 arc-sec DEM. The Sentinel-1 interferograms have relatively low level of noise and maintain good coherence up to temporal baseline of 144 days (Figure S3). However, no significant deformation has been identified in any of the co-seismic interferograms in the epicentral area (Figure 5a, b and S2) suggesting that co-seismic slip occurred at large depth and caused too small surface deformation to be measured by InSAR, as also indicated by the deep source location obtained from seismic data. To test this hypothesis, we produced a series of simulated interferograms assuming different depth of possible fault slip. We used an Okada shear dislocation within a homogeneous, elastic half-space with a Poisson's ratio of 0.25 and a shear modulus (μ) of 3.2×10^{10} Pa (Okada, 1985). We assumed a 10 km-by-10 km normal fault, striking NS and dipping to the west with an angle of 70°, following the hypocenter distribution and the fault geometry deduced from the focal mechanisms (Figure 4 and Table 1). Normal slip was fixed at 245 mm to simulate a M_W 5.2, as reported by the USGS NEIC catalogue. We produced forward models using the incidence angles from descending tracks 079 to estimate the surface displacement field in the Line-Of-Sight (LOS) component of the InSAR measurements assuming a progressively increasing depth of the fault top edge between 1 km and 15 km, with a step size of 5 km (Figure 5c-f). The simulations show that LOS displacement decreases rapidly at increasing depth of faulting. For a fault having the top edge at 15 km depth (and bottom edge at ~24 km depth) we see < 1 cm of LOS displacement, which would be difficult to resolve in a single interferogram. Such a model is likely applicable to our observations of an earthquake with a hypocentral depth of ~19 km, and would cause a too small surface displacement to be detected by InSAR.

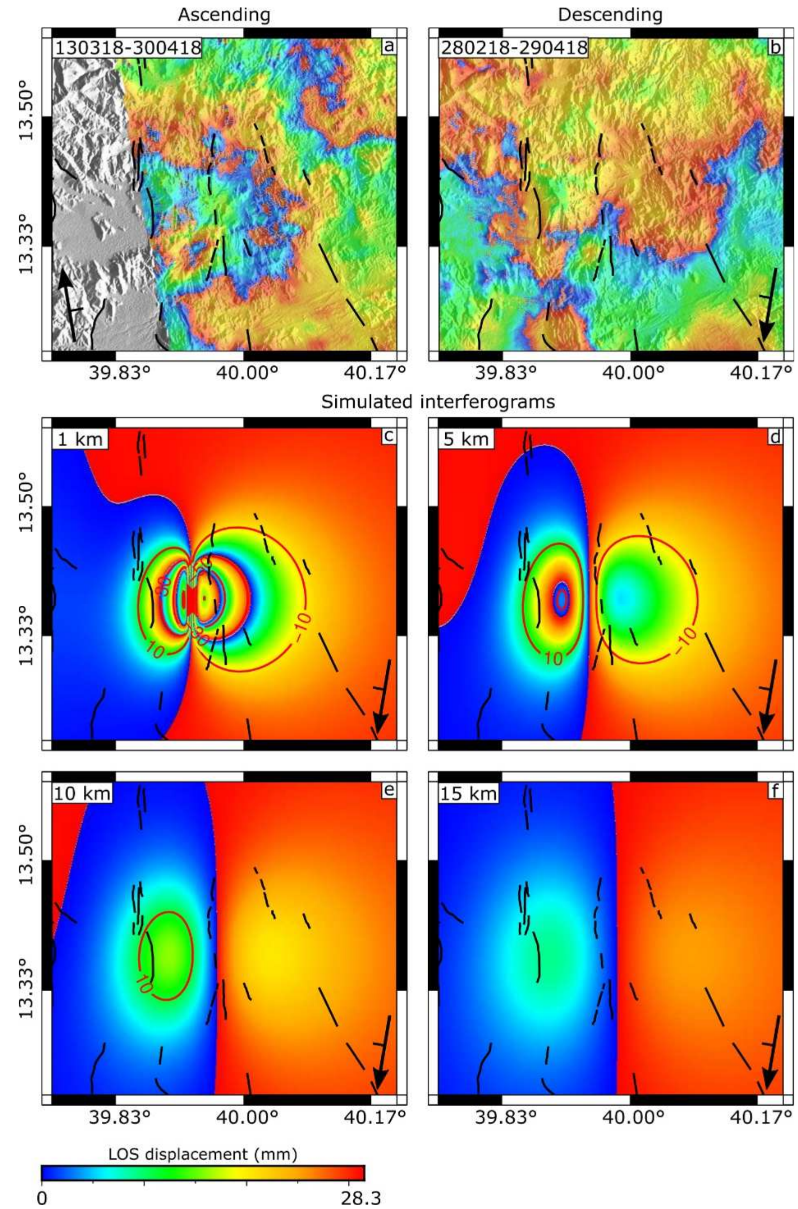

Figure 5 - a), b) Measured wrapped co-seismic interferograms from Sentinel-1 acquisitions. **c)-f)** Simulated wrapped interferograms assuming Okada shear dislocation model located at increasing depth. The red contour lines display the unwrapped deformation in mm. Black solid lines are faults reported by Zwaan et al. 2020c.

