

# Rift Focussing and Magmatism During Late-Stage Rifting in Afar, Ethiopia

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## Key Points:

- From Sentinel-1 InSAR and GNSS observations, we resolve 3D average surface velocities from 2014-19 across the whole Afar rift
- Rift focusing increases with rift maturity, with distributed extension in southern Afar, and localised extension in north and central Afar
- We observe surface deformation related to magmatism at several volcanic centres including Dallol, Erta 'Ale, Nabro, and Dabbahu-Manda-Hararo

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**Abstract**

Processes that facilitate the transition between continental rifting and sea-floor spreading remain unclear. Variations in the spatial distribution of extension through Afar and into the Red Sea are indicative of temporal evolution of the rift. We develop a time series of Sentinel-1 interferometric synthetic aperture radar (InSAR) observations of ground deformation covering the whole Afar Rift from 2014-2019, to study the distribution of extension across all magmatic segments. By incorporating GNSS observations, we resolve 3D average velocities in the vertical, rift-perpendicular, and rift-parallel directions. Results show the spatial distribution of long-term plate motions over the rift, as well as deformation at individual volcanic centres, including Dallol, Nabro, and Erta 'Ale. We find that in northern and central Afar, the majority of extension is accommodated within  $\pm 15$ -30 km of magmatic spreading centres. In southern Afar, near the Nubia-Arabia-Somalia triple-junction, extension is distributed over 90-180 km, which may indicate an increase in rift focussing with rift maturity. We also observe rapid surface uplift and rift-perpendicular extension at the Dabbahu-Manda-Hararo segment with velocities of  $33 \pm 4$  mm/yr and  $37 \pm 4$  mm/yr respectively. These are higher than the background extension rate of 18-20 mm/yr, but have decreased by 55-70 % since 2006-10. The data suggests that this is due to an on-going long-lived response to the 2005-10 rifting episode, with potential continued processes below the segment including a lower-crustal viscous response and magma movement. Continued long-term observations of surface deformation provide key constraints on tectono-magmatic processes in Afar.

**1 Introduction**

Magma plays a significant role in accommodating the final stages of continental breakup and the transition into early sea-floor spreading, and the Afar region of Ethiopia is uniquely placed to allow the observation of these processes sub-aerially (e.g. Ebinger, 2005; Kendall et al., 2005; Wright et al., 2012). Extensional strain in Afar is concentrated onto elongate rifting segments (Ebinger & Casey, 2001) which are maintained by rifting episodes that include effusive eruptions and dyking (Wright et al., 2006). Magmatic intrusions at these spreading segments produce time-dependent surface deformation, observable using time series of interferometric synthetic aperture radar (InSAR). These long time series can help separate surface deformation related to magma movement and viscoelastic relaxation, and have been used to constrain, and highlight the importance of viscous rheology in late-stage rifting (Pagli et al., 2014; J. Hamlyn et al., 2018).

**1.1 Regional Setting**

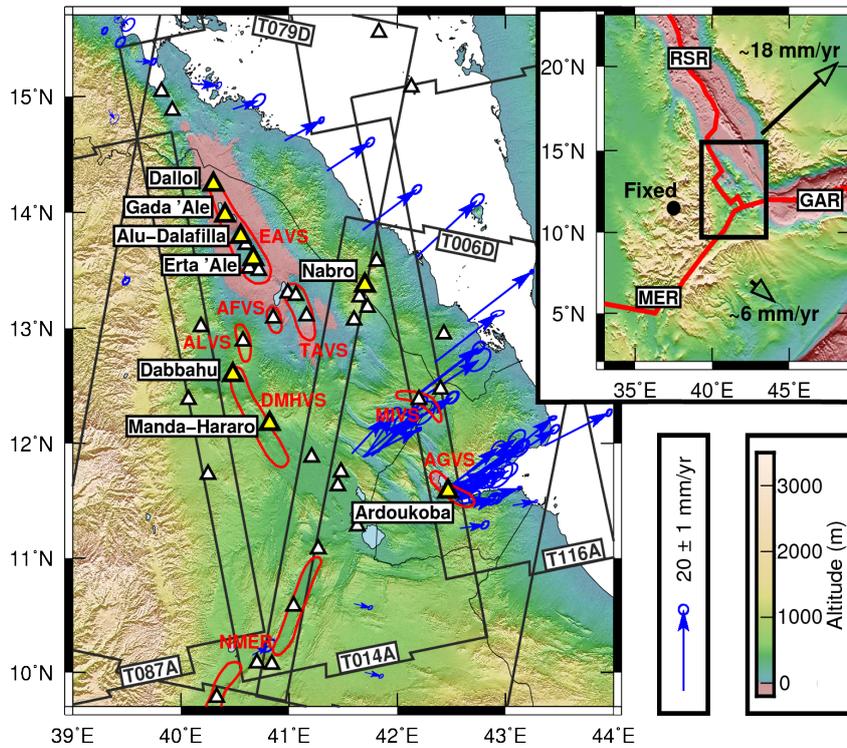
Upwelling of a mantle plume initiated rifting in Afar around 30 Ma with abundant flood-basalt volcanism, which has evolved into the ridge-ridge-ridge triple junction observed in Afar today (Wolfenden et al., 2004; Furman et al., 2006; Hammond et al., 2013). Relative to the Nubian Plate, the Arabian Plate is moving at a rate of 18-20 mm/yr to the NE (McClusky et al., 2010; ArRajehi et al., 2010), accommodated by the opening of the Red Sea Rift (RSR); while the Somalian Plate is moving to the SE at  $\sim 6$  mm/yr (Saria et al., 2014), accommodated by the Main Ethiopian Rift (MER) which is the northernmost segment of the larger East African Rift.

The crust beneath Afar is significantly thinned in comparison to the surrounding Ethiopian highlands and MER. Crustal thicknesses range from 20-45 km in the Ethiopian plateau, 18-30 km in central Afar, and 15-20 km in northern Afar (Tiberi et al., 2005; Bastow & Keir, 2011; Hammond et al., 2011; Lavayssière et al., 2018). Low seismic velocities indicate partial melt within the crust (Gallacher et al., 2016), particularly below volcanic segments in Afar (Stork et al., 2013; Hammond, 2014; Hammond & Kendall, 2016). Seismicity in the upper and lower crust along the Erta 'Ale volcanic segment (EAVS)

61 also indicates the presence of melt below the Erta 'Ale and Alu-Dalafilla volcanic centres  
 62 (Ilsley-Kemp et al., 2018).

63 Active volcanism in Afar is largely concentrated within discrete rifting segments.  
 64 The EAVS is the immediate on-land expression of the RSR. Erta 'Ale volcano on the EAVS  
 65 is host to an lava lake with recent overflows in 2010 (Field et al., 2012; Barnie, Oppen-  
 66 heimer, & Pagli, 2016) and 2017, where a flank eruption indicated the presence of a shal-  
 67 low magma body at  $\sim 1$  km depth (Moore et al., 2019). At Gada 'Ale, magma withdrawal  
 68 and normal faulting caused subsidence from 1993-1996 (Amelung et al., 2000), and a dyke  
 69 intrusion fed from a magma chamber 2-3 km below Dallol was detected in 2004 (Nobile  
 70 et al., 2012). The 2008 eruption at Alu-Dalafilla was sourced from a  $\sim 1$  km deep axis-  
 71 aligned reservoir and a magma chamber at  $\sim 4$  km depth (Pagli et al., 2012).

72 The largest recent volcano-tectonic rifting episode in Afar occurred from 2005-10  
 73 on the Dabbahu-Manda-Hararo volcanic segment (DMHVS) (Barnie, Keir, et al., 2016).  
 74 The initial dyke in September 2005 ruptured the whole 60 km long segment, and intruded  
 75  $2.4\text{-}2.6$  km<sup>3</sup> of magma over  $\sim 2$  weeks (Wright et al., 2006). Seismicity indicates that  
 76 this dyke initiated beneath the Dabbahu and Gabho volcanoes at the northern end of



**Figure 1.** The Afar Rift with white triangles indicating Holocene volcanoes and key volcanoes highlighted in yellow. Simplified volcanic segments (VS) are shown in red: AFVS - Afdera, ALVS - Alayta, AGVS - Asal-Ghoubbet, DMHVS - Dabbahu-Manda-Hararo, EAVS - Erta 'Ale, MI - Manda-Inakir, NMER - Northern Main Ethiopian Rift, TAVS - Tat 'Ale. A subset of GNSS velocity vectors with 95% confidence error ellipses (blue arrows) from (King et al., 2019) show the long-term plate motions. Grey box outlines show the Sentinel-1 coverage from 3 ascending (T014A, T087A, T116A) and 2 descending (T006D, T079D) tracks. Inset map shows the relative movement of the Arabian and Somalian plates to the Nubian plate, with plate boundaries from Bird (2003). RSR - Red Sea Rift, GAR - Gulf of Aden Rift, MER - Main Ethiopian Rift.

77 the DMHVS, before focussing on the segment centre (Ayele et al., 2009). 13 subsequent  
 78 dykes were emplaced between 2006-2010, drawing comparisons to the 1975-1984 Kraffa  
 79 rifting episode where extension in both settings is accommodated by magmatic intru-  
 80 sions (Hamling et al., 2010; Ferguson et al., 2010; Wright et al., 2012; Barnie, Keir, et  
 81 al., 2016). Throughout the rifting episode there was an ongoing post-rifting response to  
 82 the initial 2005 intrusion, which was modelled using magmatic sources in the upper crust,  
 83 and the inflation of a deeper source at the segment centre, as viscoelastic relaxation alone  
 84 was insufficient to reproduce geodetic observations (Grandin et al., 2010; Hamling et al.,  
 85 2014).

86 The Manda-Inakir (MIVS) and Asal-Ghoubbet (AGVS) volcanic segments in south-  
 87 ern Afar have also shown recent activity with the 1928-1929 eruption of Kammourta vol-  
 88 cano in the MIVS (Audin et al., 1990), and the 1978 eruption at Ardoukoba volcano in  
 89 the AGVS (Allard et al., 1979; Tarantola et al., 1979). Cattin et al. (2005) identified a  
 90 post-rifting response in the AGVS to the 1978 eruption, with rift-perpendicular veloc-  
 91 ities decaying back to the long-term spreading rate 6-8 years after the eruption.

