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1 **Local seismicity near the actively deforming Corbetti volcano in the Main Ethiopian Rift**

2

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18 **Declarations of interest:** none.

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30 **Abstract**

31 Corbetti is currently one of the fastest uplifting volcanoes globally, with strong evidence from
32 geodetic and gravity data for a subsurface inflating magma body. A dense network of 18 stations
33 has been deployed around Corbetti and Hawassa calderas between February 2016 and October
34 2017, to place seismic constraints on the magmatic, hydrothermal and tectonic processes in the
35 region. We locate 122 events of magnitudes between 0.4 and 4.2 using a new local velocity model.
36 The seismicity is focused in two areas: directly beneath Corbetti caldera and beneath the city of
37 Hawassa. The shallower 0-5 km depth below sea level (b.s.l.) earthquakes beneath Corbetti are
38 mainly focused in EW- to NS-elongated clusters at Urji and Chabbi volcanic centres. This
39 distribution is interpreted to be mainly controlled by a northward propagation of hydrothermal
40 fluids away from a cross-rift pre-existing fault. Source mechanisms are predominantly strike-slip
41 and different to the normal faulting away from the volcano, suggesting a local rotation of the stress-
42 field. These observations, along with a low V_p/V_s ratio, are consistent with the inflation of a gas-
43 rich sill, likely of silicic composition, beneath Corbetti. In contrast, the seismicity beneath Hawassa
44 extends to greater depth (16 km b.s.l.). These earthquakes are focused on 8-10 km long segmented
45 faults, which are active in seismic swarms. One of these swarms, in August 2016, is focused
46 between 5 and 16 km depth b.s.l. along a steep normal fault beneath the city of Hawassa,
47 highlighting the earthquake hazard for the local population.

48

49 **Keywords: (max 6)**

50 East African Rift; Corbetti volcano; local seismicity; Main Ethiopian Rift; continental tectonics

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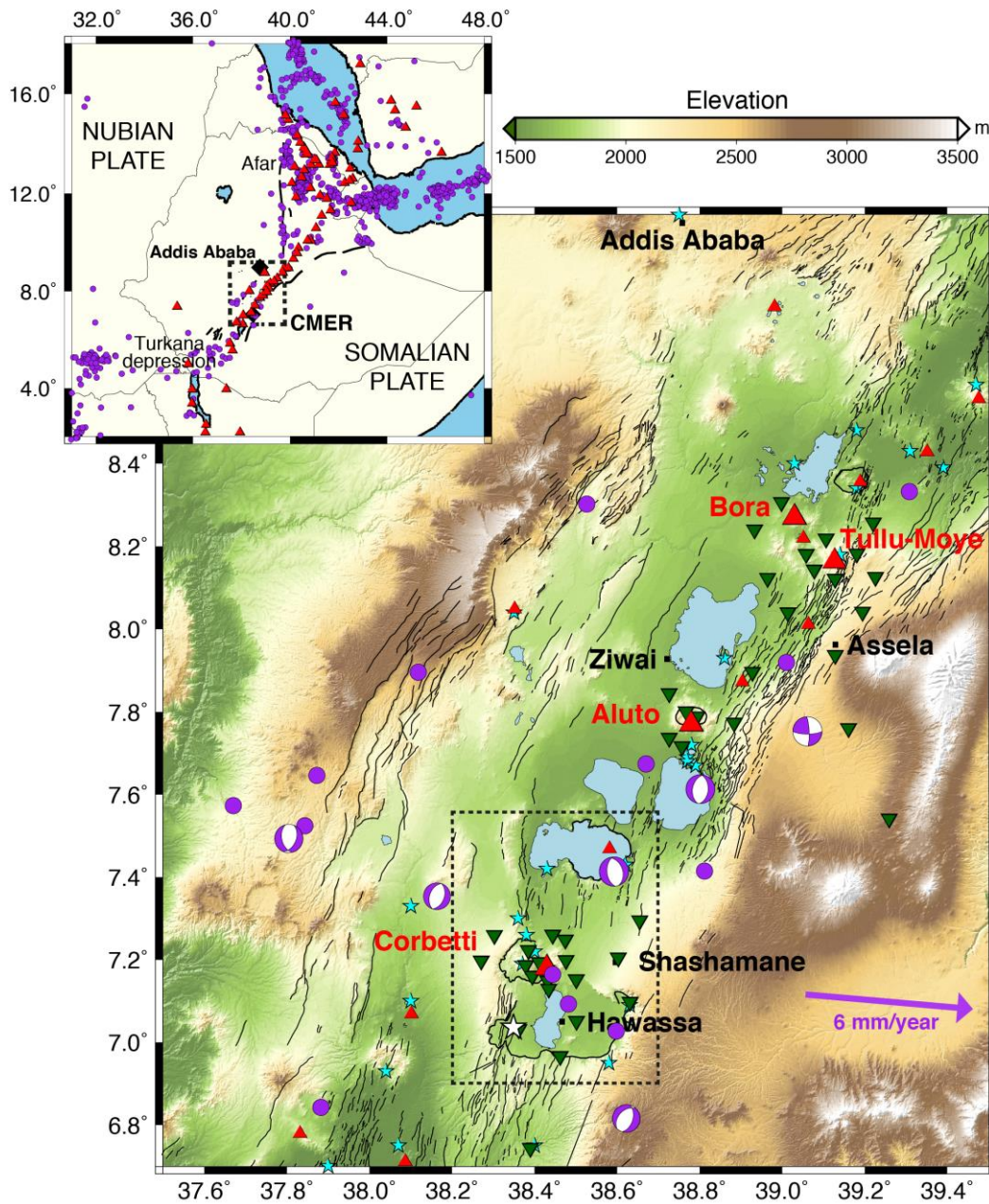
52 **1 Introduction**

53 Seismicity in the East African Rift has previously been linked to tectonic faulting and magmatic
54 processes (Ebinger et al., 2008; Grandin et al., 2011; Greenfield et al., 2018; Lavayssière et al.,
55 2019; Wilks, Kendall, et al., 2017). The earthquake patterns commonly highlight rift segments and
56 volcanic centres (map inset, Figure 1), and can be used to reveal faults systems and migration of
57 fluids or magma beneath active volcanoes. Despite improvements in monitoring, how individual
58 magmatic systems modify and interact with tectonic faulting in discrete portions of the rift remain
59 poorly understood. This is particularly the case for the central Main Ethiopian Rift (MER) (Figure
60 1), since a previous lack of dense seismic networks means that very few earthquakes have been
61 detected.

62 The Main Ethiopian Rift (MER) is a magmatically active portion of the East African Rift System
63 (EARS) that lies between the Afar depression in the north and the Turkana depression in the south
64 (Figure 1). The MER includes nearly 60 volcanoes that are thought to have erupted in the past
65 10,000 years, of which Corbetti, Bora, Aluto and Haledebi are actively deforming (Biggs et al.,
66 2011). In particular, Corbetti is currently uplifting at 7 cm per year (Lloyd, Biggs, Birhanu, et al.,
67 2018), making it one of the fastest deforming volcanoes on Earth. In addition, recent earthquake
68 activity near Corbetti has been significant. On the 24th January 2016, a Mw 4.3 normal slip
69 earthquake occurred south of Corbetti that was widely felt in the town of Hawassa (Figure 1)
70 (Wilks, Ayele, et al., 2017). Volcanoes in the MER have the potential to be used for geothermal
71 energy, a resource that is starting to be exploited in Ethiopia on Aluto and Corbetti volcanoes

72 (Gíslason et al., 2015; Kebede, 2014). Hydrothermal systems are likely in volcanic fields due to
 73 the interaction of the subsurface magma plumbing system with the ground water.