6. Discussion

We analyzed the seismicity in a time period of 41 days, covering the M_L 5.3 of March 2018, to investigate the fault activity across the NWAM. Seismic location and well-constrained focal mechanisms give constraints on the fault kinematics characterizing the marginal grabens during the time period under study.

We observed earthquakes focused in an area of the NWAM (N13.3°-N13.8°) characterized by continuous seismicity and several $M_W > 5$ in the past few decades (Figure

2) (USGS NEIC; Ayele et al., 2007; Belachew et al., 2011; Illsley-Kemp et al., 2018). The largest part of the catalog consists of the seismicity that occurred in the Dergaha graben and within the minor grabens to the north between 24 March 2018 and 30 April 2018. The results show the main seismic sequence was distributed through the entire crust, with the largest, M_L 5.3, earthquake occurring at ~19 km and the other major earthquakes also located in the lower crust between 15 and 30 km (Figure 4b and S1b). InSAR data do not show any significant surface deformation related to the M_L 5.3, earthquake suggesting that the hypocentral depth of the episode was greater than 15 km (Figure 5), in agreement with the seismic results. Lower crustal depths in this region have already been reported in global catalogues for other $M_W > 5$ earthquakes in 1989-1990, as well as in local catalogs (Belachew et al., 2011; Illsley-Kemp et al., 2018; Zwaan et al., 2020b), suggesting that part of the seismic moment in this sector of the NWAM is released at greater depth. Conversely, the M_W 5.6 sequence of August 2002 close to Dergaha was shallower (5-15 km), as also the low magnitude seismicity north of ~N°13.6 reported by Illsley-Kemp et al (2018) and Zwaan et al. (2020b) during the time period 2011-2013.

The relocated seismicity in the Dergaha graben clearly highlights two steep crustal faults with a main west-dipping fault and a conjugate east-dipping fault (Figure 4b). The latter seems to rupture just at the northern tip of the Dergaha graben. The fault planes deduced from the alignment of the seismic cluster are consistent with the orientation of nodal planes of the focal mechanisms. Together, the earthquake locations and the focal mechanisms indicate dominant normal faulting accompanied by a minor right-lateral slip along west-dipping faults at the southern and central parts of the Dergaha graben. To the north, the dominant normal component is instead associated with minor left-lateral slip along east-dipping faults. The structural setting of the two fault planes at Dergaha, along with the higher magnitude content of earthquakes occurring along west-dipping faults suggest that west-dipping faulting is dominant. The T-axes calculated from the focal solutions indicate that the average extension direction is oriented ~EW. Structural field measurements in the Abala graben, along with the seismicity distribution and the focal mechanisms south of Berhale indicate similar extension directions and fault architecture (Zwaan et al., 2020b). About 130 shallow earthquakes along east and west-dipping faults in Dergaha have also been reported by Zwaan et al. (2020b, 2020c).

On the basis of the diffuse seismicity and the structural evidences of active faulting at surface, Zwaan et al. (2020b) suggested that extension is still ongoing along the NWAM.

The spatial correspondence between our observations of dominant normal faulting and their structural and seismic dataset are consistent. Additionally, we also show that deep seismicity occurs in this region and that dissimilarities between the temporal and spatial distribution of the seismicity in Dergaha and in the other sectors of the NWAM exist. In particular, the seismicity south of Berhale is spread over time and seems to occur independently from the main seismic sequence striking the Dergaha graben. Furthermore, our new observations of the 2018 sequence coupled with the ~50 year-long USGS NEIC catalog (Figure 2) showing deep earthquakes focused below the Dergaha graben suggests that the mechanism driving seismicity here may be different from that causing seismicity along the rest of the NWAM, where only upper crustal earthquakes are observed (e.g. Ayele et al. 2007; Illsley-Kemp et al., 2018; Zwaan et al., 2020b).