92 The Nabro Volcanic Range (NVR) is an off-axis volcanic-centre that sits within the  
 93 Danakil Block, a rigid micro-plate which is moving away from Nubia with extension in  
 94 Afar (Eagles et al., 2002). The NVR has hosted explosive eruptions at Dubbi volcano  
 95 in 1861 (Wiert & Oppenheimer, 2000), and Nabro volcano in 2011 (J. E. Hamlyn et al.,  
 96 2014; Goitom et al., 2015). Persistent subsidence was detected at Nabro for  $> 1$  year fol-  
 97 lowing the 2011 eruption which was attributed to viscoelastic relaxation around a magma  
 98 chamber at  $6.4 \pm 0.3$  km depth (J. Hamlyn et al., 2018).

## 99 1.2 InSAR Velocity Methods & Applications in Afar

100 Methods for extracting a one-dimensional line-of-sight (LOS) displacement time  
 101 series from a sequence or network of interferograms are well established. These small-  
 102 baseline algorithms utilise multiple interferogram connections between acquisition dates  
 103 to produce a more robust estimate of the incremental LOS ground displacement than  
 104 a simple stacking of interferograms (Berardino et al., 2002; Lanari et al., 2007; Biggs et  
 105 al., 2007). This methodology may be automated by software packages such as  $\Pi$ -RATE  
 106 (Wang et al., 2012, and references therein), StaMPS (Hooper et al., 2012), GIAN-T (Agram  
 107 et al., 2013), and LiCSBAS (Morishita et al., 2020) in order to obtain linear displace-  
 108 ment rates and uncertainties at each pixel, while reducing the effect of common sources  
 109 of error such as atmospheric and orbital delays. These methods may be supplemented  
 110 by additional filtering to remove the atmospheric phase screen (APS) from the time se-  
 111 ries, by firstly high-pass filtering in time, then low-pass filtering in space to calculate the  
 112 APS, which is then removed from the time series (e.g. Sousa et al., 2011). The conven-  
 113 tional method for APS calculation relies on the assumption that the atmospheric delay  
 114 is not temporally correlated. With recent SAR missions providing shorter satellite re-  
 115 visit times, this assumption may no longer be appropriate. Previous studies have pro-  
 116 posed improvements to the APS correction, including applying a global weather model  
 117 (e.g. Jung et al., 2013), and accounting for the temporal variance of a pixel (e.g. Liu et  
 118 al., 2011; Refice et al., 2011).

119 The only previous InSAR derived velocity map covering the whole Afar region was  
 120 developed by Pagli et al. (2014), who used  $\Pi$ -RATE to produce a displacement time se-  
 121 ries between 2005-10. After removing large deformation steps associated with the DMH  
 122 dyke intrusion events, Pagli et al. (2014) smoothed the time series by removing the APS,  
 123 employing consistent Gaussian temporal and Butterworth spatial filters. Pagli et al. (2014)  
 124 extracted 3D (east, north, vertical) velocities from ascending and descending LOS and  
 125 Global Navigation Satellite Systems (GNSS) observations on a 10-20 km resolution mesh  
 126 following the method of Wang and Wright (2012). Surface velocities between 2005-10  
 127 from Pagli et al. (2014) showed a long-term plate spreading rate of 15-20 mm/yr in East-

ern Afar (relative to a stable Nubian plate), and large extension rates of  $\sim 100$  mm/yr at Dabbahu associated with the background response during the 2005-10 DMH rifting episode. Other InSAR velocity maps within Afar have focussed on individual rift segments, such as the DMHVS (Hamling et al., 2014) from 2006-10, the AGVS from 1997-2005 (Dobre & Peltzer, 2007), and around the Tendaho Graben from 2004-10 (Temtime et al., 2018).

In this study, we make use of the high temporal and spatial resolution data from the Sentinel-1 satellite to extract surface velocities from 2014-19 across the whole of the Afar region. We develop and apply a small baseline methodology with spatial and temporal variance weighted filtering to improve the removal of the APS, reference the data to a stable Nubia GNSS reference frame, and calculate 3D (vertical, rift-perpendicular horizontal, and rift-parallel horizontal) velocities.

## 2 Data Processing and Time Series Methods

### 2.1 Sentinel-1 Data

We use Sentinel-1A/B acquisitions from ascending tracks 14 (014A), 87 (087A), and 116 (116A), and descending tracks 6 (006D) and 79 (079D) between October 2014 and August 2019. For processing efficiency, we divide each track into 12 ( $\sim 250 \times 250$  km) frames (Table S1). We produce a network of geocoded unwrapped interferograms for each frame from single-look complex (SLC) images of each date using the LiCSAR software (González et al., 2016; Lazecky et al., in review.), which automates the mass production of interferograms using GAMMA (Werner et al., 2000). To reduce noise and data size, we multi-look the SLCs at 20:4 range to azimuth looks, equating to  $\sim 100 \times 100$  m pixel size. We apply a topographic correction using an SRTM (Shuttle Radar Topography Mission) 3-arc-second ( $\sim 90$  m resolution) DEM (Digital Elevation Model) (Farr & Kobrick, 2000), filter the interferograms using a power spectrum filter (Goldstein et al., 1998), and unwrap using SNAPHU (Chen & Zebker, 2002). We manually quality check the interferogram network for each frame to remove interferograms with decorrelation, co-registration, or obvious unwrapping errors. We ensure that each epoch is connected to the network by a minimum of 3 interferograms by creating new interferograms as needed. Each interferogram is referenced to the mean value, excluding areas of deformation around volcanic centres.

To mitigate for atmospheric phase delay for each interferogram we compare the effectiveness of corrections from a linear trend of phase with elevation over the whole frame (e.g. Elliott et al., 2008), and the GACOS atmospheric model (e.g. Yu et al., 2017, 2018). For a linear phase-elevation trend correction, the mean root-mean-square (RMS) misfit for all 12 frames is reduced by 2.9 mm in comparison to the mean RMS misfit for all frames with no atmospheric correction. The GACOS correction gives a reduction in mean RMS misfit of 4.2 mm, but increases the RMS misfit in 29 % of interferograms. To reduce this we follow an approach similar to Shen et al. (2019), scaling the GACOS correction for each interferogram in order to minimise the resulting RMS misfit. This improves the atmospheric correction further, producing a reduction in mean RMS misfit of 5.7 mm (see Figure S1). In order to account for any residual topographic atmospheric signal in each frame, we remove a linear trend of phase with elevation from each epoch, after time series filtering.

### 2.2 Time Series

We apply an SBAS style methodology to invert for the displacement time series at each pixel in the frame, using all interferograms where a pixel is coherent. We assess the spatial and temporal variance of the time series by firstly, filtering using a Laplacian filter with a temporal width of 3 epochs and scale factor of 3, then calculating the RMS

177 misfit from this trend at each pixel for every epoch. We calculate the spatial distribu-  
 178 tion of RMS misfit from the time series misfits at each point, and the temporal distri-  
 179 bution of RMS misfit from the misfits of all pixels at each epoch (see Figure S2). To re-  
 180 solve the RMS misfit value of each pixel at every epoch, we scale the spatial RMS mis-  
 181 fit map to the temporal RMS misfit value at each epoch (see Supplementary Materials).  
 182 We use these error estimates to provide weights during time series filtering, and in the  
 183 inversion of filtered displacement time series for average velocities.

184 In order to reduce the remaining APS in the displacement time series, we filter the  
 185 time series using a high-pass temporal and a low-pass spatial filter to produce the APS,  
 186 which we then remove from the time series. To calculate a low-pass temporal filter, we  
 187 apply a weighted linear trend with a fixed temporal width of 1 year centred on each point.  
 188 To calculate the weighting for the local trend, we use the RMS misfit as a proxy for stan-  
 189 dard error, and convert the RMS misfit values into weights using the Bi-Square function  
 190 where no weight is given to RMS values that exceed 6 standard deviations of the local  
 191 misfits (e.g. Cleveland & Devlin, 1988). We also scale these weights by their temporal  
 192 distance from the target epoch of the local time series (see Supplementary Materials).  
 193 Having calculated the low-pass temporal filter, we remove it from the time series to cre-  
 194 ate a high-pass temporal filter. We then apply a Gaussian spatial filter with a half-width  
 195 of  $\sim 2$  km in order to resolve the APS for each epoch.

196 After we remove the APS, we remove a planar ramp in space and a linear trend  
 197 with height to correct for any remnant long-wavelength and elevation-correlated atmo-  
 198 spheric delay. We later correct for long-wavelength deformation using GNSS observa-  
 199 tions. For each frame, we compute the average velocity at each pixel by inverting for a  
 200 single linear trend through time, allowing for a constant offset. We produce a variance-  
 201 covariance matrix (VCM) for each pixel, treating the temporal variation of the scaled  
 202 RMS misfit as independent errors. By including the VCM in the inversion, we can quan-  
 203 tify the uncertainty of the resulting velocities.

204 De Zan et al. (2015) demonstrate how a potential systematic phase-bias in inter-  
 205 ferograms with decreasing temporal baseline can influence the resulting time series. We  
 206 test the magnitude of this bias by selecting consecutive 12, 24, and 36-day interferograms  
 207 from frame 079D.07694.131313 covering  $\sim 1$  year (see Figure S3). We use a ‘daisy-chain’  
 208 stack approach to resolve the cumulative displacements from the 12, 24, and 36 day un-  
 209 wrapped interferograms between December 2017 and February 2019. Any differences be-  
 210 tween these stacks indicates the presence of phase-bias and/or unwrapping errors. We  
 211 find residual differences between the 12 and 24-day, and 12 and 36-day stacks of up to  
 212 50 mm, and residuals of up to 10 mm between the 24 and 36-day stacks. While this in-  
 213 dicates that the 12-day interferograms are susceptible to a phase-bias, we find that re-  
 214 moving the 12-day interferograms from the network effects our displacement time series  
 215 by  $< 5$  mm per epoch, and our average velocities by  $< 1$  mm/yr. While we are not able  
 216 to account for any bias in the 36-day interferograms, Ansari et al. (2020) indicate that  
 217 the velocity bias is small in comparison to 12-day interferograms.