74



75 **Figure 1:** Map of the central Main Ethiopian Rift (CMER) with National Earthquake Information Centre (NEIC)
 76 events catalog (1976 – 2018; purple circles) and Centroid Moment Tensor (CMT) source mechanisms catalog
 77 (purple focal mechanisms). The white star represent the location of the 24th January 2016 earthquake (Wilks, Ayele,
 78 et al., 2017). The map inset shows the CMER (dashed rectangle) in the context of the northern East African Rift.
 79 Black squares indicate the main cities. Green inverted triangles are the seismic stations. Red triangles are volcanic
 80 centres with the main volcanoes in the CMER named. Black lines represent mapped faults (Agostini et al., 2011;
 81 Corti et al., 2013). Cyan stars highlight hydrothermal vents and wells. The dashed rectangle is the area shown in
 82 Figures 2 and 4. Purple arrow is the extension direction (Stamps et al., 2018).

83 Here we present a detailed study of the local seismicity at the Corbetti and Hawassa calderas,
84 following the January 2016 earthquake. Using a dense network deployed across the region and
85 generating a local seismic velocity model, we detect and precisely locate seismicity beneath a
86 deforming caldera and nearby active rift valley faults. Local seismicity is used to understand
87 magma and hydrothermal pathways beneath Corbetti volcano and show active faulting beneath rift
88 valley faults.

89

90 **2 Geological and geophysical setting**

91

92 The MER is characterized by several *en-echelon* magmatic segments and volcanic centres
93 associated with continental extension between the Nubian and Somalian plates (Figure 1; Ebinger
94 & Casey, 2001). The MER is rifting at approximately 6 mm/year in a near east-west direction
95 (Figure 1; Saria et al., 2014; Stamps et al., 2018). Extension is thought to have started in the
96 Miocene (Wolfenden et al., 2004) and its basins were initially bounded by large border faults that
97 accommodated the majority of the extension. The transition to magma-assisted rifting at 2 Ma
98 (Wolfenden et al., 2004) formed short and *en-echelon* NNE-SSW intra-rift faults, including the
99 present-day Wonji Fault Belt (WFB) along the rift valley floor of the MER (Agostini et al., 2011;
100 Corti et al., 2013; Ebinger & Casey, 2001; Pizzi et al., 2006). This structure is interspersed by
101 Quaternary to Recent volcanic centres such as Boset, Bora, Aluto and Corbetti (Ebinger & Casey,
102 2001). Although known to be seismically active, only few earthquakes have been detected in the
103 central MER, mostly normal faulting events at border faults and events near volcanic centres
104 (Figure 1).

105 Corbetti volcano is considered as one of the most frequently active volcanoes in East Africa in
106 term of moderate-scale explosive eruptions with 1 to 3 eruptions per thousand years (Fontijn et
107 al., 2018). Its caldera is 10 by 15 km (Hutchison et al., 2016), and elongate at an orientation of
108 097° (Lloyd et al., 2018) (Figure 2). The Corbetti silicic centre has a three-stage volcanic history
109 (Fontijn et al., 2018; Di Paola, 1971) with effusive and explosive activity separated by a caldera
110 collapse at 182 ± 18 ka. It has been highly active in the Late Quaternary with eruptions up to VEI
111 4-5 (Fontijn et al., 2018).

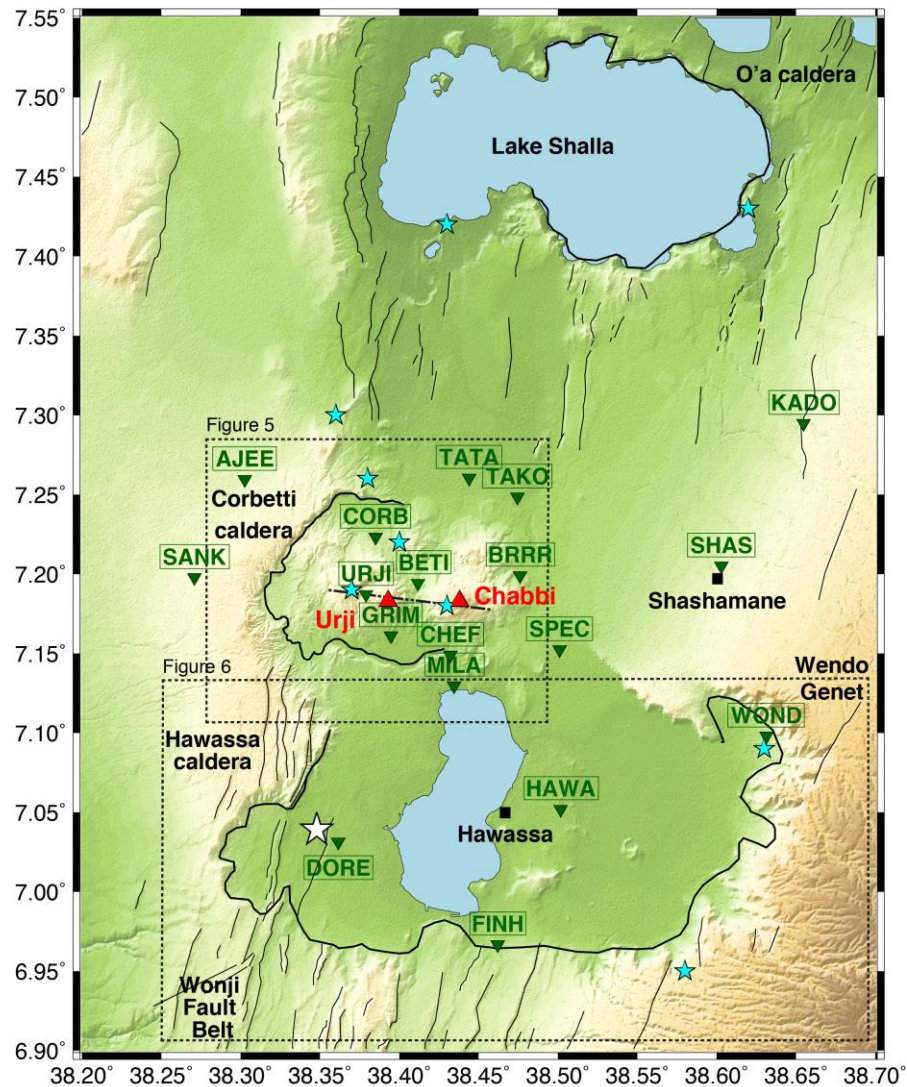
112 Two major centres of resurgent volcanisms, Urji (also called Wendo Koshe) and Chabbi (Mohr,
113 1966; Di Paola, 1971), have both erupted pantellerites. Urji is mainly composed of pumice flows,
114 highlighting explosive activity, whereas Chabbi is composed of obsidian flows, highlighting
115 contrasting effusive eruptions (Mohr, 1966; Rapprich et al., 2016). The last Plinian eruption at Urji
116 occurred around 396 BC and dispersed deposits over 1000 km² with ~50 cm of deposits in
117 Shashamene and more than 10 cm in Hawassa, enough to cause widespread disruption (Fontijn et
118 al., 2018; Rapprich et al., 2016). At least four obsidian and 9 explosive eruptions post-date this
119 massive activity (Fontijn et al., 2018; Rapprich et al., 2016).

