



HAL
open science

Images of the East African Rift System by Global Adaptive-Resolution Surface-Wave Tomography

Félicie Korostelev, Yang Lu, Fabrizio Magrini, Lapo Boschi, Sylvie Leroy,
William Vétel

► **To cite this version:**

Félicie Korostelev, Yang Lu, Fabrizio Magrini, Lapo Boschi, Sylvie Leroy, et al.. Images of the East African Rift System by Global Adaptive-Resolution Surface-Wave Tomography. *Journal of Geophysical Research: Solid Earth*, 2022, 127 (6), pp.e2021JB023570. 10.1029/2021JB023570 . insu-03747376

HAL Id: insu-03747376

<https://insu.hal.science/insu-03747376v1>

Submitted on 20 Oct 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Images of the East African Rift System by Global Adaptive-Resolution Surface-Wave Tomography

Félicie Korostelev¹, Yang Lu^{2,3}, Fabrizio Magrini^{4,5}, Lapo Boschi^{1,6}, Sylvie Leroy¹, William Vétel⁷

¹Sorbonne Université, CNRS, INSU, Institut des Sciences de la Terre de Paris, ISTeP UMR 7193, F-75005

Paris, France.

²Department of Earth Sciences, University of Southern California, USA

³Department of Meteorology and Geophysics, University of Vienna, Austria

⁴Department of Geological Science, Università degli Studi Roma Tre, Italy

⁵Institute of Geosciences, Johannes Gutenberg University, Mainz, Germany

⁶Dipartimento di Geoscienze, Università degli Studi di Padova, Italy

⁷Total Exploration et Production, Pau, France

Key Points:

- Joint inversion of global and regional phase-velocity measurements using an adaptive parameterization
- Global phase-velocity maps characterized by an improved resolution throughout the East African Rift System
- Low-velocity anomaly beneath Mozambique Channel probably ascribed to a significant magmatic system

Abstract

In this study we map the entire East African Rift System (EARS) within a global surface-wave velocity model to better constrain the structure of the underlying mantle, as well as patterns that might be associated with its continuation in the Mozambique Channel. We use all publicly available seismograms from the African continent, amounting to 1296 stations and more than 30 years of recordings. From these data, we obtain dispersion curves using both ambient noise and teleseismic earthquakes. To our measurements, we add global counterparts and jointly invert them for phase-velocity maps. We exploit a linearized inversion based on the ray theory, with an adaptive parameterization that allows for maximizing the resolution of the final maps based on the density of data coverage. We thus image the main African cratons and also some of the Archean blocks within them. We highlight the discontinuous nature of magmatic activity along the EARS and also display low-velocity anomalies beneath the Comores Archipelago, Madagascar and Bassas da India volcanic islands and seamounts. This last low-velocity anomaly is in the direct continuation of the EARS and could unveil an important magmatic system in the Mozambique Channel.

Plain Language Summary

The East African Rift System (EARS) is where tectonic plates are breaking and drifting apart in Africa. The opening of the EARS most probably finds its origin in the forces existing in the underlying mantle. The goal of this study is to better understand the structure of the inside of the Earth in the region. To do that, we use waves registered by seismometers to create maps of the crust and upper mantle (the lithosphere). These maps display where the waves travel at different speed, giving us information about the Earth's structure. In our maps of wave speed, we see several very interesting things. First, we see fast speeds in areas of thick lithosphere (cratons), and our resolution gives us some details on their inner structure. Then, we see three patches of slow speeds along the EARS, suggesting that this system is discontinuous, with some very active points where volcanic fields are present. Finally, we see slow speeds in the Mozambique Channel, where no such feature was reported before. This suggests that the lithosphere is hot there and perhaps contains some melt. This may show the development of the EARS southwards into the Mozambique Channel.

1 Introduction

The East African Rift system (EARS) is a complex feature that runs approximately from north to south in East Africa, i.e. from Eritrea, Djibouti and Ethiopia to Mozambique (McConnell, 1972; Chorowicz, 2005; Ring, 2014). At its northern end, the EARS connects to the Red Sea and Gulf of Aden rifts in the wide Afar depression. The Main Ethiopian Rift is located directly south of the Afar depression. Afar and the Main Ethiopian Rift are characterized by active magmatic segments in which extension mainly occurs (Ebinger & Casey, 2001). Further south, the EARS splits into two branches that surround the Tanzanian craton (see fig. 1). The eastern branch (B. H. Baker et al., 1972; Ebinger, 2005) consists of the wide Turkana Depression and the Kenya narrow rift. The western branch (Ebinger, 1989; Daly et al., 1989) is composed of the Albert-Edward (NE-SW), Kivu (N-S) and Tanganyika-Rukwa (NW-SE) rifts (fig.1). It is prolonged in the south by the Malawi rift (Ring et al., 1992; Laó-Dávila et al., 2015) that has an active volcanic province at its northern end: the Rungwe volcanic province, in Tanzania (Ebinger, 1989; Fontijn et al., 2012; Borrego et al., 2018).

The emergence of the EARS is linked to an extensive volcanic activity with voluminous Tertiary flood basalts on the Ethiopian high plateaus, and is possibly due to one, two or three mantle plumes (e.g., Bastow et al., 2008; Benoit et al., 2006; Hansen & Nyblade, 2013; Ritsema et al., 2011; S.-J. Chang et al., 2020). Its particular geometry is ascribed to the location of different Archean cratons (McConnell, 1972; Mohr, 1982). The eastern and western branches circle the Archean Tanzanian craton (Bell & Dodson, 1981; Chesley et al., 1999; Many, 2011). The Western branch is flanked in the west by the Congo craton (De Waele et al., 2008), composed of several smaller blocks. To the south, the Zimbabwe, Kaapval and Kalahari cratons are the main large-scale structures (Nguuri et al., 2001; Jacobs et al., 2008) (fig. 1).