### 218 **2.3 3D Velocities**

219 We tie frames together within their respective tracks by sub-sampling the InSAR  
 220 data points to a  $5 \times 5$  km spacing in the overlap between frames, and  $10 \times 10$  km spac-  
 221 ing elsewhere, then solving for and removing a planar ramp for each frame that minimises  
 222 residuals in the along-track frame overlap regions. Removing these ramps does not bias  
 223 the results as long-wavelength signals are later corrected using GNSS. In the frame over-  
 224 lap region, we use the mean value of LOS velocity for each point. We find that using lin-  
 225 ear ramps to combine frames within tracks produces the fewest boundary artefacts when  
 226 compared to using a single offset value calculated from the median value in the frame  
 227 overlap region, or solving for a 2D quadratic function for each frame. Boundary arte-

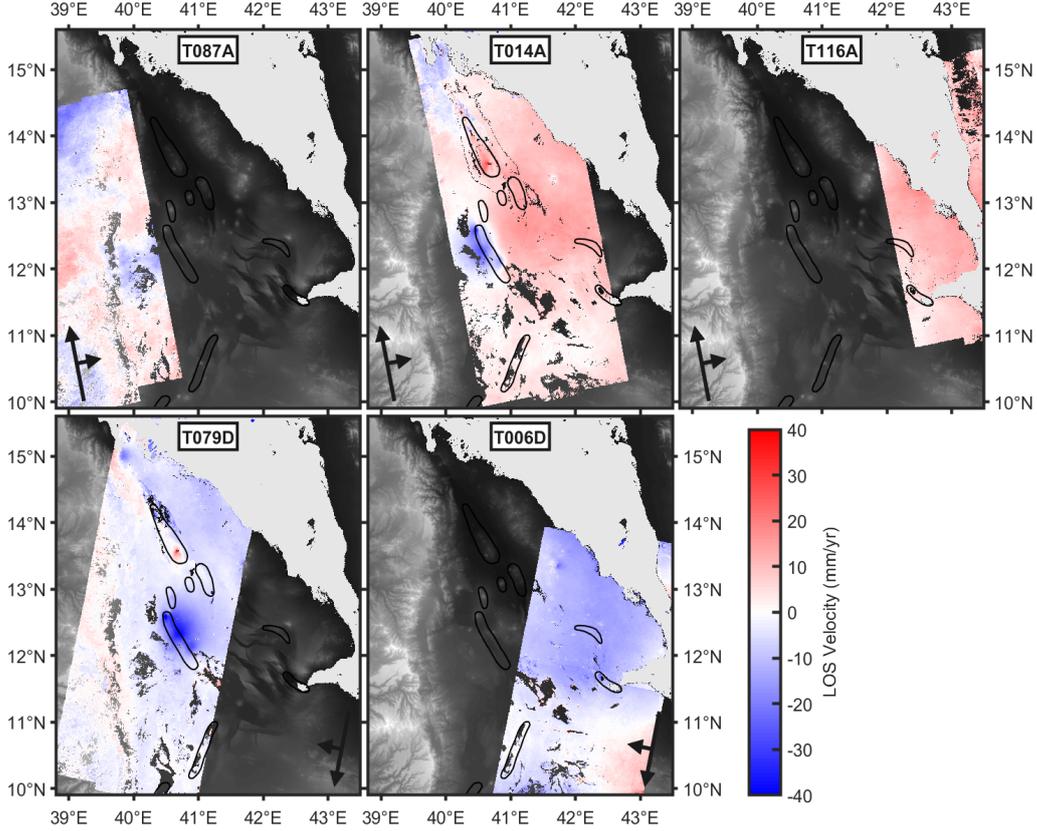
228 facts within tracks can occur due to differences between frames in time series length, the  
 229 variation in acquisition dates used, relative weighting during time-series filtering, and  
 230 orbital ramp removal. Although in principle it would be possible to only process and use  
 231 interferograms that cover the whole along-track extent of the study region, this would  
 232 require excluding several epochs where data were not acquired over the whole area, re-  
 233 sulting in truncated time series.

234 To reference the LOS velocity in each track to a stable Nubian plate, we use a net-  
 235 work of 105 GNSS stations in the Afar region to characterise long-wavelength plate mo-  
 236 tions. The data are a subset of the GeoPRISMS community velocity field for East Africa  
 237 in a Nubia-fixed International Terrestrial Reference Frame (ITRF2014) (King et al., 2019).  
 238 We remove 32 stations in central Afar where the velocities are dominated by the ground  
 239 motions associated with the 2005-10 DMH rifting episode. As the resulting network is  
 240 sparse, with the majority of stations concentrated in Eastern Afar and few points on the  
 241 Nubian and Somalian plates; we add 17 additional fabricated GNSS stations on the sta-  
 242 ble Nubian plate, with an assumed zero velocity (with uncertainties of  $\pm 1$  mm/yr and  
 243  $\pm 2$  mm/yr in the horizontal and vertical components), to help constrain the velocity  
 244 field where data are sparse. We project East and North GNSS horizontal velocities into  
 245 the rift-perpendicular (e.g. Hamling et al., 2014), and rift-parallel directions, oriented  
 246 at  $61^\circ\text{N}$  and  $-29^\circ\text{N}$  respectively.

247 From this network, we interpolate a smooth GNSS velocity field in the rift-perpendicular  
 248 and rift-parallel directions over the whole Afar region at  $100 \times 100$  m grid spacing (Fig-  
 249 ure S4) using the natural neighbour algorithm (e.g. Boissonnat & Cazals, 2002). As the  
 250 additional pseudo-observations define where this interpolated field reaches zero veloc-  
 251 ity, we selected these points such that they are on the Nubian plate, away from the rift  
 252 border faults. We are not concerned with the precise locations, as where the interpolated  
 253 velocity field reaches zero does not significantly influence the data within the Afar from  
 254 the Rift. We estimate the error in the interpolated velocities by systematically remov-  
 255 ing each GNSS station from the network, interpolating new velocity fields in the rift-perpendicular  
 256 and rift-parallel directions from the reduced network, then calculating the residual be-  
 257 tween the interpolated fields and the GNSS observation. We take the standard devia-  
 258 tion of these residuals as the error in the rift-perpendicular and rift-parallel GNSS ve-  
 259 locity field.

260 We sub-sample the InSAR LOS track velocities as previously, then extract points  
 261 where there are ascending, descending, and interpolated GNSS data. We also mask points  
 262 around the active rift segments so that volcanic ground deformation does not interfere  
 263 with the referencing to the long-term plate motions. Using these points, we solve for the  
 264 3D velocity (rift-perpendicular, rift-parallel, vertical) at each point and a residual 2D (East,  
 265 North) quadratic function for each track. We remove the respective quadratic from each  
 266 InSAR track to resolve LOS velocity in a stable Nubia reference frame. The resulting  
 267 LOS velocities and standard deviations are shown in Figures 2 and S5 respectively.

268 In order to resolve a full 3D velocity field (vertical, rift-perpendicular horizontal,  
 269 rift-parallel horizontal) at  $100 \times 100$  m resolution, we use the smooth rift-parallel GNSS  
 270 field to provide a constraint on the rift-parallel velocity at each point, as the rift-parallel  
 271 velocities are small in comparison to the rift-perpendicular and vertical velocities. We  
 272 include this constraint with the ascending and descending LOS InSAR observations to  
 273 calculate 3D velocities at each point using a least-squares inversion (Wright et al., 2004;  
 274 Hussain et al., 2016; Weiss et al., 2020). The decomposition of InSAR LOS velocities ( $L$ )  
 275 into rift-perpendicular ( $H1$ ), rift-parallel ( $H2$ ), and vertical ( $Z$ ) velocities is shown in  
 276 Equation 1 for the incidence angle ( $\theta$ ), satellite heading ( $\alpha$ ), rift angle from North ( $\phi$ ).  
 277 We weight the inversion and resolve uncertainties by including a diagonal VCM using  
 278 the previously calculated variance at each point.



**Figure 2.** LOS average velocities over the Afar region between November 2014 and August 2019 from Sentinel-1 tracks T087A, T014A, T116A, T079D, and T006D. LOS velocities are referenced to a stable Nubia reference frame using long-term plate motions from the regional GNSS network (King et al., 2019). Arrows indicate the track look directions, and the volcanic segments are shown as black outlines.

Results (Figure 3), discussed in Section 3, show both the long-term plate motion and surface deformation associated with magmatism. As we use the interpolated GNSS velocity field as an additional constraint in the rift-parallel direction, the resulting rift-parallel error estimates are lower than the rift-perpendicular errors, which we calculate using only the InSAR observations to retain high spatial resolution (see Figure 3).

$$L = [-\sin(\theta)\cos(\alpha + \phi) + \sin(\theta)\sin(\alpha + \phi) - \cos(\theta)] \begin{bmatrix} H1 \\ H2 \\ Z \end{bmatrix} \quad (1)$$