120 Geological and geophysical evidence suggest that Corbetti remains seismically and magmatically
121 active and may erupt in the future. Satellite imaging has shown significant surface deformation
122 over the past twenty years (Biggs et al., 2011; Lloyd, Biggs, Birhanu, et al., 2018). InSAR
123 observations show periods of uplift and subsidence between 1997 and 2010 (Biggs et al., 2011)
124 and continuous uplift at a rate of ~7 cm/year since 2009 (Biggs et al., 2011; Lloyd, Biggs, Birhanu,
125 et al., 2018). Lloyd, Biggs, Birhanu, et al. (2018) show that the recent continuous uplift is a

126 response to a volume change of $\sim 10^7$ m³/year of magma intruding into a pre-existing reservoir at
 127 ~ 6.6 km depth below surface.

128 Deformation studies also highlight structures that control magmatic and tectonics processes.
 129 Lloyd, Biggs, Wilks, et al. (2018) and Korme et al. (2004) observe a linear feature cross-cutting
 130 the caldera coincidentally with the caldera long axis (Figure 2). This fault structure is interpreted
 131 to control the migration of magma and hydrothermal fluids to the surface, visible by the alignment
 132 of post-caldera vents (Lloyd, Biggs, Wilks, et al., 2018).

133



134 **Figure 2:** Map of the seismic network. Black squares represent the main cities. Main volcanic centres are named
 135 and located as red triangles. The black dashed line crossing Corbetti caldera represents a cross-rift fault structure
 136 (Lloyd, Biggs, Wilks, et al., 2018). Cyan stars highlight hydrothermal vents and wells. Green inverted triangle are
 137 stations with their associated name. The white star is the location of the 24th January 2016 earthquake (Wilks,
 138 Ayele, et al., 2017). Dashed rectangles are sub-regions explored in this study (Figures 5 and 6).

139

140 Magnetotelluric and resistivity measurements around Corbetti indicate a sharp resistivity change
141 along the caldera long-axis at 0-2 km below surface and another at depth greater than 10 km below
142 surface (Gíslason et al., 2015). The shallow change in resistivity is thought to be a buried strike-
143 slip fault, coincident to the fault structure identified by Lloyd, Biggs, Wilks, et al. (2018),
144 controlling migration of hot hydrothermal fluids to the northern half of the caldera (Gíslason et al.,
145 2015). On the surface, this hydrothermal system consists of numerous fumaroles and thermally
146 altered soils. The deep conductive layer has been interpreted as a possible magma body (Gíslason
147 et al., 2015).

148 Little is known about the seismicity and crustal structure of the Corbetti caldera. Regional studies
149 have constrained the crustal structure of the MER (Daly et al., 2008; Keir, Ebinger, et al., 2006)
150 and local studies have identified seismically active structures at the nearby volcanic fields of Tullu-
151 Moye (Greenfield et al., 2018) and Aluto (Wilks, Kendall, et al., 2017). Previous monitoring of
152 local seismicity at Corbetti has been done in 2012-2014 with a sparse network of seven stations
153 (Lloyd, Biggs, Birhanu, et al., 2018; Lloyd, Biggs, Wilks, et al., 2018). It showed dispersed
154 seismicity with events located between Chabbi and Urji down to 9 km depth and a large number
155 of events at Wendo Genet, east of Hawassa caldera (Lloyd, Biggs, Birhanu, et al., 2018; Lloyd,
156 Biggs, Wilks, et al., 2018) (Figure 2). However, the velocity model used in these earlier works was
157 a regional 1D velocity model of the MER (Daly et al., 2008).

158 Teleseismically detected earthquakes are infrequent in this area of the rift with only 5 events
159 detected within 50 km of Corbetti (Figure 1). The most recent event occurred on the 24th January
160 2016, immediately before the seismic network was deployed. The magnitude 4.68 earthquake
161 (Wilks, Ayele, et al., 2017) was large enough to be felt up to 100 km away and caused damage to
162 buildings in the city of Hawassa that hosts a population of ~320,000 people. The event was located
163 to the southwest of Hawassa at a depth of 4.55 km depth using regional stations > 200 km away
164 from the hypocentre (Wilks, Ayele, et al., 2017) (Figure 2). The earthquake focal mechanism
165 reveals that the event is a normal slip on a north-south-striking fault associated with the caldera
166 rim of the Hawassa caldera (Wilks, Ayele, et al., 2017).

167 South of Corbetti, the Quaternary Hawassa caldera is located at the eastern escarpment of the rift,
168 forming an EW-elongated, 35 by 20 km, topographic depression, filled by the 92 km² Lake
169 Hawassa (Figure 2). The caldera is composed of silicic lava flows, pumices and welded tuff dated
170 at 1.85-1.1 Ma, and has also been filled by products of more volcanic activities associated with the
171 formation of Corbetti volcano (Mohr et al., 1980; Di Paola, 1971; WoldeGabriel et al., 1992). It
172 has been affected by NS-trending faults that formed a down-faulted central sector where Lake
173 Hawassa is located (Boccaletti et al., 1998) (Figure 2).

174 North of Corbetti is located one of the largest calderas in the central Main Ethiopian Rift, the O'a
175 caldera (120 km³; Mohr et al., 1980) (Figure 2). It contains the volcanically and tectonically
176 controlled Lake Shalla (Le Turdu et al., 1999). Observations show ESE-trending transverse faults

177 with 5 to 30 m throw on the eastern caldera walls (Mohr et al., 1980; Le Turdu et al., 1999) but
 178 the deep structure beneath Lake Shalla and the O'a caldera remains unknown.

179

180 3 Data and Methods

181

182 3.1 Seismic network and earthquake detection

183 37 stations were deployed across the MER (Figure 1), including 18 installed around Corbetti and
 184 Hawassa calderas, in February 2016 (Figure 2). The network consists of 3-component, broadband
 185 instruments: 25 Guralp CMG-6TD and 12 Guralp CMG-ESPCD seismometers, recording at 50
 186 samples per second. The instruments were removed in October 2017, yielding 1.5 years of data.

187 Earthquakes were detected using the Coalescence Microseismic Mapping (CMM) technique
 188 (Drew et al., 2013). We generate our catalogue using only events with signal-to-noise ratio above
 189 3. A total of 286 events were detected using these parameters over the duration of the experiment.
 190 To improve the accuracy of the phase arrival times we manually refine a total of 3450 P-wave and
 191 3641 S-wave arrival times using the entire network of 37 stations.