Deep earthquakes have been widely observed elsewhere at both mature and young basins along the East African Rift System (e.g. Main Ethiopian Rift, Muluneh et al., 2020; Lapins et al., 2020; Keir et al., 2009; Western Rift Branch, Albaric et al., 2009, 2014; Tanganyika Rift, Shudofsky, 1985; Lavayssière et al., 2019; Magadi-Natron basin, Lee et al., 2016) as well as other active rifts worldwide (e.g. Doser & Yarwood, 1994; Déverchère et al., 2001). Deep (15-30 km) moderate earthquakes (M_W < 6.0) occur across hundreds of kilometers-long segments of the Western and Eastern Rift Systems in Tanzania. Several authors (e.g. Shudofsky, 1985; Albaric et al., 2009, 2014; Muluneh et al., 2020) related such seismicity to the presence of a strong, intruded, mafic lower crust which can deform in a brittle manner at greater depths. The same mechanism has been also invoked by Déverchère et al. (2001) to explain deep seismicity in the Baikal rift. Similarly, Lavayssière et al. (2019) analyzed seismicity in the Rukwa and Tanganyika during 2014-2015 and suggest that deep earthquakes are related to the activity of steep border faults cross-cutting the entire crust, which is enabled by a cold lower crust and a very thick mantle lithosphere in the region (Craig et al., 2011). In contrast, Seno and Saito (1994) explained deep earthquakes across the East African Rift System as induced by the locally high strain rates induced by migration of fluids, such as from the upper mantle. Similarly, Lee et al. (2016) compared flux measurements and isotope compositions of CO_2 emissions with lower crustal earthquakes along large-offset fault scarps in the Magadi-Natron Basin (Kenya-Tanzania border) to suggest that deep seismicity (15-27 km) in the area is caused by tectonic degassing of mantle-derived CO_2. Deep seismicity has been also reported by Keir et al. (2009) near the flank of the Main Ethiopian Rift, where spatial associations between lower crustal earthquakes and high conductivities imaged in magneto-telluric data led them to propose that such seismicity is related to either melt migration or fluid circulation resultant from magma emplacement.

The presence of NS oriented mafic dikes along the NWAM such as those observed between Berhale and Abala (Zwaan et al., 2020b) indicates that mafic intrusions has been emplaced below the NWAM in the past. Most of Miocene dykes are coeval with those observed along the margin of the Red Sea and likely associated with early magma-assisted rifting (e.g. Buck, 2006). A possible explanation for deep seismicity in the study area could thus be that the lower crust beneath the NWAM is mafic and therefore strong enough to be capable of brittle deformation at large depths. However, such a factor would likely facilitate deep seismicity along most of the WAM, like the large (several hundreds of km) along-rift spatial extent of deep seismicity occurring in Tanzania and along the Baikal rifts (Déverchère et al., 2001; Albaric et al., 2009). Since we observe more localized deep seismicity, we therefore do not favor this explanation.

By comparing our results with other local and global seismic catalogs (e.g. Figure 2), we observe that the area showing deep seismicity in the NWAM is strongly focused around the Dergaha graben only. This brings us to hypothesize that a more local factor could play a role in triggering the deep earthquakes. Seismic imaging of the lithosphere by Hammond et al. (2011), Korostelev et al. (2015) and Chambers et al. (2019) have shown anomalously high Vp/Vs (~ 2.0) and slow seismic velocities beneath Dergaha which have been interpreted as due to the current presence of partial melt in the lower crust and upper mantle. The presence of magma is also supported by geological evidences of recent (0.12±0.05 Ma) axial volcanism at the adjacent Ma'Alalta magmatic segment (Figure 1) (Barberi et al., 1972a; Tortelli et al., 2020), which is heavily offset to the west to be close to the WAM. We thus hypothesize that the deep, focused seismicity in Dergaha could be induced by migration of either melt, or other fluids through the lower crust (Figure 6). Our interpretation of fluid induced seismicity here is also supported by the migration pattern of earthquakes toward shallow crustal levels and toward the northern tip of Dergaha (Figure S2), and the presence of micro-seismicity preceding the main sequence (Figure 3e) (Belachew et al., 2011; Illsley-Kemp et al., 2018 and this study). Patterns of earthquakes migration have been widely observed during seismic sequences, and in some case, they have been interpreted as induced by fluids (e.g. Antonioli et al., 2005; Yamada et al., 2015; Yoshida & Hasegawa 2018). In addition, hot springs are present near the Dergaha graben, but absent further north where the earthquakes are only in the upper crust (Figure 1). The shape of the clusters together with their focal mechanisms would suggest that the fluids induce failure of deep fault systems connected to the upper crustal faults, as also suggested by the presence of hydrothermal activity in the area. Fluid induced fault slip could assist extension in the region by reducing the yield strength of the surrounding crust and triggering seismic slip along crustal faults as observed in the Main Ethiopian Rift (Keir et al., 2009; Lapins et al., 2020), in the Magadi-Natron Basin (Tanzania-Kenya) (Lee et al., 2016), in the Asal Rift (Djibouti) (Doubre & Peltzer, 2007), and along the magmatic rifted margin of the Red Sea (Blanchette et al., 2018). Deep seismicity in the Magadi-Natron Basin generated by tectonic degassing of mantle-derived CO_2 highlights the deep section of steep rift-parallel border faults (Lee et al., 2016), similar to what we observed in the Dergaha graben.