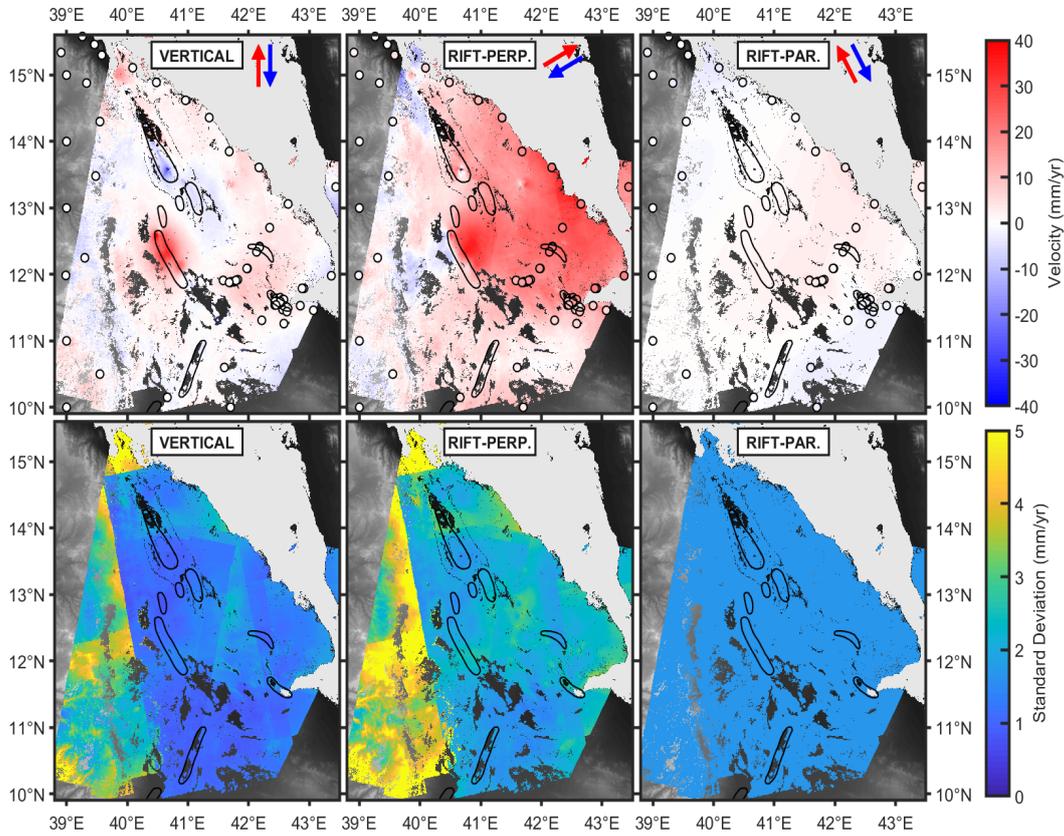
### 3 Key Findings & Discussion

#### 3.1 Plate Motions & Rift Focussing

Our 2014-2019 horizontal velocity maps (Figure 3) show the rift-perpendicular extension over the Afar rift at rates of up to  $25 \pm 5$  mm/yr, with negligible motions in the rift-parallel direction. We also observe the ‘trapdoor’ motion of the Danakil micro-plate relative to the stable Nubian plate (Kidane, 2016), where rift-perpendicular extension in the RSR is gradually transferred into Afar between 13-16°N. Areas of noise up to  $\pm 10$  mm/yr over the Ethiopian highlands region on the Nubian plate, are highlighted in the standard

287 deviation maps shown in Figure 3. The regions of high error in T087A, and the northern-  
 288 most portion of T014A (see Figure S5), are a result of the shorter time series length in  
 289 these regions producing more uncertainty in the long-term velocity estimates. Elsewhere,  
 290 errors of up to  $\pm 5$  mm/yr are likely due to uncorrected atmospheric delays, and arte-  
 291 facts over track boundaries, where we are unable to account for small LOS velocity vari-  
 292 ations between overlapping tracks.

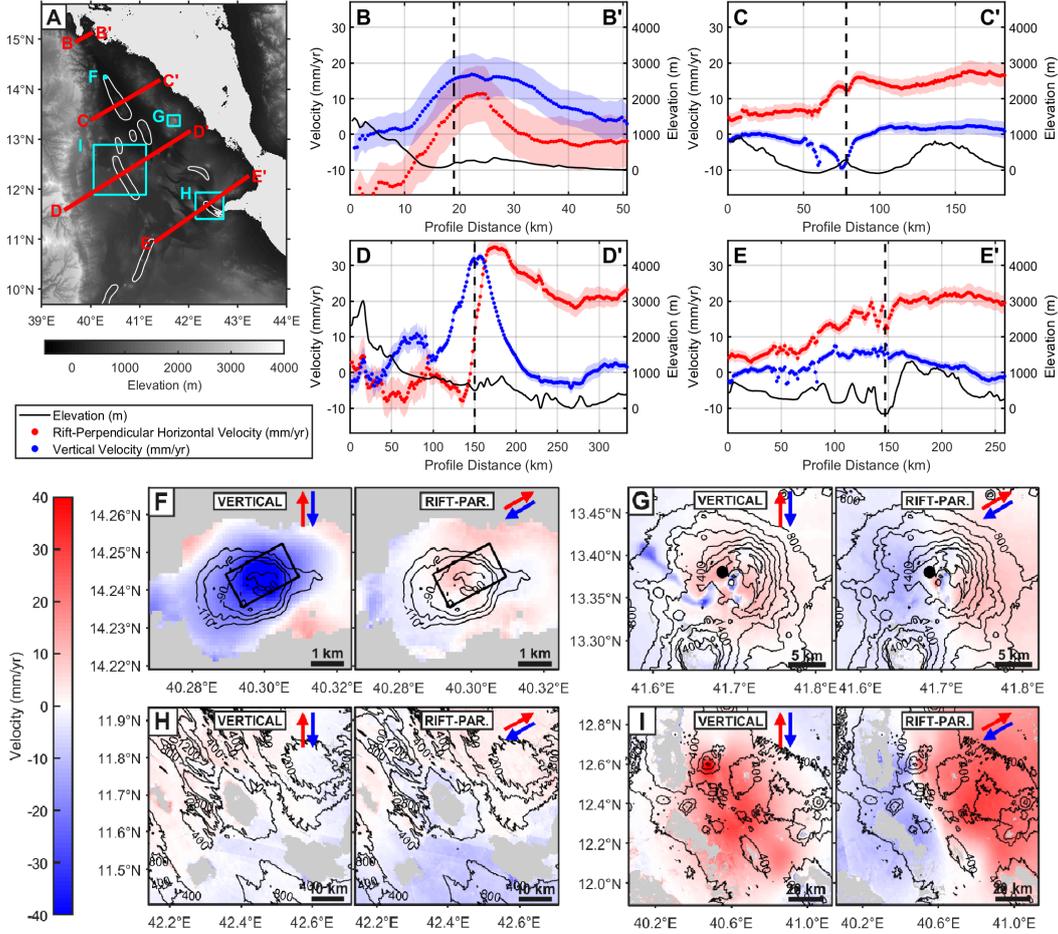
293 Profiles taken across the rift highlight the focussing of extension in Afar. Profiles  
 294 covering the Alid graben, at northern-most tip of the Afar rift (Figures 4B and 5B), show  
 295 that a broad uplift and extensional signal of up to  $\sim 20$  mm/yr is centred within  $\pm 10$ -  
 296 15 km of the rift axis. This may be indicative of deep magmatic intrusion in an area with  
 297 the smallest background extension rates throughout Afar, but comparable to extension  
 298 rates at the active volcanic islands at the southern end of the oceanic RSR (Eyles et al.,  
 299 2018). Profiles traversing the EAVS in the Danakil Depression (Figures 4C and 5C) high-  
 300 light that the majority of extension here is focussed into a region within  $\pm 15$ -20 km of  
 301 the rift axis. We also observe subsidence on the EAVS between the Erta 'Ale and Alu



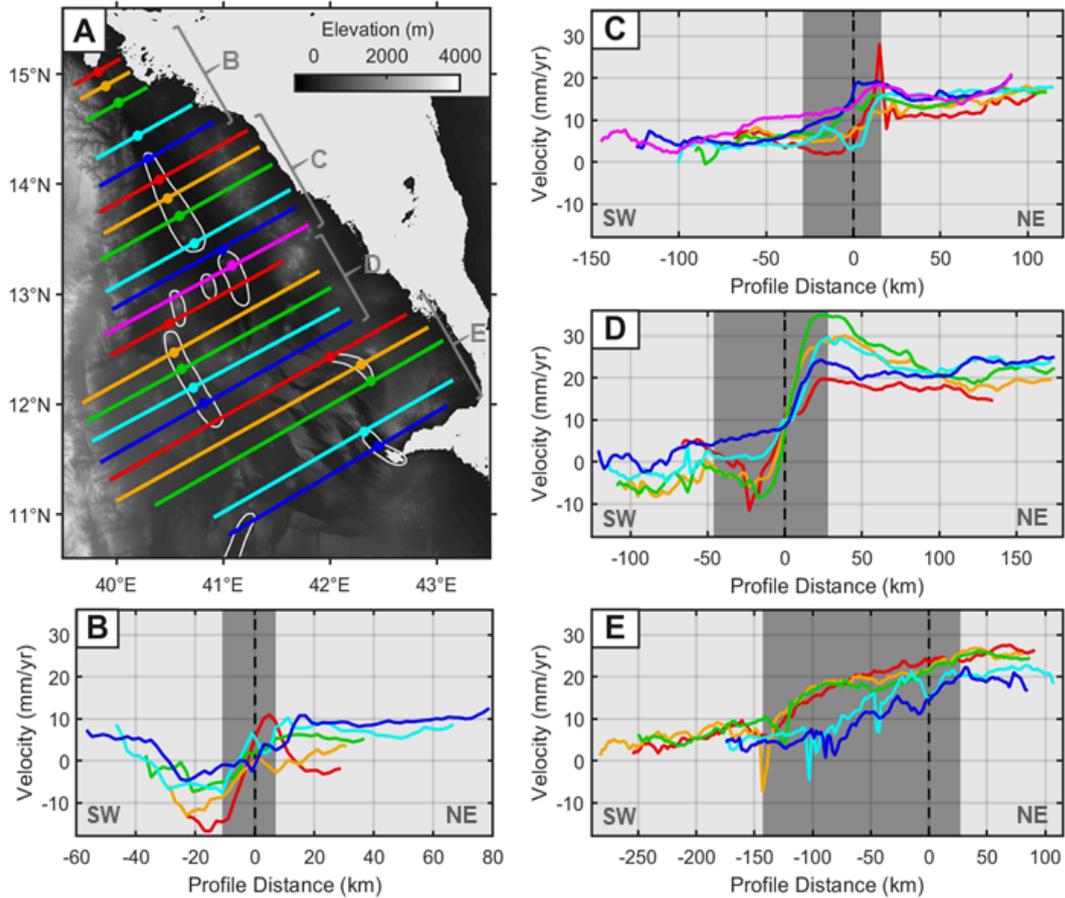
**Figure 3.** Vertical, rift-perpendicular, and rift-parallel average velocities and standard deviation over the Afar region between November 2014 and August 2019. All velocities are referenced to a stable Nubian plate. Vertical velocities are positive upwards, rift-perpendicular velocities are positive to the NE ( $61^\circ\text{N}$ ), and rift-parallel velocities are positive to the NW ( $-29^\circ\text{N}$ ). Standard deviation colour-scale is limited to 5 mm/yr to highlight variation in regions of low variance. Maximum standard deviations are (2 s.f.): 7.2 mm/yr (vertical), 9.5 mm/yr (rift-perpendicular), and 1.7 mm/yr (rift-parallel). GNSS stations are shown as circles with GNSS velocities on the same colour-scale as the InSAR velocities, and volcanic segments as black outlines.