The African continent, and more particularly its eastern part, has been widely studied in the last decades, but not thoroughly characterized. Several seismological studies (e.g., Korostelev et al., 2015; Adams et al., 2018; Plasman et al., 2019; White-Gaynor et al., 2020; Clutier et al., 2021) only focused on the small-scale structure of specific parts of the EARS, based on temporary and permanent seismic networks deployed in the respective regions of interest. On the contrary, global studies (e.g., Ekström, 2011; Auer et al., 2014; Ruan et al., 2019; Celli et al., 2020) can only afford a coarser resolution, and display the Afar and Main

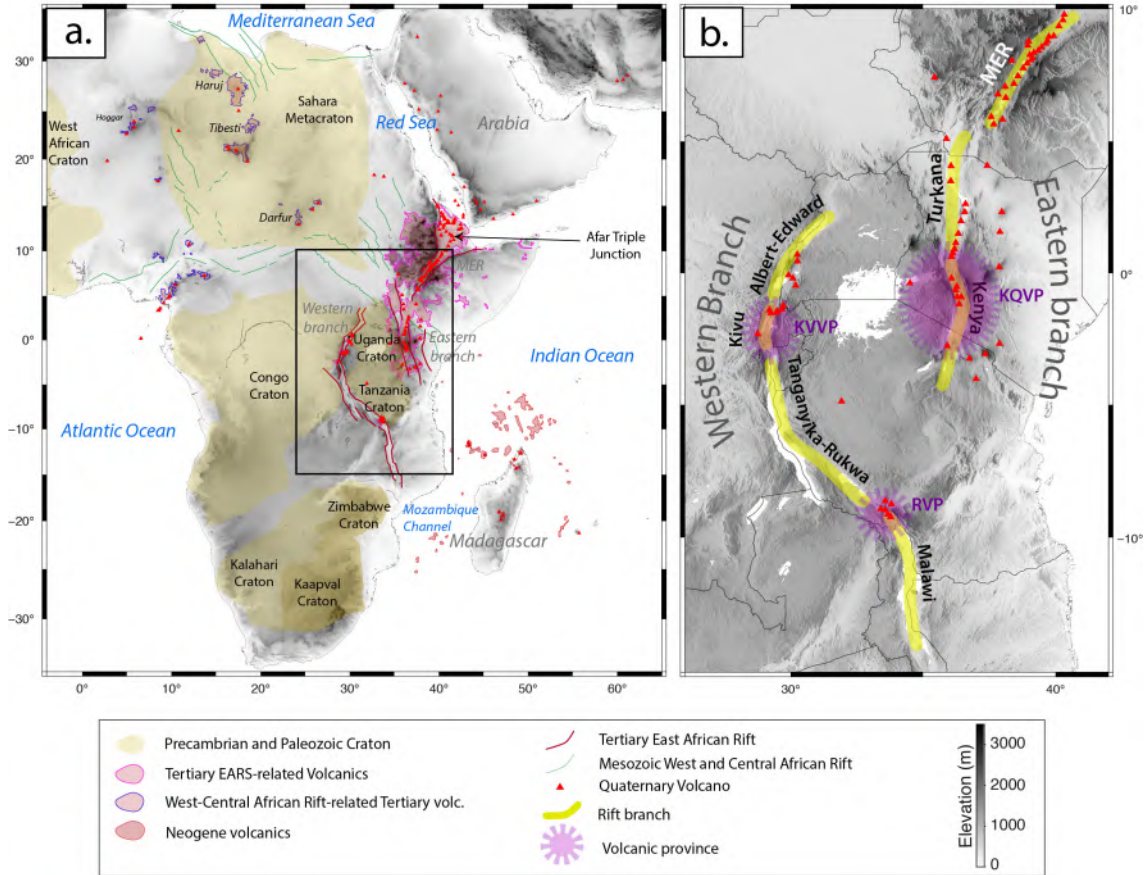


Figure 1. a. Structural map of our interest region, showing the location and extent of the Archean cratons, Tertiary volcanism and EARS main structures. Red triangles are volcanoes (modified from Global Volcanism Program (2013)). Structures are from Globig et al. (2016). b. Map of the EARS showing the main rifts and volcanic provinces. Abbreviations: KVVP Kivu Virunga Volcanic Province, KQVP Kenya Quaternary Volcanic Province, RVP Rungwe Volcanic Province, MER Main Ethiopian Rift.

81 Ethiopian Rift as a large low velocity anomaly in the upper mantle, and the South African
 82 Superswell in the lower mantle (Ritsema et al., 1999; Davaille & Romanowicz, 2020).

83 The aim of this study is to enhance the resolution of the seismic images of the EARS. To
 84 do that, we use publicly available seismograms to obtain Rayleigh-wave dispersion curves.
 85 We combine these dispersion curves with the global ones measured by Ekström (2011). We
 86 then translate the collected dispersion curves into global maps using a linearized inversion
 87 based on the ray theory, as explained in section 3. Our inversion scheme allows for an
 88 adaptive parameterization based on the density of data coverage, that enables us to obtain
 89 a global model characterized by an improved resolution across Eastern Africa in comparison
 90 with previous studies. We present the results and our interpretation of the most relevant
 91 features of our maps in section 4. A 3D analysis will be the subject of a future study based
 92 on a larger regional dataset.