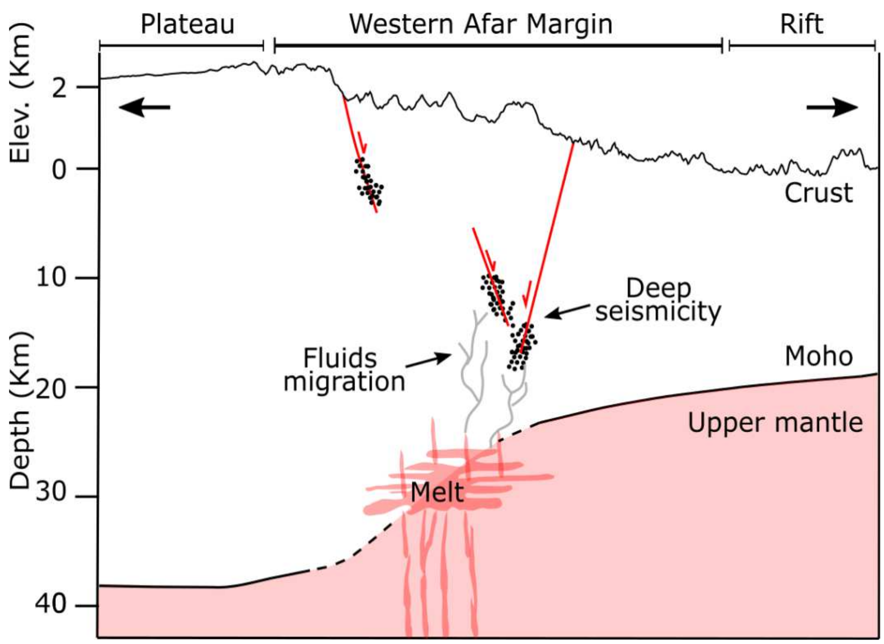

Figure 6 – Simplified sketch showing the interpretation and proposed mechanism controlling the deep seismicity below the Dergaha graben. We interpret deep seismic activity along rift border faults to be induced by magma migration or the release of fluids such as mantle derived CO_2.

7. Conclusion

In this study, we provided new observations of the fault activity across the NWAM. We located 673 during the time period between 20 March 2018 and 30 April 2018, covering the seismic sequence of March 2018, east of Mekele. The sequence started on 24 March

2018 with a M_L 5.3 earthquake rupturing the deep portion (15-30 km) of tens of kilometers-long crustal faults in the Dergaha graben, where other deep seismic sequences occurred in the past. During the seismic sequence, major west-dipping and minor conjugate east-dipping crustal faults activated accommodating an extension oriented ~EW, consistent with a tectonic regime of the area inferred from other seismic and structural observation in previous studies (Illsley-Kemp et al., 2018; Zwaan et al., 2020b). Deep seismicity focuses in a crust characterized by high Vp/Vs ratios and slow seismic velocities which could indicate the presence of partial melt or other fluids (Hammond et al., 2011; Korostelev et al., 2015; Chambers et al., 2019).

Our results support the hypothesis that extension is still ongoing in the NWAM and provide new constrains on the kinematics of previously poorly investigated areas of the margin, especially the marginal grabens. However, we also suggest that extension in the region near the Dergaha graben is accompanied by fluid induced faulting in the lower crust as indicated by the deep seismicity, presence of hot springs, and by independent geophysical and geological evidences of partial melt beneath Dergaha (Figure 6) (Barberi et al., 1972a; Hammond et al., 2011; Korostelev et al., 2015; Chambers et al., 2019; Tortelli et al., 2020). Such evidences could thus suggest that partial melt may play an important role in influencing the fault activity at the rift margins during incipient break-up in Northern Afar.

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http://www.fdsn.org/networks/detail/YP_2017/). The data will become fully open access with the publication of this manuscript, or once the 3-year embargo period finishes at the end of 2021, whichever is sooner. We thank the regional authorities of the Afar, Tigray and Amhara states for their administrative support. We also thank the wider staff body at the IGSSA of Addis Ababa University and the Centre Français d'Etudes Ethiopiennes (CFEE, USR3117) for the support in Ethiopia.

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