302 Dalafilla volcanoes (Figure 4C), which could be linked to magma withdrawal associated  
 303 with the 2017-19 eruption at Erta 'Ale (Moore et al., 2019). Profiles between the EAVS  
 304 and the DMHVS (Figure 5C) show that extension in this region is shared between the  
 305 ALVS and the TAVS, and focussed to within  $\pm 10$ -20 km of the rift segments.

306 Profiles covering the DMHVS (Figures 4D and 5D) also show that the long-term  
 307 extension is concentrated near the rift-axis, with only small variations in rift-perpendicular  
 308 velocity away from  $\pm 20$ -30 km of the segment centre. Elevated velocities close to the  
 309 segment centre are associated with the 2005-10 DMHVS rifting episode, and are discussed



**Figure 4.** (B-E) Vertical (blue, positive up) and rift-perpendicular (red, positive towards 61°N) velocities over 4 10 km wide cross-rift profiles marked on insert map, covering (B) the northern tip of the Afar triangle, (C) the Erta 'Ale volcanic segment, (D) the Dabbahu-Manda-Hararo volcanic segment (DMHVS), and (E) the Asal-Ghoubbet volcanic segment (AGVS). Black lines show surface elevation along the profiles, with vertical dashed lines indicating the location of the major rift axis on the profile. (F-I) Vertical and rift-perpendicular velocity maps at (F) Dallol volcano, (G) Nabro volcano, (H) the AGVS, and (I) the DMHVS. Velocities in each subset are referenced to the local background mean value, with contours indicating elevation. The location of modelled deformation sources for a 0.9-1.3 km deep sill (Okada, 1985) at Dallol (F, Figure S6) and a 5.5-6.8 km deep point source (Mogi, 1958) at Nabro (G, Figure S7) are shown as black outlines.



**Figure 5.** Map of 21 10 km wide rift-perpendicular velocity (relative to stable Nubia, positive towards 61°N) profiles over the Afar rift (A), with rift segments outlined in white. To help distinguish between profiles, profiles alternate between solid and dashed lines. The velocity profiles cover northern Afar (B), the Erta 'Ale and Tat 'Ale segments (C), the Dabbahu-Manda-Hararo segment (D), and southern Afar (E). The standard deviation of rift-perpendicular velocities varies from  $\pm 2\text{-}7$  mm/yr (see Figure 3). Profile distances are relative to the rift axis, with positive towards the NE. The location of the rift axis is marked by circles on the map (A), and dashed black lines on profiles (B-E). Grey shading on the profiles indicates the region where the majority of rift extension is accommodated.

310 in Section 3.2. Profiles over southern Afar and the AGVS (Figures 4E and 5E) show a  
 311 more distributed pattern of extension with an increase in rift-perpendicular velocities  
 312 80-160 km to the SW of the rift axis, before velocities stabilise at  $\sim 20$  mm/yr on the  
 313 Danakil micro-plate within 10-20 km to the NE of the rift axis. In southern Afar, ex-  
 314 tension between 2014-19 may be largely accommodated by tectonic rather than magmatic  
 315 mechanisms, with strain being distributed across a sequence of horst and graben struc-  
 316 tures.

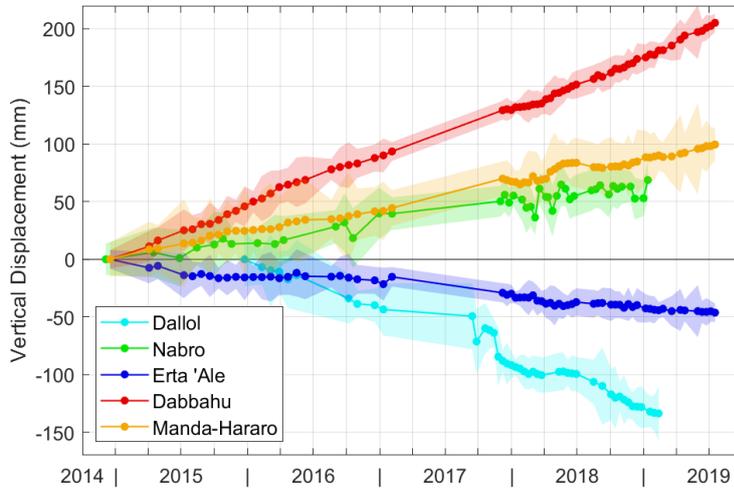
317 Our results indicate that at the more mature segments with active magmatism in  
 318 central and northern Afar, extension is largely focussed to within  $\pm 15\text{-}30$  km of the rift  
 319 axis; while at less mature segments without active magmatism in southern Afar, ex-  
 320 tension may be distributed over a 90-180 km. The broad distribution of strain in south-  
 321 ern Afar is in general agreement with 1992-2010 GNSS observations from Kogan et al.

322 (2012), who suggest that extension along a profile in southern Afar occurs over  $\sim 175$  km.  
 323 Kogan et al. (2012) also suggest that extension becomes more distributed with rift de-  
 324 velopment. In contrast, our results suggest an increase in focussing with rift maturity  
 325 during late-stage continental break-up, in keeping with strain localisation assisting the  
 326 transition into oceanic spreading centres.

### 327 3.2 Magmatic Deformation

328 Figure 4 highlights the localised surface deformation at Dallol (4F) and Nabro (4G)  
 329 volcanoes, and at the DMHVS (4I), where localised deformation, likely associated with  
 330 magma migration, is visible. Figure 4H over the AGVS indicates the lack of magma re-  
 331 lated deformation at this segment between 2014-19. As magmatic deformation may not  
 332 be steady in time, we look at time series for points located in the middle of these cen-  
 333 tres. Time series of vertical displacements at the Dallol, Nabro, Dabbahu, and Manda-  
 334 Hararo volcanic centres show that the deformation is linear through time, indicating that  
 335 the velocities are representative (Figure 6). For Erta 'Ale volcano, we select a point  $\sim 2$  km  
 336 to the north of the summit caldera in order to avoid the step surface deformation asso-  
 337 ciated with a dyke intrusion in January 2017 (Moore et al., 2019). Following this intru-  
 338 sion the Erta 'Ale edifice shows linear subsidence at a rate of  $15 \pm 4$  mm/yr (Figure 6).

339 At Dallol volcano, at the northern end on the EAVS, we observe a high rate of sub-  
 340 sidence of up to  $45 \pm 4$  mm/yr, with negligible horizontal movement. The subsidence  
 341 signal is focussed on the central cone at Dallol. We model this signal using the Markov-  
 342 Chain Monte-Carlo Geodetic Bayesian Inversion Software (GBIS) (Bagnardi & Hooper,  
 343 2018). For the T014A and T079D LOS deformation between 2014-19, we test source ge-



**Figure 6.** 2014-19 time series of vertical displacements (uplift positive) with 1 standard deviation estimates, at 5 deforming volcanic centres in Afar. The points used for the time series are representative of the whole edifice deformation and are positioned at the centre of the volcanic edifice; with the exception of Erta 'Ale where the point selected is  $\sim 2$  km North of the summit lava lake in order to avoid surface deformation associated with the Jan 2017 dyke intrusion event (Moore et al., 2019). Coordinates of points used for each volcanic centre: Dallol -  $40.3^{\circ}\text{E}/14.243^{\circ}\text{N}$ , Nabro -  $41.685^{\circ}\text{E}/13.38^{\circ}\text{N}$ , Erta 'Ale -  $40.65^{\circ}\text{E}/13.62^{\circ}\text{N}$ , Dabbahu -  $40.48^{\circ}\text{E}/12.58^{\circ}\text{N}$ , Manda-Hararo -  $40.88^{\circ}\text{E}/12.13^{\circ}\text{N}$ .

344 ometries including a point pressure source (Mogi, 1958), a planar dislocation (Okada,  
 345 1985), and a penny-shaped crack (Fialko et al., 2001). We find that a  $\sim 1 \times 2$  km hor-  
 346 izontal sill at 0.9-1.3 km depth with  $\sim 0.27$  m of contraction gives the lowest residual  
 347 RMS misfit (Figure S6). This is in agreement with Nobile et al. (2012) who inferred the  
 348 presence of a deflating magma body at 1.5-3.3 km depth beneath Dallol between 2004-  
 349 06.

350 At Nabro volcano, we observe edifice uplift and extension at rates of up to  $12 \pm 3$  mm/yr,  
 351 combined with the subsidence of lava flows from the 2011 eruption (J. E. Hamlyn et al.,  
 352 2014), and a highly localised subsidence and contraction signal of up to  $14 \pm 3$  mm/yr  
 353 at the centre of the Nabro caldera. This uplift of the Nabro edifice shows a change from  
 354 InSAR observed subsidence of 150-200 mm/yr from 2011-12, after the 2011 eruption (J. Ham-  
 355 lyn et al., 2018). As our vertical displacement time series (Figure 6) indicates that the  
 356 uplift at Nabro is linear between 2014-19, we suggest that this post-eruption edifice sub-  
 357 sidence must have stopped between 2012-14. We model T006D, T014A, and T079D LOS  
 358 observations at Nabro volcano between 2014-19 using a point pressure source (Mogi, 1958),  
 359 and penny-shaped crack (Fialko et al., 2001) using GBIS (Bagnardi & Hooper, 2018).  
 360 Figure S7 shows the optimal Mogi source at 5.5-6.8 km depth with a volume increase  
 361 of  $7-11 \times 10^6$  m<sup>3</sup>. The location of this source is in agreement with the magma chamber  
 362 at  $6.4 \pm 0.3$  km depth inferred by (J. Hamlyn et al., 2018) between 2011-12, indicating  
 363 re-charge of the melt storage below Nabro volcano.