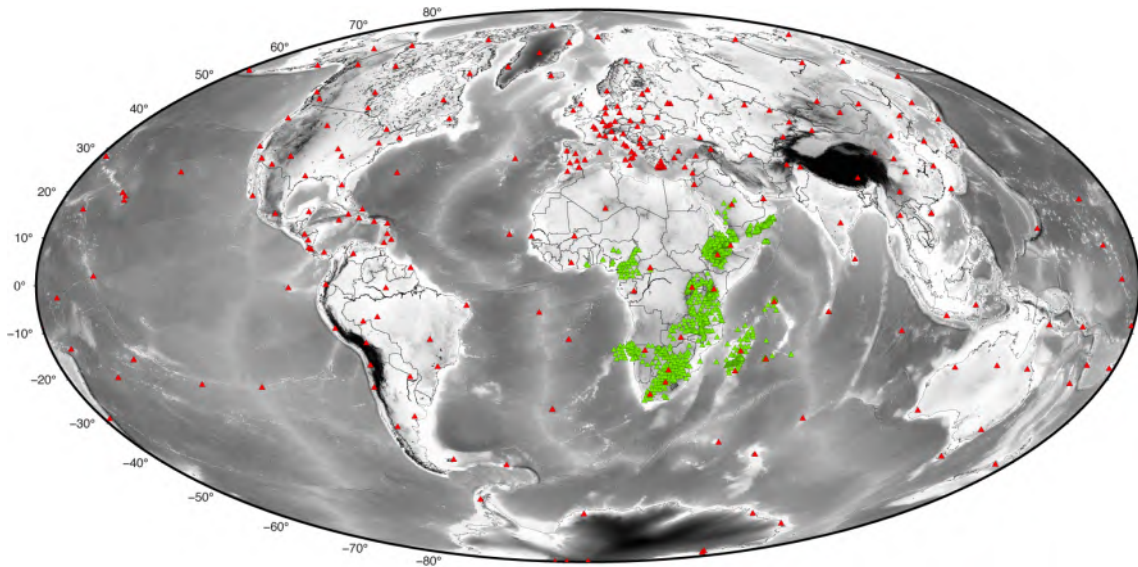


Figure 2. Regional and global datasets. Stations from global dataset are shown in red (Ekström, 2011), stations from regional dataset are shown in green. Regional stations are mainly located along eastern Africa, with a particularly dense coverage over the Afar rift (Ethiopia).

93 2 Rayleigh-wave phase-velocities

94 We download publicly-available seismograms from 54 seismic networks (fig. 2): 10
 95 permanent and 44 temporary ones. The geographic distribution of the sensors, which is

96 particularly dense across the eastern part of Africa, provides us with a relatively good
97 seismic coverage of the EARS.

98 We process the seismic data following two different criteria, detailed below, to obtain
99 measurements of fundamental-mode Rayleigh-wave phase-velocities between pairs of sensors.
100 The phase-velocities are calculated based on both teleseismic earthquakes (EQ) and seismic
101 ambient noise (AN). The two datasets carry complementary information (e.g., Zhou et al.,
102 2012): while ambient noise is dominated by relatively high frequencies and thus provides
103 information on shallow structures, teleseismic data are sensitive to deeper parts of the Earth.

104 **2.1 Seismic ambient noise**

105 We exploit continuous recordings obtained on the vertical component of 1,231 seismic
106 sensors belonging to 54 regional networks located in Africa and deployed between 1980
107 and 2017. We use these seismograms to obtain 38,469 inter-station phase velocities of AN
108 generated Rayleigh waves, using the automated algorithm of Kästle et al. (2016). In practice,
109 for each pair of stations that recorded simultaneously for at least six months, we subdivide
110 their continuous seismograms into overlapping (50%) one-hour-long time windows. In each
111 temporal interval, we apply spectral whitening (Bensen et al., 2007) to mitigate the effects
112 of anomalous signals such as strong local earthquakes or anthropic noise (Boschi et al.,
113 2013). Then we cross correlate the waveforms of the two sensors daily in the frequency
114 domain. The daily cross-correlations are added to one another, or 'stacked' to obtain a
115 unique, robust cross-spectrum, and that can be used to extract the inter-station dispersion
116 curve as explained in Ekström et al. (2009).

117 Our measurements cover the period range 3-200 s, with a maximum number of mea-
118 surements below 50 s (fig. 3a). In this study, we only focus on measurements recorded
119 between 10 and 100 s. Measurements below 25 s cannot be inverted jointly with the global
120 dataset of Ekström (2011) because it does not offer data below 25 s. Usually, AN is used
121 for periods up to 50 to 60 s (e.g., Magrini et al., 2020). However, some studies showed that
122 greater periods are also reliable (e.g., Luo et al., 2015; Emry et al., 2019).

123 **2.2 Teleseisms**

124 We exploit 1,328 teleseismic events recorded by 1,207 public sensors from 54 global or
125 regional networks located in Africa and deployed from 1980 to 2017. We select teleseismic

126 events distant of 20° to 150° from recording stations, with a minimum magnitude of 6.5
 127 to
 128 get a good signal/noise ratio (fig. 4). This results in 38,390 triplets of stations and sources
 129 approximately lying along the same great circle path.

129 We calculate earthquake-based (EQ) phase velocities using a two-station method (e.g.,
 130 Meier et al., 2004; Soomro et al., 2016), based on the automated algorithm of Magrini et al.
 131 (2020). The two-station method measures the frequency-dependent phase delay of a surface
 132 wave observed at pairs of sensors that are approximately aligned on the same great circle
 133 path as the epicenter (we set the maximum azimuthal deviation to 5°). Via tight
 134 bandpass

134 filters, the delay is calculated at discrete periods by cross-correlation and used to retrieve the
 135 phase-velocity through the dispersion relation (Magrini et al., 2020). For each station pair,
 136 the final measurement is calculated as an average carried out over at least three dispersion
 137 curves (corresponding to an equal number of earthquakes). Station pairs associated with less
 138 than three earthquakes or with dispersion curves characterized by relatively large standard
 139 deviations (we follow the Interquartile Range rule (Tukey, 1977) with outlier constant set
 140 to 0.1) are discarded.