192

193 3.2 Velocity model

194 Accurate earthquake locations depend on having a good
 195 knowledge of the subsurface velocity structure of the
 196 study area. In order to develop a sensible velocity model
 197 for the region we invert the arrival time results with the
 198 program *Velost* (Kissling et al., 1995). This program
 199 minimises the misfit between the arrival times and the
 200 model predictions. We use only the events that have at
 201 least 6 arrivals, including at least 2 S-arrivals, and
 202 recorded with an azimuthal gap of less than 200° . This
 203 results in a total of 173 events. Analysis of the P- and S-
 204 wave arrival time on a Wadati diagram yields a best-fit
 205 V_p/V_s ratio of 1.683 ± 0.003 . Applying these criteria,
 206 we determine a minimum 1D P-wave velocity model
 207 (black curve, Figure 3) with a root-mean-square error
 208 for the velocity model of 0.232 s. Since earthquakes
 209 generally cluster in depth at sharp changes in velocity,
 210 we smooth the velocity model output from *Velost* to
 211 generate the final velocity model (red line, Figure 3). It
 212 is interesting to note that the V_p structure we image is
 213 fairly similar to the Aluto velocity model (Wilks,
 214 Kendall, et al., 2017), and slower than the Bora Tullu-
 215 Moye velocity model (Greenfield et al., 2018),
 216 particularly between ~ 3 -8 km depth. This could be due
 217 to a thicker sedimentary basin in the shallow crust
 218 (Maguire et al. 2006), or to the crust being hotter and/or

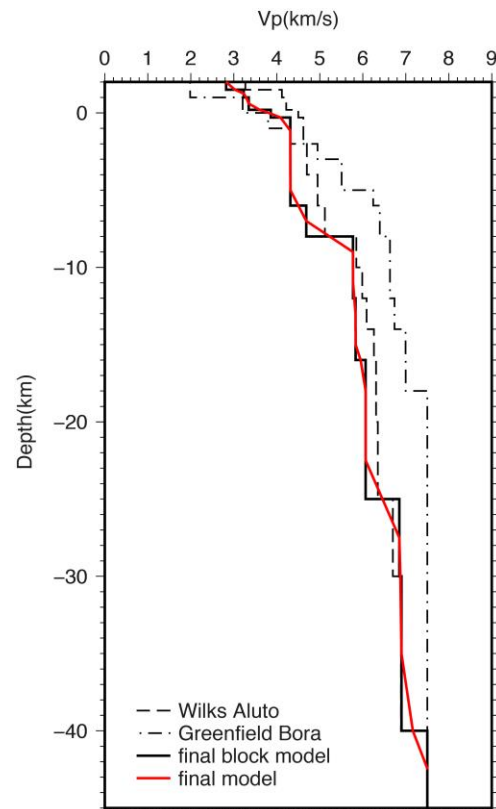


Figure 3: 1D velocity models. The final velocity model is shown in solid red and compared to previous models (dashed lines) (Wilks, Kendall, et al., 2017; Greenfield et al., 2018) and to the block model obtained from *Velost* (solid black line).

219 the presence of partial melt in the subsurface beneath our study area.

220

221 **3.3 Earthquake location**

222 The new velocity model is used to locate our catalogue of events with *NonLinLoc* (Lomax, 2008).
223 This program estimates the probability density function of the hypocentre (Lomax et al., 2000;
224 Tarantola & Valette, 1982). From the *NonLinLoc* results, we select events located within the
225 network (gap < 180°). This results in a catalogue of 122 hypocentres, used in the subsequent
226 analyses (Table S1).

227

228 **3.4 Magnitudes**

229 The local magnitude of the detected earthquakes (M_L) are calculated with the following equation,
230 adapted for the MER (Keir, Stuart, et al., 2006)

$$231 M_L = \log A_0 + 1.196997 * \log (r / 17) + 0.001066 * (r - 17) + 2 + C$$

232 where A_0 is the maximum zero-to-peak amplitude corrected to the response of a Wood-Anderson
233 seismograph, C is the station correction and r is the hypocentral distance in kilometres.
234 Considering the low number of earthquakes used in this study we chose not to calculate the b -
235 value of the catalogue.

236

237 **3.5 Focal mechanisms**

238 We determine focal mechanisms solutions for the 122 events within our catalogue using the
239 *FOCMEC* program (Snoke, 1984), which assumes a double-couple solution. The take-off angle
240 and back-azimuth from *NonLinLoc* and P-wave, first-motion polarities of the vertical waveform
241 are used to search for nodal planes solutions. The solutions are considered good if the nodal planes
242 have little spread (< 15°) and there is polarity data in at least 3 quadrants with no polarity errors
243 allowed. 22 events follow these criteria and are presented in the following section.

244

245 **4 Results and interpretations**

246

247 The 122 well-constrained earthquake locations highlight three active regions of seismicity: beneath
248 Lake Shalla, beneath Corbetti caldera and beneath the eastern shore of Lake Hawassa (Figure 4).

249

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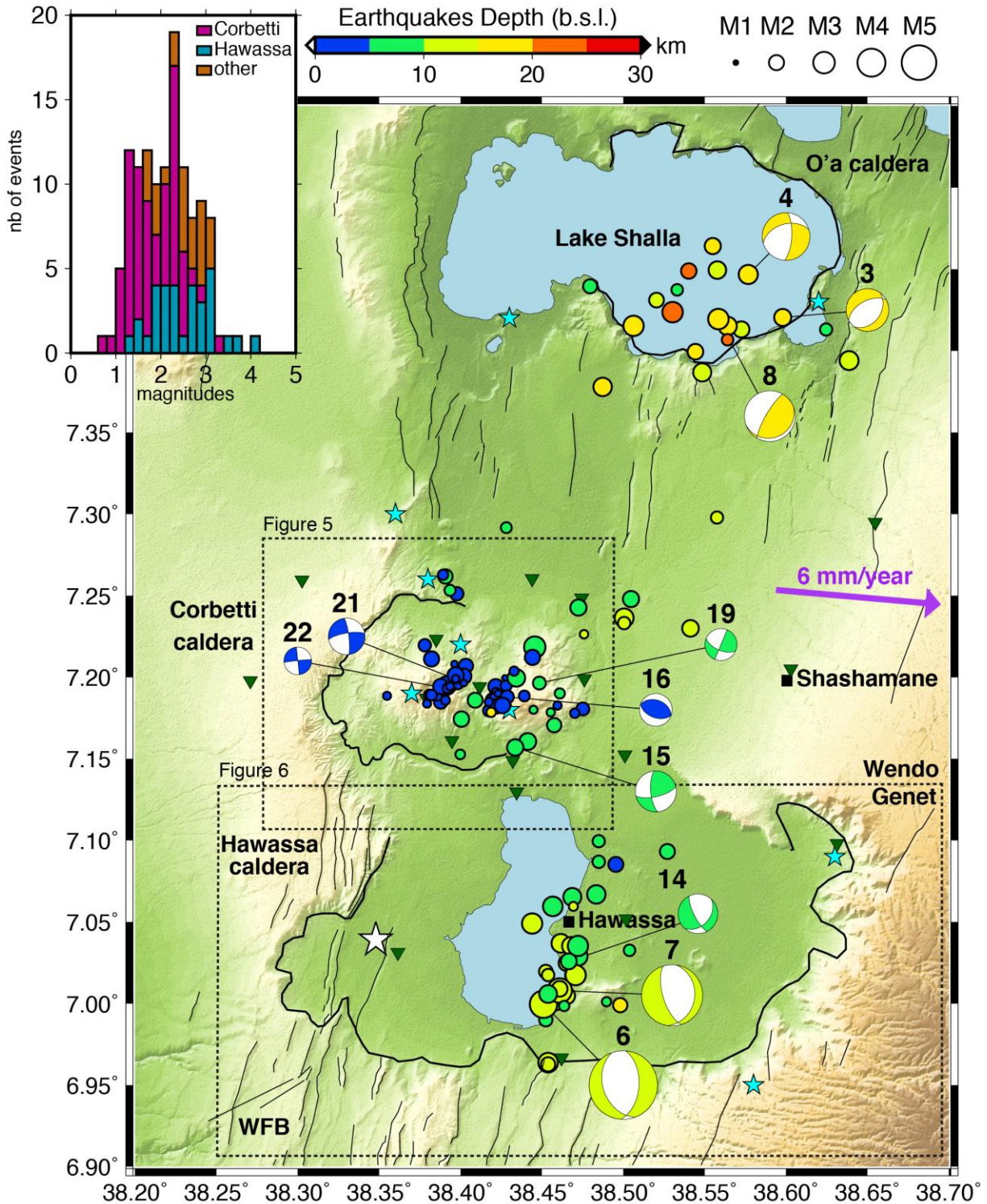
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257 **Figure 4:** Map of epicentral locations (122 earthquakes) scaled to magnitude and color-coded with depth below sea
 258 level (b.s.l.). Dashed rectangles enclose sub-regions shown in Figures 5 and 6. Green inverted triangles are seismic
 259 stations. Purple arrow indicates the extension direction. Cyan stars highlight hydrothermal vents and wells. Black
 260 squares represent the main cities. The white star is the location of the 24th January 2016 earthquake (Wilks, Ayele,
 261 et al., 2017). Inset is the magnitude histogram for the events in each part of the study area.