364 After the initial 2005 intrusion at the DMHVS, background uplift and rift-perpendicular  
 365 extension continued throughout the 2005-10 rifting episode at rates of up to 80-240 mm/yr  
 366 and 110-180 mm/yr respectively, from 2006-10 at the segment centre (Pagli et al., 2014;  
 367 Hamling et al., 2014). We show that this uplift and extension is ongoing between 2014-  
 368 19 at average rates of  $33 \pm 4$  mm/yr and  $37 \pm 4$  mm/yr respectively (Figure 4c,h). Our  
 369 vertical velocities also show that an area of  $\sim 20$  mm/yr subsidence from 2006-10 at the  
 370 southern end of the DMHVS ( $40.9^\circ\text{E}/12.1^\circ\text{N}$ ) uplifts at an average rate of  $18 \pm 4$  mm/yr  
 371 from 2014-19. This decaying post-rifting response to the initial 2005 intrusion may be  
 372 indicative of continued magma movement beneath the DMHVS and/or a time-dependant  
 373 viscous response due to a more ductile rheology generated from repeated intrusions at  
 374 the rift segment.

## 375 4 Conclusions

376 We develop Sentinel-1 displacement time series at  $100 \times 100$  m resolution between  
 377 2014-19 over 3 ascending and 2 descending tracks, covering the whole Afar rift. We im-  
 378 plement a RMS misfit weighted APS correction to clean the time series, and produce av-  
 379 erage velocity maps for each frame. Using GNSS observations of long-term plate motions,  
 380 we reference the InSAR velocities to the stable Nubian plate, and convert LOS to 3D  
 381 velocities (vertical, rift-perpendicular, rift-parallel).

382 We are able to resolve deformation at individual volcanic centres, with subsidence  
 383 of  $45 \pm 4$  mm/yr at Dallol volcano, consistent with the deflation of a shallow sill at 0.9-  
 384 1.3 km depth. We also show that edifice uplift at Nabro volcano of  $12 \pm 3$  mm/yr is sourced  
 385 from a magma chamber at 5.5-6.8 km depth, consistent with the source of post-eruption  
 386 subsidence observed between 2011-12 (J. Hamlyn et al., 2018).

387 Pagli et al. (2014) and Hamling et al. (2014) identify vertical and rift-perpendicular  
 388 horizontal surface velocities between 2006-10 of 80-240 mm/yr and 110-180 mm/yr, re-  
 389 spectively associated with a background post-rift response to the initial 2005 dyking episode  
 390 at the DMHVS. We show that this response is ongoing between 2014-19, but at lower  
 391 rates of  $33 \pm 4$  mm/yr and  $37 \pm 4$  mm/yr respectively. We suggest that this  $\sim 15$  year  
 392 response to the 2005 dyke intrusion is indicative of continued magma movement and/or  
 393 time-dependant viscous processes within the crust below the rift segment.

394 We resolve the long-term motion of the Danakil micro-plate with rift-perpendicular  
 395 velocities of up to  $25 \pm 5$  mm/yr, with negligible motions in the rift-parallel direction.  
 396 From cross-rift profiles, we find that extension is largely focussed to within  $\pm 15$ -30 km  
 397 of the rift-axis on the active magmatic segments in northern Afar, while strain in south-  
 398 ern Afar is distributed across 90-180 km of the rift. This trend of increased focussing of  
 399 extension with rift maturity is in contrast to the trend suggested by Kogan et al. (2012),  
 400 but consistent with strain localisation assisting the transition into oceanic spreading cen-  
 401 tres.

## 402 Acknowledgments

403 All Sentinel-1 data is sourced from the European Union Copernicus Programme. We per-  
 404 form data processing on the JASMIN facility, operated by the Centre for Environmen-  
 405 tal Data Analysis (CEDA), and post-processing and figure generation using MATLAB  
 406 and GMT. Processed LiCSAR interferograms are available in the Centre for Environ-  
 407 mental Data Analysis (CEDA) archive (<http://archive.ceda.ac.uk>) here: [http://](http://data.ceda.ac.uk/neodc/comet/data/licsar_products)  
 408 [data.ceda.ac.uk/neodc/comet/data/licsar\\_products](http://data.ceda.ac.uk/neodc/comet/data/licsar_products). This work was funded by the  
 409 NERC RiftVolc project (NE/L013649/1), and supported by the Centre for Observation  
 410 and Modelling of Earthquakes, Volcanoes, and Tectonics (COMET).

## 411 References

- 412 Agram, P., Jolivet, R., Riel, B., Lin, Y., Simons, M., Hetland, E., . . . Lasserre, C.  
 413 (2013). New radar interferometric time series analysis toolbox released. *Eos,*  
 414 *Transactions American Geophysical Union*, *94*(7), 69–70.
- 415 Allard, P., Tazieff, H., & Dajlevic, D. (1979). Observations of seafloor spreading  
 416 in Afar during the November 1978 fissure eruption. *Nature*, *279*(5708), 30–33.  
 417 doi: 10.1038/279030a0
- 418 Amelung, F., Oppenheimer, C., Segall, P., & Zebker, H. (2000). Ground deforma-  
 419 tion near Gada 'Ale volcano, Afar, observed by radar interferometry. *Geophys-*  
 420 *ical Research Letters*, *27*(19), 3093–3096. doi: 10.1029/2000GL008497
- 421 Ansari, H., De Zan, F., & Parizzi, A. (2020). Study of Systematic Bias in Measur-  
 422 ing Surface Deformation with SAR Interferometry. *IEEE Transactions on Geo-*  
 423 *science and Remote Sensing*, 1-1.
- 424 ArRajehi, A., McClusky, S., Reilinger, R., Daoud, M., Alchalbi, A., Ergintay, S.,  
 425 . . . Kogan, L. (2010). Geodetic constraints on present-day motion of the  
 426 Arabian Plate: Implications for Red Sea and Gulf of Aden rifting. *Tectonics*,  
 427 *29*(TC3011). doi: 10.1029/2009TC002482
- 428 Audin, J., Vellutini, P. J., Coulon, C., Pigué, P., & Vincent, J. (1990). The 1928-  
 429 1929 eruption of Kammourta volcano - Evidence of tectono-magmatic activity  
 430 in the Manda-Inakir rift and comparison with the Asal Rift, Afar depression,  
 431 Republic of Djibuti. *Bulletin of Volcanology*, *52*, 551–561.
- 432 Ayele, A., Keir, D., Ebinger, C., Wright, T. J., Stuart, G. W., Buck, W. R., . . .  
 433 Sholan, J. (2009). September 2005 mega-dike emplacement in the Manda-  
 434 Harraro nascent oceanic rift (Afar depression). *Geophysical Research Letters*,  
 435 *36*(L20306). doi: 10.1029/2009GL039605
- 436 Bagnardi, M., & Hooper, A. (2018). Inversion of Surface Deformation Data  
 437 for Rapid Estimates of Source Parameters and Uncertainties: A Bayesian  
 438 Approach. *Geochemistry, Geophysics, Geosystems*, *19*. doi: 10.1029/  
 439 2018GC007585
- 440 Barnie, T. D., Keir, D., Hamling, I., Hofmann, B., Belachew, M., Carn, S., . . .  
 441 Wright, T. (2016). A multidisciplinary study of the final episode of the Manda  
 442 Hararo dyke sequence, Ethiopia, and implications for trends in volcanism dur-  
 443 ing the rifting cycle. *Geological Society, London, Special Publications*, *420*,  
 444 149–163. doi: 10.1144/SP420.6

- 445 Barnie, T. D., Oppenheimer, C., & Pagli, C. (2016). Does the lava lake of Erta Ale  
446 volcano respond to regional magmatic and tectonic events? An investigation  
447 using Earth Observation data. *Geological Society, London, Special Publica-*  
448 *tions*, *420*, 181–208. doi: 10.1144/SP420.15
- 449 Bastow, I. D., & Keir, D. (2011). The protracted development of the continent-  
450 ocean transition in Afar. *Nature Geoscience*, *4*(4), 248–250. doi: 10.1038/  
451 ngeo1095
- 452 Berardino, P., Fornaro, G., Lanari, R., & Sansosti, E. (2002). A new algorithm for  
453 surface deformation monitoring based on small baseline differential SAR inter-  
454 ferograms. *IEEE Transactions on Geoscience and Remote Sensing*, *40*(11),  
455 2375–2383. doi: 10.1109/TGRS.2002.803792
- 456 Biggs, J., Wright, T., Lu, Z., & Parsons, B. (2007). Multi-interferogram method for  
457 measuring interseismic deformation: Denali Fault, Alaska. *Geophysical Journal*  
458 *International*, *170*(3), 1165–1179. doi: 10.1111/j.1365-246X.2007.03415.x
- 459 Bird, P. (2003). An updated digital model of plate boundaries. *Geochemistry, Geo-*  
460 *physics, Geosystems*, *4*(3). doi: 10.1029/2001GC000252
- 461 Boissonnat, J.-D., & Cazals, F. (2002). Smooth surface reconstruction via natural  
462 neighbour interpolation of distance functions. *Computational Geometry*, *22*(1-  
463 3), 185–203.
- 464 Cattin, R., Doubre, C., de Chabalier, J. B., King, G., Vigny, C., Avouac, J. P., &  
465 Ruegg, J. C. (2005). Numerical modelling of quaternary deformation and post-  
466 rifting displacement in the Asal-Ghoubbet rift (Djibouti, Africa). *Earth and*  
467 *Planetary Science Letters*, *239*(3-4), 352–367. doi: 10.1016/j.epsl.2005.07.028
- 468 Chen, C. W., & Zebker, H. A. (2002). Phase unwrapping for large SAR interfero-  
469 grams: Statistical segmentation and generalized network models. *IEEE Trans-*  
470 *actions on Geoscience and Remote Sensing*, *40*(8), 1709–1719.
- 471 Cleveland, W. S., & Devlin, S. J. (1988). Locally weighted regression: an approach  
472 to regression analysis by local fitting. *Journal of the American statistical asso-*  
473 *ciation*, *83*(403), 596–610.
- 474 De Zan, F., Zonno, M., & Lopez-Dekker, P. (2015). Phase inconsistencies and mul-  
475 tiple scattering in SAR interferometry. *IEEE Transactions on Geoscience and*  
476 *Remote Sensing*, *53*(12), 6608–6616.
- 477 Doubre, C., & Peltzer, G. (2007). Fluid-controlled faulting process in the Asal Rift,  
478 Djibouti, from 8 yr of radar interferometry observations. *Geology*, *35*(1), 69–  
479 72. doi: 10.1130/G23022A.1
- 480 Eagles, G., Gloaguen, R., & Ebinger, C. (2002). Kinematics of the Danakil mi-  
481 croplate. *Earth and Planetary Science Letters*, *203*(2), 607–620. doi: 10.1016/  
482 S0012-821X(02)00916-0
- 483 Ebinger, C. J. (2005). Continental break-up: the East African perspective. *Astron-*  
484 *omy & Geophysics*, *46*(2), 2–16.
- 485 Ebinger, C. J., & Casey, M. (2001). Continental breakup in magmatic provinces: An  
486 Ethiopian example. *Geology*, *29*(6), 527–530. doi: 10.1130/0091-7613(2001)  
487 029(0527:CBIMPA)2.0.CO;2
- 488 Elliott, J. R., Biggs, J., Parsons, B., & Wright, T. J. (2008). InSAR slip rate  
489 determination on the Altyn Tagh Fault, northern Tibet, in the presence of  
490 topographically correlated atmospheric delays. *Geophysical Research Letters*,  
491 *35*(12), 1–5. doi: 10.1029/2008GL033659
- 492 Eyles, J. H., Illsley-Kemp, F., Keir, D., Ruch, J., & Jónsson, S. (2018). Seismicity  
493 associated with the formation of a new island in the Southern Red Sea. *Front-*  
494 *iers in Earth Science*, *6*, 141.
- 495 Farr, T. G., & Kobrick, M. (2000). Shuttle Radar Topography Mission produces  
496 a wealth of data, *Eos Trans. Eos, Transactions American Geophysical Union*,  
497 *81*(48), 583–585. doi: 10.1029/EO081i048p00583
- 498 Ferguson, D. J., Barnie, T. D., Pyle, D. M., Oppenheimer, C., Yirgu, G., Lewi,  
499 E., . . . Hamling, I. (2010). Recent rift-related volcanism in Afar, Ethiopia.