141 To account for possible deviations from the great-circle path in the wave propagation,
 142 we apply a procedure which Magrini et al. (2020) refer to as "arrival-angle correction". In
 143 practice, the dispersion measurements are corrected by measuring the arrival azimuth of the
 144 Rayleigh-waves at the sensors. The arrival angle is used to convert apparent phase velocity
 145 into true phase velocity (eq.(11) of Magrini et al., 2020). We obtain 10,362 dispersion
 146 curves without correction and 7,233 dispersion curves with the arrival-angle correction. As
 147 illustrated in figure 3b, the difference between EQ and AN is always small (less than 0.05
 148 km/s), which means that EQ and AN data are compatible. The arrival-angle correction has
 149 the effect of reducing the bias until at least 60 seconds. This bias is commonly amounting
 150 to few percentage points (e.g., Yao et al., 2006; Kästle et al., 2016). Above 60 seconds the
 151 correction is not obviously useful, but the bias remains smaller than 0.02 km/s.

152 **2.3 Global dataset**

153 To enhance the data coverage in regions characterized by relatively few interstation
 154 paths, we additionally take advantage of a global-scale, relatively long period database of
 155 surface-wave dispersion. The global dataset was compiled by Ekström (2011) and consists
 156 of surface-wave phase-velocity anomalies with respect to PREM (Dziewonski & Anderson,

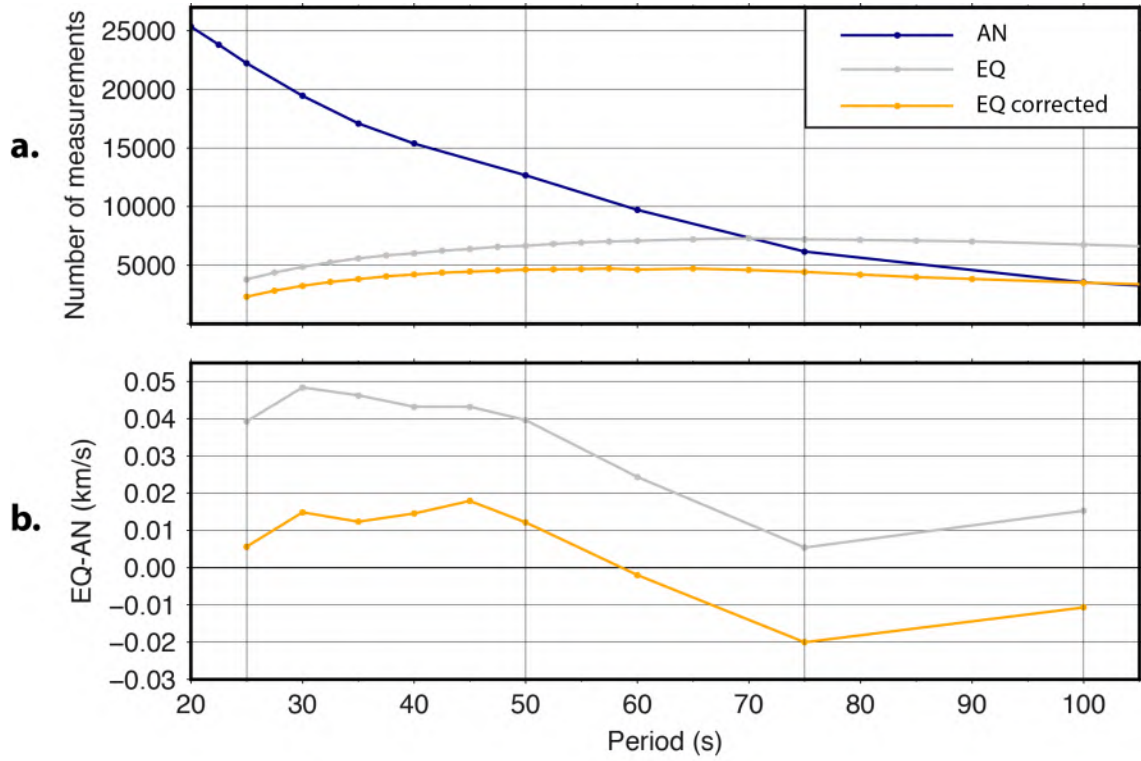


Figure 3. a. Number of measurements available for each method as function of period: ambient noise (AN) in blue, and earthquake (EQ) in orange and grey, with and without arrival-angle correction, respectively. b. Differences between the dispersion curves obtained from the ambient noise and teleseisms methods, averaged over all pairs.

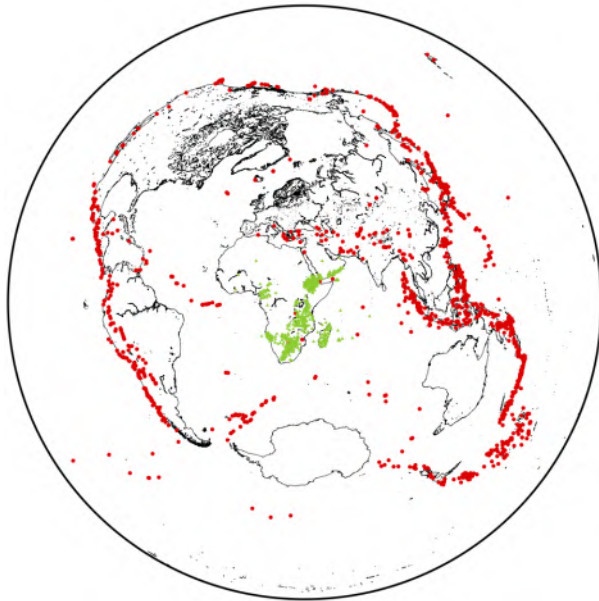


Figure 4. Teleseismic events exploited in this study are in red. Sensors from regional dataset are shown in green.