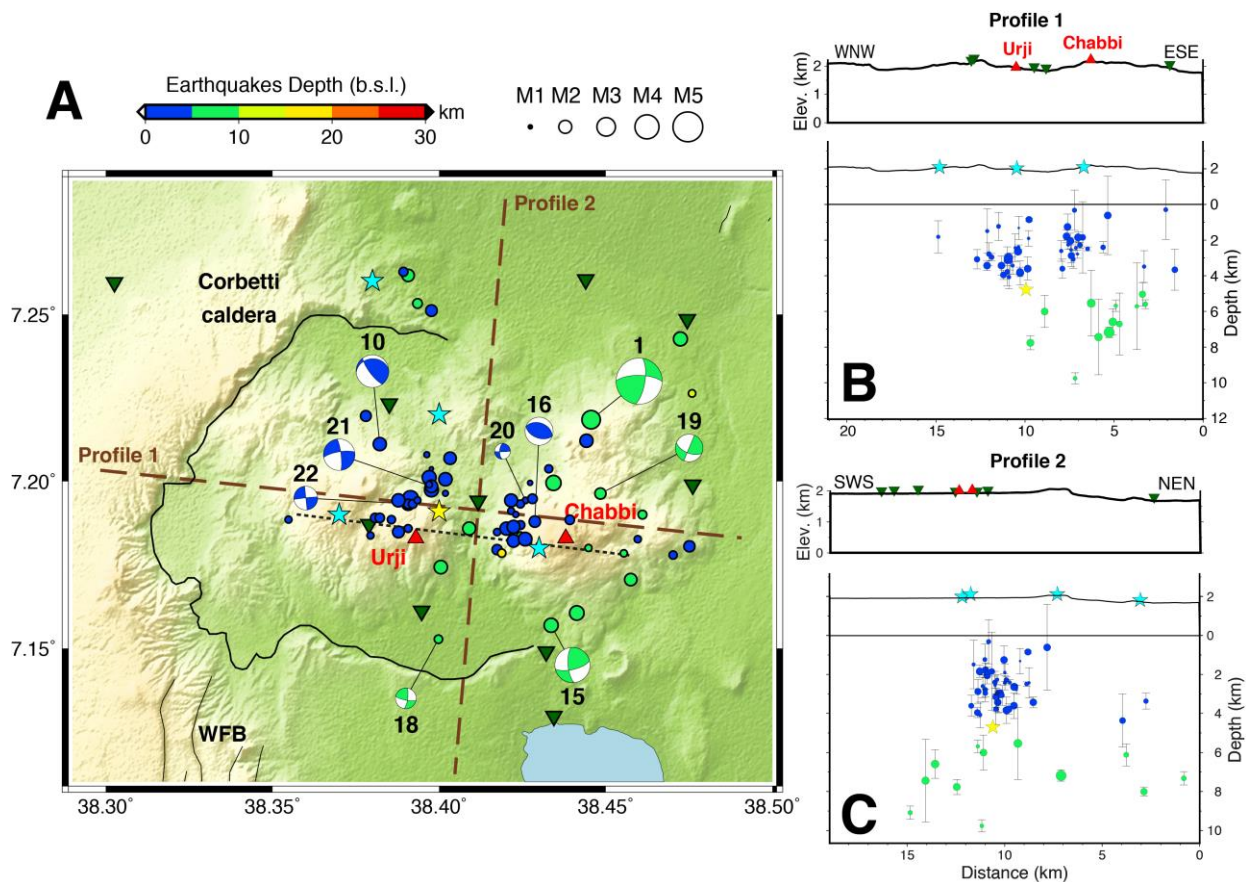
262

4.1 Corbetti caldera

263 The seismicity located within Corbetti caldera is distributed between 0 and 10 km depth below sea
 264 level (b.s.l.). The events occur at or north of a cross-rift structure (Figure 5) (Lloyd, Biggs, Wilks,
 265 et al., 2018). Most of the 5-10 km deep events are located away from the volcano vents and aligned
 266 with the caldera rim, with the exception of two events beneath the centre of the caldera (green
 267 events, Figure 5). The shallower activity (0-5 km), however, is clustered around the northwest side
 268 of Urji and the west side of Chabbi (blue events, Figure 5). The events close to Chabbi form a NS-
 269 oriented cluster whereas the events next to Urji form three groups of earthquakes that align
 270 subparallel and perpendicular to the cross-rift structure (Figure 5). All shallow events seem
 271 enclosed by the 3 hydrothermal vents in the caldera. Note also the small group of 4 earthquakes
 272 located in the north, just outside the caldera, next to a hydrothermal vent (Figure 5).

273 The Corbetti earthquake activity shows no clear pattern in time and do not occur in clear swarms
 274 of activity. Their magnitudes are relatively small, between 0.6 and 3.4 (Figures 4, 5), as expected
 275 near a deforming volcano. A high geothermal gradient and the expected high fracture density
 276 inhibit generation of larger magnitude earthquakes. Most of the focal mechanisms show strike-slip
 277 faults along the caldera rim (events 1, 15, 18 and 19; Figure 5), and strike-slip and thrust
 278 mechanisms for the clusters near the vents (events 10, 16, 20, 21 and 22; Figure 5).

279



280 **Figure 5:** Corbetti volcano seismicity. **A)** Map of epicentral locations at Corbetti volcano. The events are scaled to
 281 magnitude and color-coded with depth b.s.l. Dark brown dashed lines represent traces of cross-sections shown in B

282 and C. The black dashed line is a cross-rift structure identified by Lloyd, Biggs, Wilks, et al. (2018). Blue ellipses
 283 highlight specific groups of earthquakes (see text for details). **B**) Profile 1 across rift axis and **C**) Profile 2 along rift
 284 axis. Green inverted triangles are seismic stations, red triangles highlight the two main volcanic centres. Cyan stars
 285 highlight hydrothermal vents and wells.