- 500 *Earth and Planetary Science Letters*, 292(3-4), 409–418. doi: 10.1016/  
 501 j.epsl.2010.02.010
- 502 Fialko, Y., Khazan, Y., & Simons, M. (2001). Deformation due to a pressurized  
 503 horizontal circular crack in an elastic half-space, with applications to volcano  
 504 geodesy. *Geophysical Journal International*, 146(1), 181–190.
- 505 Field, L., Barnie, T., Blundy, J., Brooker, R. A., Keir, D., Lewi, E., & Saunders, K.  
 506 (2012). Integrated field, satellite and petrological observations of the Novem-  
 507 ber 2010 eruption of Erta Ale. *Bulletin of Volcanology*, 74, 2251–2271. doi:  
 508 10.1007/s00445-012-0660-7
- 509 Furman, T., Bryce, J., Rooney, T., Hanan, B., Yirgu, G., & Ayalew, D. (2006).  
 510 Heads and tails: 30 million years of the Afar plume. *Geological Society, Lon-  
 511 don, Special Publications*, 259, 95–119. doi: 10.1144/GSL.SP.2006.259.01.09
- 512 Gallacher, R. J., Keir, D., Harmon, N., Stuart, G., Leroy, S., Hammond, J. O.,  
 513 ... Ahmed, A. (2016). The initiation of segmented buoyancy-driven melt-  
 514 ing during continental breakup. *Nature Communications*, 7(13110). doi:  
 515 10.1038/ncomms13110
- 516 Goitom, B., Oppenheimer, C., Hammond, J. O., Grandin, R., Barnie, T., Donovan,  
 517 A., ... Berhe, S. (2015). First recorded eruption of Nabro volcano, Eritrea,  
 518 2011. *Bulletin of Volcanology*, 77(85), 1–21. doi: 10.1007/s00445-015-0966-3
- 519 Goldstein, J., Reed, I., & Scharf, L. (1998). A multistage representation of the  
 520 Wiener filter based on orthogonal projections. *IEEE Transactions on Informa-  
 521 tion Theory*, 44(7), 2943–2959. doi: 10.1109/18.737524
- 522 González, P. J., Walters, R. J., Hatton, E. L., Spaans, K., & Hooper, A. (2016).  
 523 LiCSAR: Tools for automated generation of Sentinel-1 frame interferograms.  
 524 *AGU Fall Meeting*.
- 525 Grandin, R., Socquet, A., Doin, M. P., Jacques, E., De Chabalier, J. B., & King,  
 526 G. C. (2010). Transient rift opening in response to multiple dike injections  
 527 in the Manda Hararo rift (Afar, Ethiopia) imaged by time-dependent elastic  
 528 inversion of interferometric synthetic aperture radar data. *Journal of Geophys-  
 529 ical Research: Solid Earth*, 115(B09403). doi: 10.1029/2009JB006883
- 530 Hamling, I. J., Wright, T. J., Calais, E., Bennati, L., & Lewi, E. (2010). Stress  
 531 transfer between thirteen successive dyke intrusions in Ethiopia. *Nature Geo-  
 532 science*, 3(10), 713–717. doi: 10.1038/ngeo967
- 533 Hamling, I. J., Wright, T. J., Calais, E., Lewi, E., & Fukahata, Y. (2014). In-  
 534 SAR observations of post-rifting deformation around the Dabbahu rift seg-  
 535 ment, Afar, Ethiopia. *Geophysical Journal International*, 197, 33–49. doi:  
 536 10.1093/gji/ggu003
- 537 Hamlyn, J., Wright, T., Walters, R., Pagli, C., Sansosti, E., Casu, F., ... others  
 538 (2018). What causes subsidence following the 2011 eruption at Nabro (Er-  
 539 itrea)? *Progress in Earth and Planetary Science*, 5(1), 31.
- 540 Hamlyn, J. E., Keir, D., Wright, T. J., Neuberg, J. W., Goitom, B., Hammond,  
 541 J. O. S., ... Grandin, R. (2014). Seismicity and subsidence following the  
 542 2011 Nabro eruption, Eritrea: Insights into the plumbing system of an off-rift  
 543 volcano. *Journal of Geophysical Research: Solid Earth*, 119, 8267–8282. doi:  
 544 10.1002/2014JB011395
- 545 Hammond, J. O. S. (2014). Constraining melt geometries beneath the Afar Depres-  
 546 sion, Ethiopia from teleseismic receiver functions: The anisotropic H- $\kappa$  stacking  
 547 technique. *Geochemistry, Geophysics, Geosystems*, 15(4), 1316–1332.
- 548 Hammond, J. O. S., & Kendall, J. M. (2016). Constraints on melt distribution from  
 549 seismology: a case study in Ethiopia. *Geological Society, London, Special Pub-  
 550 lications*, 420, 127–147. doi: 10.1144/SP420.14
- 551 Hammond, J. O. S., Kendall, J. M., Stuart, G. W., Ebinger, C. J., Bastow, I. D.,  
 552 Keir, D., ... Wright, T. J. (2013). Mantle upwelling and initiation of rift  
 553 segmentation beneath the Afar Depression. *Geology*, 41(6), 635–638. doi:  
 554 10.1130/G33925.1

- 555 Hammond, J. O. S., Kendall, J. M., Stuart, G. W., Keir, D., Ebinger, C., Ayele, A.,  
556 & Belachew, M. (2011). The nature of the crust beneath the Afar triple junction:  
557 Evidence from receiver functions. *Geochemistry, Geophysics, Geosystems*,  
558 *12*(12). doi: 10.1029/2011GC003738
- 559 Hooper, A., Bekaert, D., Spaans, K., & Arkan, M. (2012). Recent advances in SAR  
560 interferometry time series analysis for measuring crustal deformation. *Tectono-*  
561 *physics*, *514*, 1–13.
- 562 Hussain, E., Hooper, A., Wright, T. J., Walters, R. J., & Bekaert, D. P. (2016).  
563 Interseismic strain accumulation across the central North Anatolian Fault from  
564 iteratively unwrapped InSAR measurements. *Journal of Geophysical Research:*  
565 *Solid Earth*, *121*, 9000–9019. doi: 10.1002/2016JB013108
- 566 Illsley-Kemp, F., Keir, D., Bull, J. M., Gernon, T. M., Ebinger, C., Ayele, A., ...  
567 Belachew, M. (2018). Seismicity during continental breakup in the Red Sea  
568 Rift of Northern Afar. *Journal of Geophysical Research: Solid Earth*, *123*,  
569 2345–2362. doi: 10.1002/2017JB014902
- 570 Jung, J., Kim, D.-j., & Park, S.-E. (2013). Correction of atmospheric phase screen  
571 in time series insar using wrf model for monitoring volcanic activities. *IEEE*  
572 *Transactions on Geoscience and Remote Sensing*, *52*(5), 2678–2689.
- 573 Kendall, J. M., Stuart, G. W., Ebinger, C. J., Bastow, I. D., & Keir, D. (2005).  
574 Magma-assisted rifting in Ethiopia. *Nature*, *433*(7022), 146–148. doi:  
575 10.1038/nature03161
- 576 Kidane, T. (2016). Strong clockwise block rotation of the Ali-Sabieh/Aïsha  
577 Block: evidence for opening of the Afar Depression by a saloon-door’ mech-  
578 anism. *Geological Society, London, Special Publications*, *420*, 209–219. doi:  
579 10.1144/SP420.10
- 580 King, R., Floyd, M., Reilinger, R., & Bendick, R. (2019). GPS velocity field (MIT  
581 2019.0) for the East African Rift System generated by King et al.. Interdisci-  
582 plinary Earth Data Alliance (IEDA). *Accessed on 20 Sep 2019*.
- 583 Kogan, L., Fisseha, S., Bendick, R., Reilinger, R., McClusky, S., King, R., &  
584 Solomon, T. (2012). Lithospheric strength and strain localization in con-  
585 tinental extension from observations of the East African Rift. *Journal of*  
586 *Geophysical Research: Solid Earth*, *117*(B03402). doi: 10.1029/2011JB008516
- 587 Lanari, R., Casu, F., Manzo, M., Zeni, G., Berardino, P., Manunta, M., & Pepe, A.  
588 (2007). An overview of the Small BASeline Subset algorithm: A DInSAR tech-  
589 nique for surface deformation analysis. *Pure and Applied Geophysics*, *164*(4),  
590 637–661. doi: 10.1007/s00024-007-0192-9
- 591 Lavayssière, A., Rychert, C., Harmon, N., Keir, D., Hammond, J. O., Kendall, J.-M.,  
592 ... Leroy, S. (2018). Imaging lithospheric discontinuities beneath the Northern  
593 East African Rift Using S-to-P receiver functions. *Geochemistry, Geophysics,*  
594 *Geosystems*, *19*(10), 4048–4062.
- 595 Lazecky, M., Maghsoudi, Y., Morishita, Y., Wright, T. J., Hooper, A., Elliott, J., ...  
596 Spaans, K. (in review.). LiCSAR: An Automated InSAR Tool for Monitoring  
597 Tectonic and Volcanic Activity. *Remote Sensing*.
- 598 Liu, S., Hanssen, R., Samiei-Esfahany, S., Hooper, A., & Van Leijen, F. (2011).  
599 Separating non-linear deformation and atmospheric phase screen (APS) for  
600 InSAR time series analysis using least-squares collocation. In *Proceedings of*  
601 *the advances in the science and applications of sar interferometry, esa fringe*  
602 *2009, workshop esa*.
- 603 McClusky, S., Reilinger, R., Ogubazghi, G., Amleson, A., Healeb, B., Vernant,  
604 P., ... Kogan, L. (2010). Kinematics of the southern Red Sea-Afar Triple  
605 Junction and implications for plate dynamics. *Geophysical Research Letters*,  
606 *37*(L05301). doi: 10.1029/2009GL041127
- 607 Mogi, K. (1958). Relations between the Eruptions of Various Volcanoes and the De-  
608 formations of the Ground Surfaces around them. *Bulletin of the Earthquake*  
609 *Research Institute*, *36*, 99–134.