157 1981). We make use of Rayleigh-wave phase-velocity measurements of 3,330 teleseisms by
 158 258 seismographic stations (fig. 2) located all over the globe (Ekström, 2011).

159 We also compare delays obtained from regional and global datasets in order to assess
 160 the coherence of both datasets. Delays are the difference in travel times between observed
 161 and predicted Rayleigh waves and are calculated relative to the Preliminary Reference Earth
 162 Model (known as PREM) of Dziewonski and Anderson (1981). Figure 5 shows the distri-
 163 bution of delays from global (red) and regional (blue) datasets. Global delays spread over a
 164 wider range than regional ones. Regional dataset also displays a light shift towards slower
 165 delays at short period (25 s). This could be explained by the fact that regional networks
 166 mainly lie on eastern Africa, where the EARS displays low velocity features (e.g. Bastow et
 167 al., 2005; S. Chang et al., 2011; Adams et al., 2018). However, regional delays fall within
 168 the range of global delays.

169 **3 From dispersion curves to phase-velocity maps**

170 At discrete periods, we use the dispersion curves calculated as explained in Section 2
 171 to compute Rayleigh-wave travel times between pairs of sensors with the forward problem
 172 formulated under infinite-frequency ray approximation. The surface-waves are assumed to
 173 propagate only on the surface of the Earth and only along the great-circle path connecting
 174 sensor-sensor (for AN) or epicenter-sensor (for EQ). The inversion method used here is
 175 originally formulated in Boschi and Dziewonski (1999), and further elaborated in many
 176 recent studies (e.g., Schaefer et al., 2011; Lu et al., 2018). In the following, we describe our
 177 technical implementation, but more theoretical details could be found in the literature as
 178 listed above.

179 Adaptive parameterization has been the subject of many tomographic studies (e.g.,
 180 Curtis & Snieder, 1997; Bodin & Sambridge, 2009; Schaefer et al., 2011). These methods
 181 aim at building an optimal model grid that matches the spatial variability of seismic data
 182 content to better condition the inverse problem. This is particularly important in studies
 183 attempting to integrate the results of local and global tomography, despite the significant
 184 discrepancy in data density within the region of interest and in the rest of the globe. Here,
 185 we use an adaptive parameterization algorithm following Schaefer et al. (2011). We define
 186 an adaptive grid depending on ray-path density using a four-level stepwise refining process.
 187 The model is first discretized on an initial equal-area uniform grid with coarse ($3^\circ \times 3^\circ$) node