286

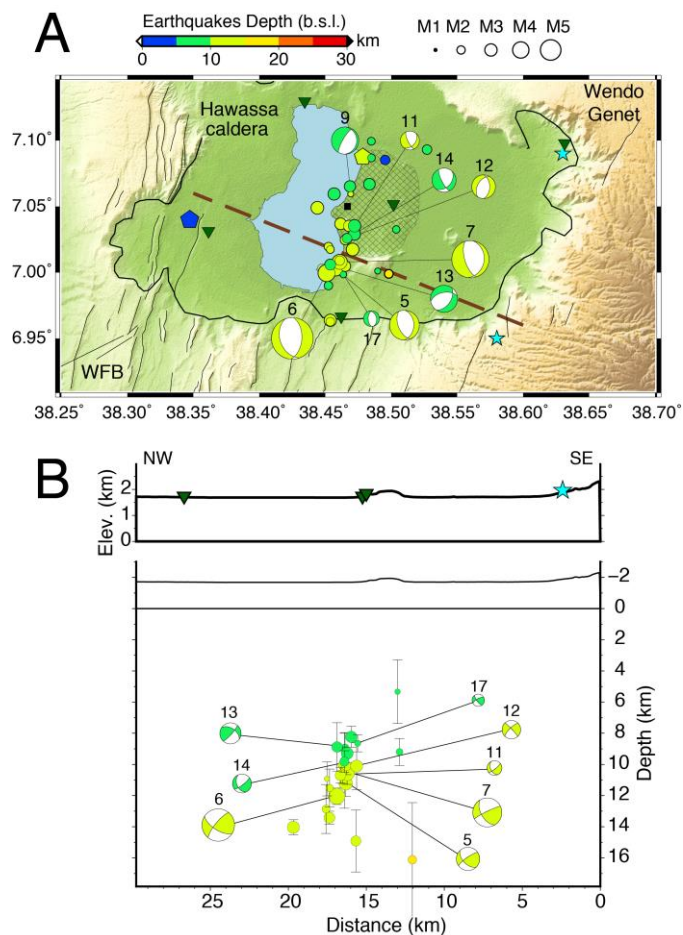
287 The cross-sections were made parallel (Figure 5B) and perpendicular (Figure 5C) to the extension
 288 direction to illustrate the structure at depth. Profile 1 highlights that there is no deep (> 5 km depth)
 289 seismicity beneath Urji and the west side of the caldera. The deep seismicity in the east might
 290 highlight a steep fault beneath the caldera rim. Profile 2 (Figure 5C) shows that the deep seismicity
 291 is not controlled by the cross-rift structure identified by Lloyd, Biggs, Wilks, et al. (2018).
 292 However, the shallow seismicity occurs only north of this structure.

293

294 4.2 Hawassa

295 The events in the Hawassa area have a magnitude range between 1.2 to 4.2 (Figures 4, 6, 7). The
 296 seismicity is distributed between 5 and 16 km depth b.s.l. along the east shore of Lake Hawassa,
 297 with most of the earthquakes located directly beneath Hawassa town (Figure 6A). The epicentral
 298 locations seem to follow the curves of the lake shoreline (Figure 6A).

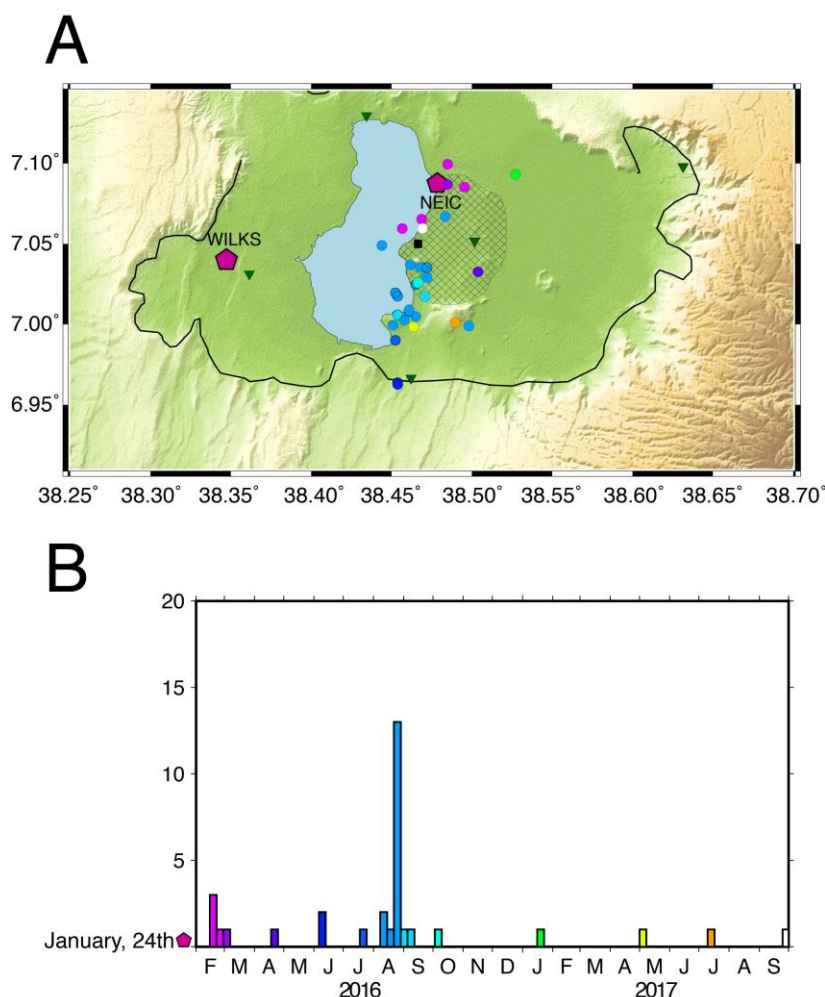
299



300 **Figure 6:** Hawassa seismicity. A) Map of epicentral locations near Hawassa. The events are scaled to magnitude
 301 and color-coded with depth. Dark brown dashed line represents the trace of the cross-section in B. The pentagons
 302 identify the locations of the 24th January 2016 earthquake as determined by the NEIC and Wilks, Ayele, et al.
 303 (2017). The gridded shape represents the extent of Hawassa town (black square). B) Cross-section across the August
 304 2016 swarm. Green inverted triangles are seismic stations. Cyan stars highlight hydrothermal vents and wells.

305
 306 In contrast to the Corbetti earthquakes, the Hawassa seismicity is clustered in time (Figure 7) with
 307 a small swarm of events in February 2016 mainly located on the northeast shore of Lake Hawassa,
 308 and the main swarm in August 2016 located just south of Hawassa town, on the southeast shore of
 309 Lake Hawassa (Figures 6, 7). The clusters highlight 8-10 km-length segments of activity, similar
 310 in length to fault scarps previously mapped (Agostini et al., 2011; Casey et al., 2006)(Figures 6,
 311 7). There is a distinct absence of seismicity on the west side of the caldera where the 24th January
 312 2016 earthquake has been located (Wilks, Ayele, et al., 2017) and in the east near Wendo Genet,
 313 a previously active region (Lloyd, Biggs, Wilks, et al., 2018) (Figures 6, 7).

314



315 **Figure 7:** A) Map of epicentral locations color-coded by time as represented in B. Locations of the 24th January
 316 2016 earthquake as identified by the NEIC and Wilks, Ayele, et al. (2017) are indicated (pink pentagons). Green
 317 inverted triangles are seismic stations. The gridded shape represents the extent of Hawassa town (black square). B)
 318 Time histogram of the seismicity at Hawassa. The January, 24th event is indicated (pink pentagon).