- 610 Moore, C., Wright, T., Hooper, A., & Biggs, J. (2019). The 2017 eruption of Erta  
611 'Ale volcano, Ethiopia: Insights in the shallow axial plumbing system of an  
612 incipient mid-ocean ridge. *Geochemistry, Geophysics, Geosystems*, *20*(12).
- 613 Morishita, Y., Lazecky, M., Wright, T. J., Weiss, J. R., Elliott, J. R., & Hooper,  
614 A. (2020). LiCSBAS: An Open-Source InSAR Time Series Analysis Package  
615 Integrated with the LiCSAR Automated Sentinel-1 InSAR Processor. *Remote  
616 Sensing*, *12*(3), 424.
- 617 Nobile, A., Pagli, C., Keir, D., Wright, T. J., Ayele, A., Ruch, J., & Acocella, V.  
618 (2012). Dike-fault interaction during the 2004 Dallol intrusion at the northern  
619 edge of the Erta Ale Ridge (Afar, Ethiopia). *Geophysical Research Letters*,  
620 *39*(L19305). doi: 10.1029/2012GL053152
- 621 Okada, Y. (1985). Surface deformation due to shear and tensile faults in a half-  
622 space. *Bulletin of the seismological society of America*, *75*(4), 1135–1154.
- 623 Pagli, C., Wang, H., Wright, T. J., Calais, E., & Lewi, E. (2014). Current plate  
624 boundary deformation of the Afar rift from a 3-D velocity field inversion of In-  
625 SAR and GPS. *Journal of Geophysical Research: Solid Earth*, *119*, 8562–8575.  
626 doi: 10.1002/2014JB011391
- 627 Pagli, C., Wright, T. J., Ebinger, C. J., Yun, S. H., Cann, J. R., Barnie, T., &  
628 Ayele, A. (2012). Shallow axial magma chamber at the slow-spreading Erta  
629 Ale Ridge. *Nature Geoscience*, *5*(4), 284–288. doi: 10.1038/ngeo1414
- 630 Refice, A., Belmonte, A., Bovenga, F., & Pasquariello, G. (2011). On the use of  
631 anisotropic covariance models in estimating atmospheric DInSAR contribu-  
632 tions. *IEEE Geoscience and Remote Sensing Letters*, *8*(2), 341–345.
- 633 Saria, E., Calais, E., Stamps, D. S., Delvaux, D., & Hartnady, C. J. (2014). Present-  
634 day kinematics of the East African Rift. *Journal of Geophysical Research:  
635 Solid Earth*, *119*, 3584–3600. doi: 10.1002/2013JB010901
- 636 Shen, L., Hooper, A., & Elliott, J. (2019). A Spatially Varying Scaling Method  
637 for InSAR Tropospheric Corrections Using a High-Resolution Weather Model.  
638 *Journal of Geophysical Research: Solid Earth*, *124*(4), 4051–4068.
- 639 Sousa, J. J., Hooper, A. J., Hanssen, R. F., Bastos, L. C., & Ruiz, A. M. (2011).  
640 Persistent Scatterer InSAR: A comparison of methodologies based on a model  
641 of temporal deformation vs. spatial correlation selection criteria. *Remote  
642 Sensing of Environment*, *115*(10), 2652–2663.
- 643 Stork, A. L., Stuart, G. W., Henderson, C. M., Keir, D., & Hammond, J. O. (2013).  
644 Uppermost mantle (Pn) velocity model for the Afar region, Ethiopia: An in-  
645 sight into rifting processes. *Geophysical Journal International*, *193*, 321–328.  
646 doi: 10.1093/gji/ggs106
- 647 Tarantola, A., Ruegg, J. C., & Lepine, J. C. (1979). Geodetic evidence for rifting  
648 in Afar a brittle-elastic model of the behaviour of the lithosphere. *Earth and  
649 Planetary Science Letters*, *45*, 435–444. doi: 10.1016/0012-821X(79)90142-0
- 650 Temtime, T., Biggs, J., Lewi, E., Hamling, I., Wright, T., & Ayele, A. (2018). Spa-  
651 tial and temporal patterns of deformation at the Tendaho geothermal prospect,  
652 Ethiopia. *Journal of Volcanology and Geothermal Research*, *357*, 56–67. doi:  
653 10.1016/j.jvolgeores.2018.04.004
- 654 Tiberi, C., Ebinger, C., Ballu, V., Stuart, G., & Oluma, B. (2005). Inverse  
655 models of gravity data from the Red Sea-Aden-East African rifts triple  
656 junction zone. *Geophysical Journal International*, *163*, 775–787. doi:  
657 10.1111/j.1365-246X.2005.02736.x
- 658 Wang, H., & Wright, T. (2012). Satellite geodetic imaging reveals internal deformation  
659 of western Tibet. *Geophysical Research Letters*, *39*(7).
- 660 Wang, H., Wright, T. J., Yu, Y., Lin, H., Jiang, L., Li, C., & Qiu, G. (2012). InSAR  
661 reveals coastal subsidence in the Pearl River Delta, China. *Geophysical Journal  
662 International*, *191*(3), 1119–1128.
- 663 Weiss, J. R., Walters, R. J., Morishita, Y., Wright, T. J., Lazecky, M., Wang, H., ...  
664 Parsons, B. (2020). High-resolution Surface Velocities and Strain for Anatolia

- 665 from Sentinel-1 InSAR and GNSS Data. *EarthArXiv*.
- 666 Werner, C., Wegmuller, U., Strozzi, T., & Wiesmann, A. (2000). GAMMA SAR and  
667 interferometric processing software. *European Space Agency, (Special Publica-*  
668 *tion) ESA SP(461)*, 211–219.
- 669 Wiart, P., & Oppenheimer, C. (2000). Largest known historical eruption in Africa:  
670 Dubbi volcano, Eritrea, 1861. *Geology*, *28*(4), 291–294. doi: 10.1130/0091-  
671 -7613(2000)28(291:LKHEIA)2.0.CO;2
- 672 Wolfenden, E., Ebinger, C., Yirgu, G., Deino, A., & Ayalew, D. (2004). Evolution of  
673 the northern Main Ethiopian rift: Birth of a triple junction. *Earth and Plane-*  
674 *tary Science Letters*, *224*(1-2), 213–228. doi: 10.1016/j.epsl.2004.04.022
- 675 Wright, T. J., Ebinger, C., Biggs, J., Ayele, A., Yirgu, G., Keir, D., & Stork,  
676 A. (2006). Magma-maintained rift segmentation at continental rup-  
677 ture in the 2005 Afar dyking episode. *Nature*, *442*(7100), 291–294. doi:  
678 10.1038/nature04978
- 679 Wright, T. J., Parsons, B. E., & Zhong, L. (2004). Toward mapping surface de-  
680 formation in three dimensions using InSAR. *Geophysical Research Letters*,  
681 *31*(L01607). doi: 10.1029/2003GL018827
- 682 Wright, T. J., Sigmundsson, F., Pagli, C., Belachew, M., Hamling, I. J.,  
683 Brandsdóttir, B., . . . Calais, E. (2012). *Geophysical constraints on the dy-*  
684 *namics of spreading centres from rifting episodes on land* (Vol. 5) (No. 4). doi:  
685 10.1038/ngeo1428
- 686 Yu, C., Li, Z., & Penna, N. T. (2018). Interferometric synthetic aperture radar  
687 atmospheric correction using a GPS-based iterative tropospheric decom-  
688 position model. *Remote Sensing of Environment*, *204*, 109–121. doi:  
689 10.1016/j.rse.2017.10.038
- 690 Yu, C., Penna, N. T., & Li, Z. (2017). Generation of real-time mode high-resolution  
691 water vapor fields from GPS observations. *Journal of Geophysical Research*,  
692 *122*(3), 2008–2025. doi: 10.1002/2016JD025753