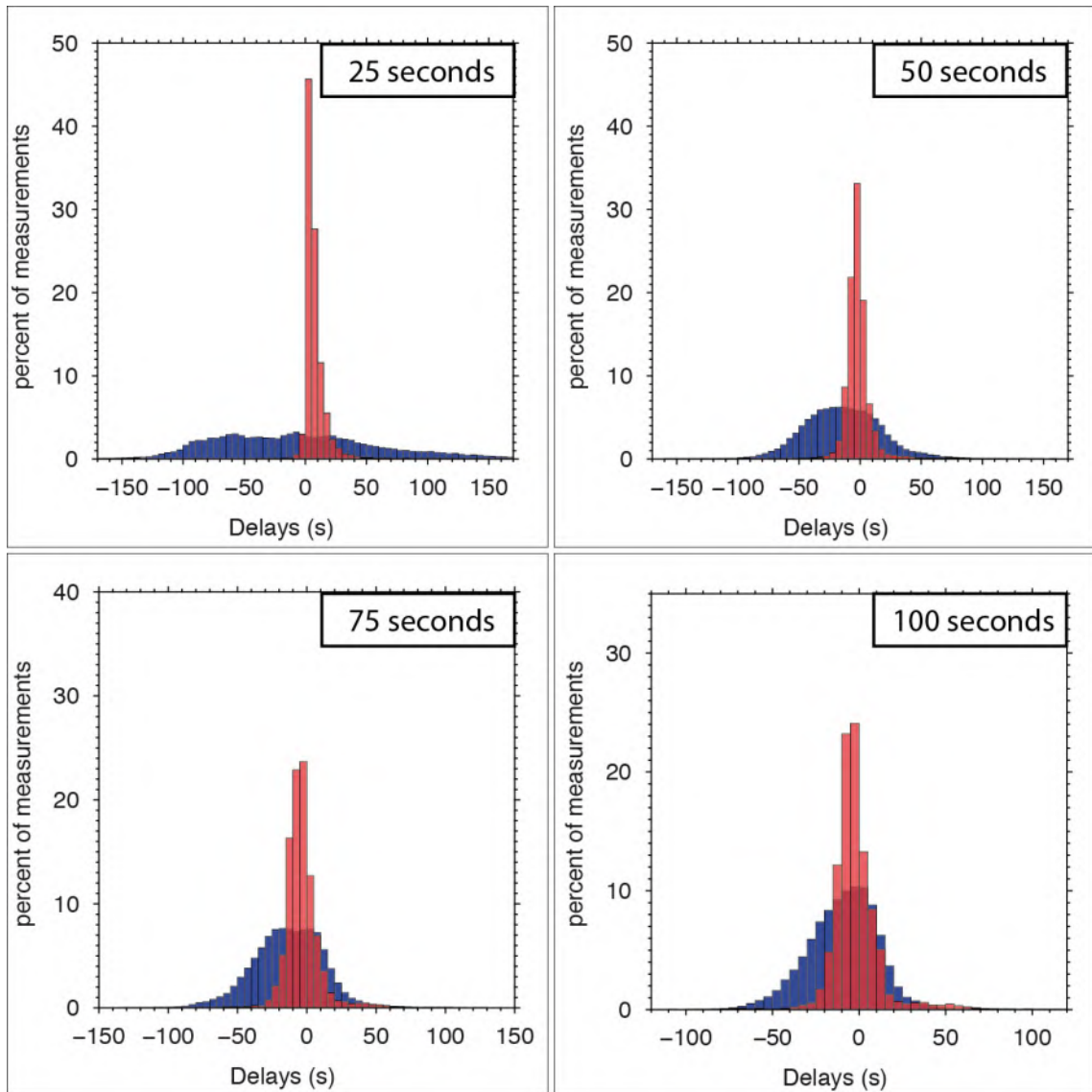


Figure 5. Distribution of Rayleigh-wave phase delays measured from global (blue) and regional (red) datasets at the periods of 25, 50, 75, and 100 s in percent. Delays are the difference in travel times between observed and predicted Rayleigh waves and are calculated relative to the Preliminary Reference Earth Model (known as PREM) of Dziewonski and Anderson (1981). Global data are from the study of Ekström (2011). Regional data are from 2-station observations of Rayleigh waves from both noise and teleseisms.

188 spacing, and then the grid cells intersected by more than 4000 great-circle paths associated
 189 with surface-wave measurements are iteratively refined in three steps. In each step, any
 190 grid cell meeting a preset number of intersecting great-circle paths (4000 hitcounts here)
 191 will be further split into four smaller cells. The final constructed grid allows for eight
 192 times of node spacing differences between the coarsest grid cell and the finest one (0.375°
 X
 193 0.375°). This procedure implicitly contributes to regularize the inverse problem by optimizing
 194 the constraints given by the data on each model parameter. This also results in a better
 195 resolution in the regions characterized by good data coverage.

196 The tomographic problem is usually solved in the least square sense with regularization
 197 to reduce instabilities in the solution. Following Boschi and Dziewonski (1999), we define
 198 the linear inverse problem in the following matrix form

$$199 \begin{bmatrix} \mathbf{A} \\ \mu \mathbf{G} \end{bmatrix} * x = \begin{bmatrix} \mathbf{d} \\ \mathbf{0} \end{bmatrix} \quad (1)$$

200

201

202 where the first relation $A * x = d$ describes the generally ill-conditioned forward prob-
 203 lem, and the second relation represents the roughness damping regularization term. In the
 204 first relation, the matrix A denotes the kernels discretized in the grid basis, d the data, and
 205 x the model unknowns. μ denotes the weight assigned to the regularization constraint, and
 206 G the first-order differential operator of model parameter x with respect to location.

207 Roughness damping imposes a regional smoothing effect by minimizing the gradient of
 208 the model solution, thus removing the bias toward the initial model. The assumption of
 209 regional smoothness is actually reasonable seeing that small-scale heterogeneities would not
 210 be properly accounted for in a ray-approximation tomographic framework, and smoothing
 211 somewhat ends up playing the role of finite frequency kernels (De Hoop & van Der Hilst,
 212 2005). The roughness damping term is implemented by the differential operator G , which
 213 implies the first-order smoothness for adjacent grid cells. The solution of the linear problem
 214 is approximated via an iterative LSQR algorithm (Paige & Saunders, 1982).

215 **4 Results and discussion**

216 **4.1 Checkerboard Test**

217 Synthetic checkerboard tests are computed in order to investigate the robustness of
218 the solution model for large- and small-scale velocity anomalies. For these tests we use the
219 same pairs of stations as in our dataset to predict the Rayleigh-wave phase-velocities for a
220 synthetic checkerboard structure.

221 The large-scale checkerboard consists of $15^\circ \times 15^\circ$ anomalies that alternate
between

222 slow (-10%) and fast (+10%) velocity (see fig. 6). The dataset calculated through this
223 synthetic velocity model is then inverted, and the retrieved velocity variations provide an
224 indication of the resolution that can be achieved in our solution velocity model (shown in
225 fig. 6). At all periods, the $15^\circ \times 15^\circ$ checkerboard pattern is retrieved well by our
global
226 dataset. We notice that resolution is higher from 50 seconds on, which can be explained by
227 the larger size of the global dataset at these periods. The resolution is poorer at the poles
228 due to reduced station density and data coverage.

229 Figure 7 shows the small-scale checkerboard test, illustrating the resolution provided
230 by regional networks in Africa. The exact same dataset as for the global test is used, but
231 the checkerboard consists of $3^\circ \times 3^\circ$ velocity anomalies separated by 1.5° gaps (input
model
232 in fig. 7). Solution models shown in figure 7 confirm the best resolution is obtained in the
233 areas covered by most stations, where we can resolve structures of a lateral extent down to
234 3° . The 3° blocks are too small to be resolved beneath western Africa and under the
oceans.

235 Figure 8 shows two checkerboard resolution tests at 10 s. The first one displays 6°
X
236 6° checkers whereas the second one displays $3^\circ \times 3^\circ$ checkers. At this period we are
able
237 to retrieve the anomalies along the EARS, southern Africa and Madagascar, which are the
238 areas with the best data coverage.