319 The profile in Figure 6B was made perpendicular to the August swarm and only uses events from
320 this cluster. The distribution highlights a steep, $\sim 75^\circ$ dip, fault beneath the lake and the town of
321 Hawassa (Figure 6B). Focal mechanisms all show normal faulting (Figure 6). Correlation with the
322 distribution of the seismicity shows that the fault plane is likely to strike NE-SW and dip toward
323 the west (Figure 6).

324

325 **4.3 Lake Shalla**

326 The Lake Shalla seismicity is located beneath the southeast corner of the lake and is distributed
327 between 5 and 30 km depth b.s.l. Focal mechanism solutions indicate normal faulting along the
328 O'a caldera wall (event 3), as well as beneath the lake (event 4) (Figure 4). The latter contains a
329 strike-slip component. Event 8 from the central group of earthquakes show a near-vertical nodal
330 plane in a normal mechanism (Figure 4). However, Lake Shalla and the O'a caldera are relatively
331 far from our network, and the events' depth are not particularly well constrained.

332

333 **5 Discussion**

334

335 **5.1 Seismogenic thickness and length of faulting**

336 The depth distribution of earthquakes beneath Corbetti and Hawassa calderas map the seismogenic
337 thickness in this area (Scholz, 1988; Watts & Burov, 2003). Moho depth estimates for this region
338 of the MER vary between 30 and 37 km (Dugda, 2005; Stuart et al., 2006), and therefore beneath
339 Hawassa the imaged fault extends to the mid-crust (16 km depth). The seismogenic thickness is
340 similar to the maximum depth of earthquakes further north beneath the MER, constrained at < 18
341 km using a local seismic network (Keir, Ebinger, et al., 2006). It is also consistent with the effective
342 elastic thickness in the MER, constrained at < 15 km by inversion of topography and gravity data
343 (Hayward & Ebinger, 1996; Pérez-Gussinyé et al., 2009). This relatively shallow seismogenic
344 thickness is comparable with other magmatic rifts in the EARS, such as the Afar triple junction ($<$
345 7 km) (Ayele et al., 2007; Pérez-Gussinyé et al., 2009), where the lithosphere is weaker due to
346 intense magmatism (Daniels et al., 2014). On the contrary, regions with little to no magmatic
347 activity have a thicker seismogenic layer (Lavayssière et al., 2019).

348 Earthquakes shallow significantly beneath Corbetti where the maximum earthquake depth is
349 12km. This shallowing of the brittle-ductile transition beneath Corbetti volcano is consistent with
350 a locally higher geothermal gradient. Indeed, most earthquakes are clustered even shallower, above
351 5km depth, beneath the main volcanic centres (Figures 5, 7). This fits geodetic models constrained
352 by InSAR and GPS observations of current surface uplift suggesting the presence of an inflating
353 magma body at 4.6 km depth b.s.l. beneath Corbetti (Lloyd, Biggs, Wilks, et al., 2018). Hence the
354 abrupt shallowing of the brittle-ductile transition beneath Corbetti is interpreted to be caused by
355 magmatic processes.

356 Fault depth is generally scaled to fault length (Foster & Jackson, 1998; Hayward & Ebinger, 1996),
357 relation controlled by the strength of the lithosphere. Indeed, the development of rifting involves
358 thinning and heating of the crust, leading to a decrease in the effective elastic thickness of the

359 lithosphere (Hayward & Ebinger, 1996). The relatively shallow seismogenic layer thickness
360 observed near Lake Hawassa is consistent with the length of active faults in the region. The
361 seismicity detected near Hawassa during our deployment is spatially arranged into 8-10 km long
362 clusters that correlate well with the length of mapped intra-rift faults (Agostini et al., 2011; Casey
363 et al., 2006) (Figures 6, 7). Most of these faults are inactive during our experiment, apart from the
364 two NS-striking faults on the eastern shore of Lake Hawassa. These two adjacent fault segments
365 seem to be active during discrete time periods. The activity on one segment may change the stress
366 field locally and induce activity on the adjacent segment (Cowie, 1998). The relatively short fault
367 segment lengths observed at Hawassa are different to less magma-rich segments in the EARS,
368 such as in the Tanganyika rift where seismicity defines ~30 km-long cluster along the border faults
369 (Lavayssière et al., 2019).

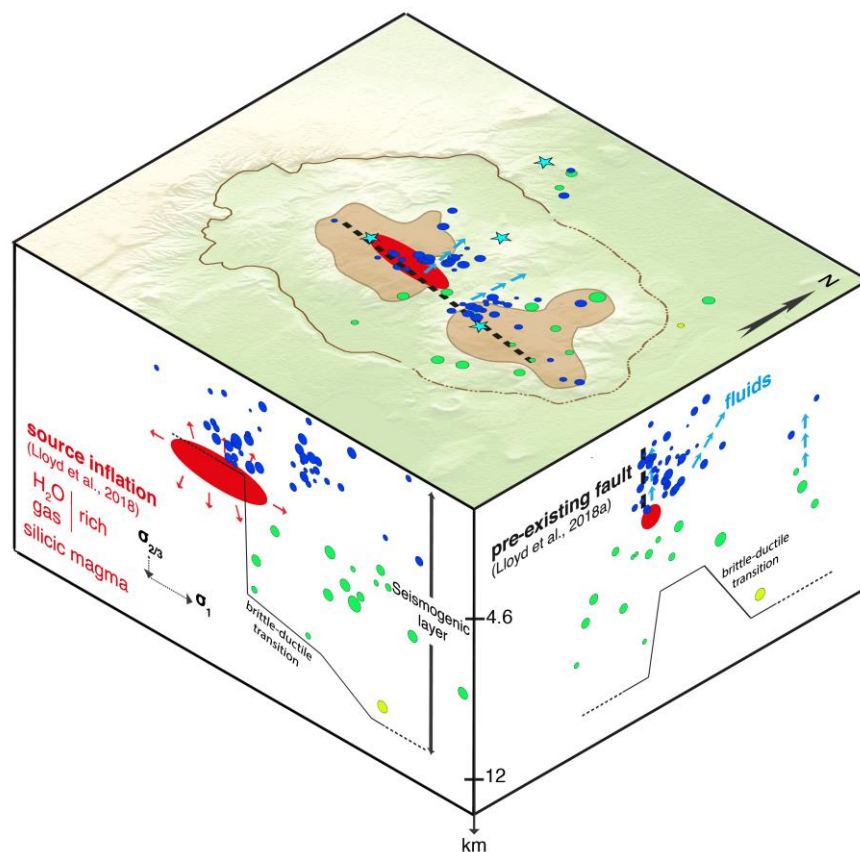
370

371 **5.2 Corbetti volcano**

372 A striking feature of the local seismicity at Corbetti volcano is a distribution of clusters of shallow
373 events beneath Urji and Chabbi and enclosed by hydrothermal vents to the north, west and east of
374 the volcanic centres (Gíslason et al., 2015) (Figures 5, 7). These events are also located north of a
375 previously identified cross-rift structure through Corbetti (Lloyd, Biggs, Wilks, et al., 2018)
376 (Figures 5, 8). Previous interpretations of the fluid flow beneath Corbetti suggest that this structure
377 acts as an impermeable barrier that forces fluids to migrate northward (Gíslason et al., 2015, Lloyd,
378 Biggs, Wilks, et al., 2018). Hence the distribution of earthquakes is consistent with them being
379 induced by pore pressure changes in and near the fracture system from the migration of hot
380 upwelling fluids northward from the cross-rift structure (Figure 8). A similar interpretation of fluid
381 motion induced by fault slip has previously been used to interpret fault-aligned clusters of
382 microseismicity in the Asal-Goubbet rift (Dobre et al., 2007). Alternatively, the seismicity close
383 to the reservoir could also be caused by thermally induced volume changes (contraction and
384 dilatation) of the surrounding rocks (Dobre et al., 2007).