239 **4.2 Maps**

240 Following the procedure explained in section 3, we obtained phase-velocity maps at
241 different surface-wave periods at both global (fig. 9) scale and regional (fig. 10) scale.
242 Our global phase-velocity maps display all the prominent features of those of Ekström
243 (2011) at the same periods, such as cratonic areas and mid-oceanic ridges for instance. The

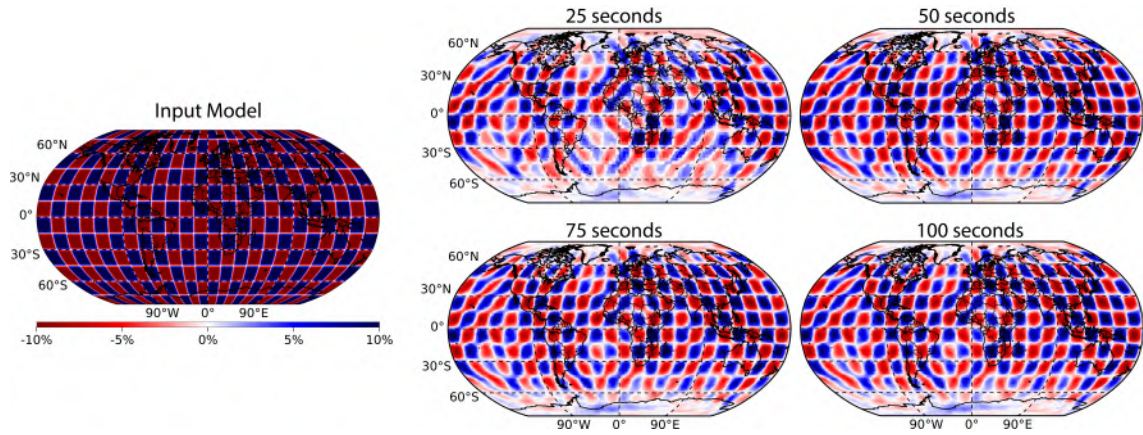


Figure 6. Large-scale checkerboard test. Left panel shows the input model, solution models for 25, 50, 75 and 100 s are to the right.

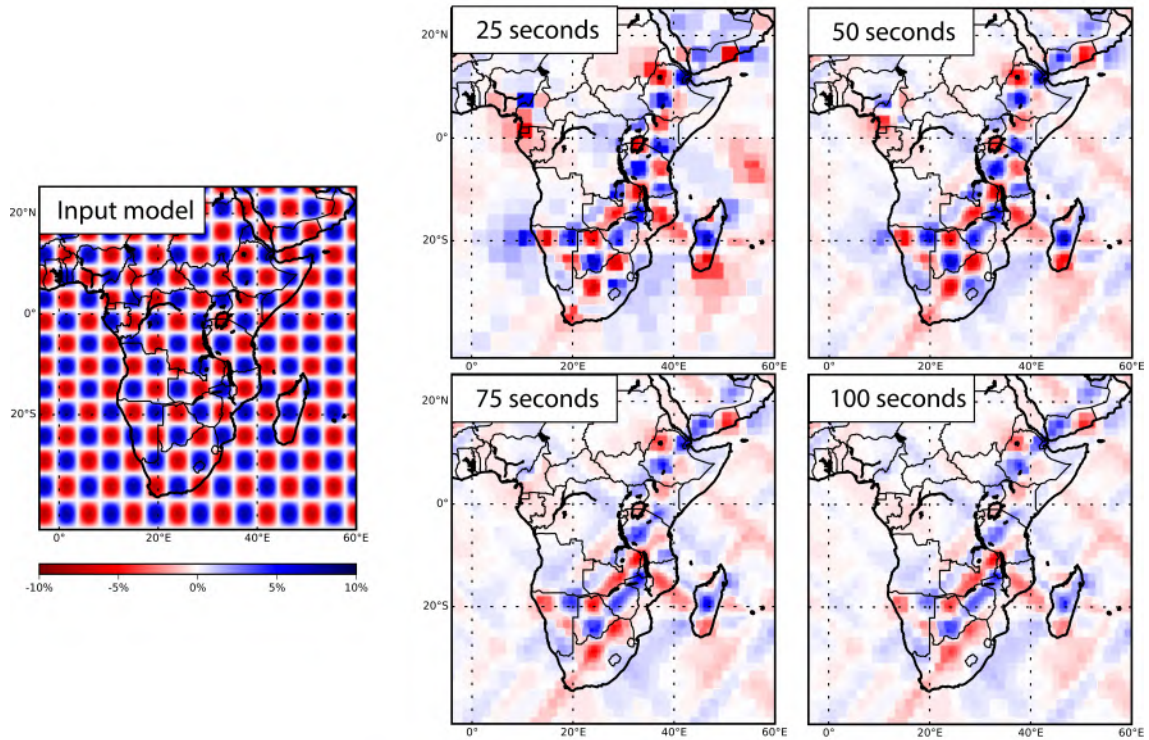


Figure 7. Small-scale checkerboard test. Left panel shows the input model, solution models for 25, 50, 75 and 100 s are to the right.