385 Measurement of V_p/V_s ratios can provide crucial subsurface constraints on rock type and fluid
386 content (Christensen, 1996). The V_p/V_s ratio of 1.683 found for our catalogue is relatively low
387 compared to the global average of 1.75 (Christensen, 1996) and to the 1.76 regionally constrained
388 for the upper crust in the region (Greenfield et al., 2018; Keir, Ebinger, et al., 2006). Instead our
389 low V_p/V_s is consistent with the presence of geothermal fluids with heated vapor in the subsurface
390 and/or with silicic magma charged with gas at depth. A low V_p/V_s at depth is often interpreted as
391 a magma chamber with high (55-75%) silica contents (Christensen, 1996; Zhang & Lin, 2014),
392 with a small percent (~2%) of water content (Lin & Shearer, 2009; Nakajima et al., 2001), and/or
393 with the presence of gas (Husen et al., 2004; Lin, 2013). This is consistent with the on-going
394 geothermal activity (Gíslason et al., 2015) and with the silicic volcanic history at Corbetti with 75
395 wt% SiO₂ (Fontijn et al., 2018) and a high content of chemically bound water (Rapprich et al.,
396 2016).

397



398 **Figure 8** : 3D interpretation of Corbetti volcano seismicity. The events are scaled to magnitude and color-coded
 399 with depth b.s.l. The black dashed line represents the cross-rift structure (Lloyd, Biggs, Wilks, et al., 2018). An
 400 assumption on the depth to the brittle-ductile transition is indicated. Cyan stars highlight hydrothermal vents and
 401 wells. See text for details.

402

403 Combination of source mechanisms and shape of the earthquake's distribution can provide
 404 evidence on the position, geometry and slip style of the active fault structures. Nodal planes
 405 solutions at Corbetti are mostly EW and NS but there is no conclusive evidence for which one the
 406 fault plane is. Two groups of earthquakes in the Urji cluster seem to align in an EW orientation
 407 (Figure 5), subparallel to the cross-rift structure (Lloyd, Biggs, Wilks, et al., 2018), indicating that
 408 the EW nodal plane might be the fault plane. However, the northern group of Urji events and the
 409 Chabbi cluster are aligned NS. Hence, as they get further from the pre-existing structure, the faults
 410 seem to change strike from EW (tectonic rift-related stress field or stress due to upward fluid
 411 migration from depth) to NS (possibly related to northward fluid migration). This variation in the
 412 stress field is also evident in observations of shear-wave splitting in local events, which are
 413 interpreted in terms of fracture-induced anisotropy (Lloyd, Biggs, Wilks, et al., 2018). The
 414 anisotropy shows a roughly EW orientation south of the cross-rift structure and more NS to the
 415 north. It is plausible that the stress is perturbed by strike-slip motion and pore-pressure effects
 416 along the cross-rift fault.

417 The difference of focal mechanisms between Corbetti and in the rest of the rift valley show that
418 uplift processes modify the stress-field beneath the volcano. The presence of strike-slip and thrust
419 events at Corbetti vents can be explained by locally reducing the magnitude of the vertical stress
420 to be lower than the regional horizontal stresses. Lloyd, Biggs, Birhanu, et al. (2018) suggest that
421 the pressurization of a horizontal dislocation, or sill, oriented 097° and at 4.6 km depth b.s.l., fit
422 the volume change and uplift of the caldera (Figure 8), and is consistent with our observations.
423 The inflation of a horizontal reservoir would decrease the vertical stress and increase the horizontal
424 stress, leading to a local change of the stress field at the volcano (Figure 8). Thus, the pressure
425 changes due to the inflation explains the occurrence of the strike-slip events (σ_1 horizontal and σ_2
426 vertical) and thrust events (σ_1 horizontal and σ_3 vertical).

427

428 **5.3 Earthquake hazard**

429 The locations of earthquakes we derive for Hawassa shows seismic activity focused on a steep
430 fault on the eastern shore of Lake Hawassa. This does not correlate with the best fitting location
431 of the 24th January 2016 event made by Wilks, Ayele, et al. (2017), but it does correlate with the
432 NEIC location (Figures 6, 7). Both locations were calculated using distant stations (distances $>$
433 200 km) and have large locations errors (1.8 km in latitude, 8 km in longitude and 3 km in depth;
434 Wilks, Ayele, et al., 2017). The January event was interpreted by Wilks, Ayele, et al. (2017) to be
435 a slip along a WFB fault, associated with the caldera rim fault of the Hawassa caldera. It correlates
436 with previous normal faulting events in 1983 and 1995, also located at WFB faults near the caldera
437 west wall. However, there is no evidence for any activity in this area during our period of study.
438 In the contrary, the swarm of activity in February 2016 is located on the northeast shore of Lake
439 Hawassa, coincident with the NEIC location of the January 2016 event. It is likely that aftershocks
440 of the relatively large January 2016 event occurred in the following month and should have been
441 detected by our network. This might indicate that the January event have occurred beneath the
442 northern part of Hawassa, coincident with the February activity.

443 The seismicity is distributed in segments that are particularly visible near Hawassa. The segments
444 on the east shore of Lake Hawassa follow the shape of the lake at the surface, indicating that the
445 fault may reach the surface. Most of the seismicity is located directly beneath Hawassa town
446 (Figures 6A, 7A), increasing the earthquake hazard in this region and showing the importance of
447 a continuous, close monitoring of the area.

448

449 **6 Conclusions**

450

451 To constrain the local seismicity at a rapidly deforming volcano, and better understand magmatic,
452 hydrothermal and fault slip processes, a dense network of 17 stations recorded 122 earthquakes at
453 Corbetti and Hawassa calderas between February 2016 and October 2017. The events, of
454 magnitude 0.4 to 4.2, were located using a new local velocity model. Their spatial distribution is
455 mainly focused between Corbetti caldera and beneath Hawassa town, along the eastern shore of
456 Lake Hawassa.

457 The distribution of the seismicity around Corbetti volcano is focused at shallow depths (0-5 km
458 b.s.l.) beneath its two main volcanic centres, Urji and Chabbi. The earthquake locations are

459 consistent with a northward propagation of hydrothermal fluids coming from beneath Urji and
 460 propagating along a cross-rift, pre-existing structure. Source mechanisms give evidence for a local
 461 stress field change due to the inflation of a gas-rich, silicic sill with a small percent of water content
 462 in the upper crust.

463 The 10-km thick seismogenic layer beneath Corbetti is thinner than beneath Hawassa where it
 464 reaches 16 km, probably due to elevated temperature and fluids beneath the volcano. The deeper
 465 events beneath Hawassa are also higher magnitude and are active in swarms along 8 to 10 km-
 466 long segmented normal faults. The network used in this study detects one of these swarm in August
 467 2016 and give evidence for a steep normal fault beneath the town of Hawassa, demonstrating the
 468 significant earthquake hazard for its population.

469

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478

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