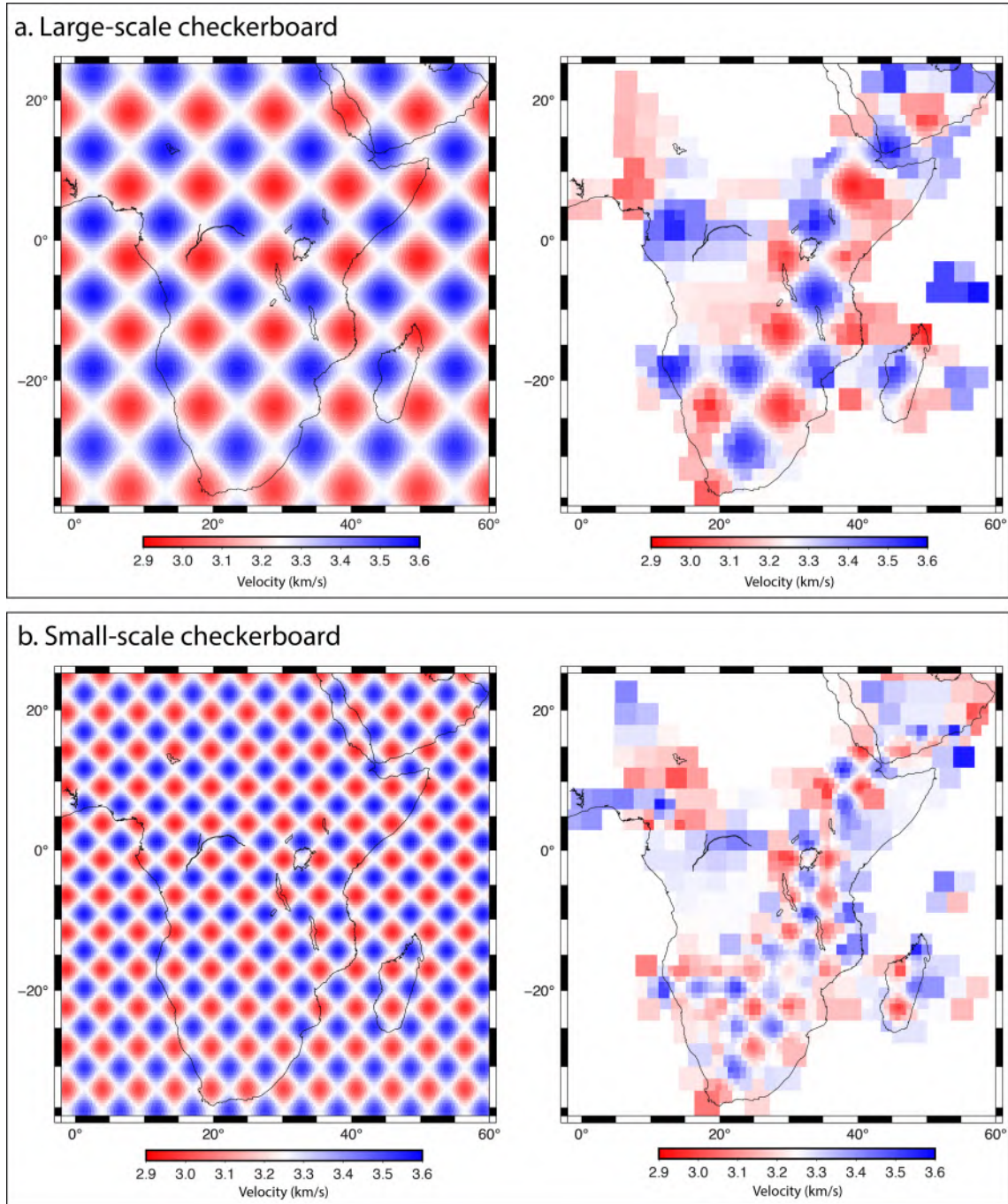


Figure 8. Checkerboard tests at 10 s. a. Large-scale checkerboard test. Left panel shows the input model ($6^\circ \times 6^\circ$ anomalies separated by a 1.5° gap), solution model is to the right. b. Small-scale checkerboard test. Left panel shows the input model ($3^\circ \times 3^\circ$ anomalies separated by a 0.75° gap), solution model is to the right.

245 increased resolution in this area relatively to other global studies (e.g. Ekström, 2011; Auer
246 et al., 2014; Ruan et al., 2019). A comparison of resolution tests over Africa using (i) the
247 global dataset and (ii) the global and regional dataset are found as Supporting Information.
248 We additionally show another map at 10 s, computed from the regional dataset only, and
249 centered on the EARS (fig. 11).

250 Rayleigh-wave phase-velocity maps show velocity anomalies at discrete periods. We
251 can use the sensitivity kernels as shown in figure 12c to understand the depth range that
252 can be resolved at each period. At 10s, the sensitivity kernel peak is above 20 km depth,
253 meaning that the Rayleigh-waves mainly sample the crust. At 50 s, the peak is around 65 km
254 depth, so the maps show velocity anomalies that reflect the structure of the crust and the
255 uppermost mantle. For larger period we present in this study Rayleigh-waves mainly sample
256 the upper mantle.

257 The adaptative grids calculated at each period are also shown in figure 9. The best
258 illuminated areas are located in the Pacific Ocean, North America, Europe and Asia, because
259 of a high seismicity and/or high concentration of permanent stations. As we added regional
260 African networks to our global study, we increase the data coverage over eastern Africa.
261 The adaptative grid thus displays smaller grid cells on this area.

262 Figure 10 shows ray-paths for the regional dataset at each period. The number of
263 ray-paths for our regional dataset decreases from 25 to 100 seconds, as shown also in figure
264 3a. Noise data provide information mainly on the eastern part of Africa, Madagascar and
265 the Mozambique Channel. EQ ray-paths quantity is the highest at 50 seconds, and provide
266 informations on eastern Africa as well as in the Indian Ocean. Global ray-path density from
267 Ekström (2011) increases from 25 s to 100 s (fig. 10).

268 Figure 11b is a 2D Rayleigh-wave phase velocity map at 10 s. At this period, we can
269 resolve crustal structures. This map has been computed without the addition of global data,
270 and thus displays the inversion of only regional data. Ray-paths at 10 s (fig. 11a) show
271 that we have a very high density of rays above the EARS region, southern Africa, southern
272 Arabia and Madagascar.

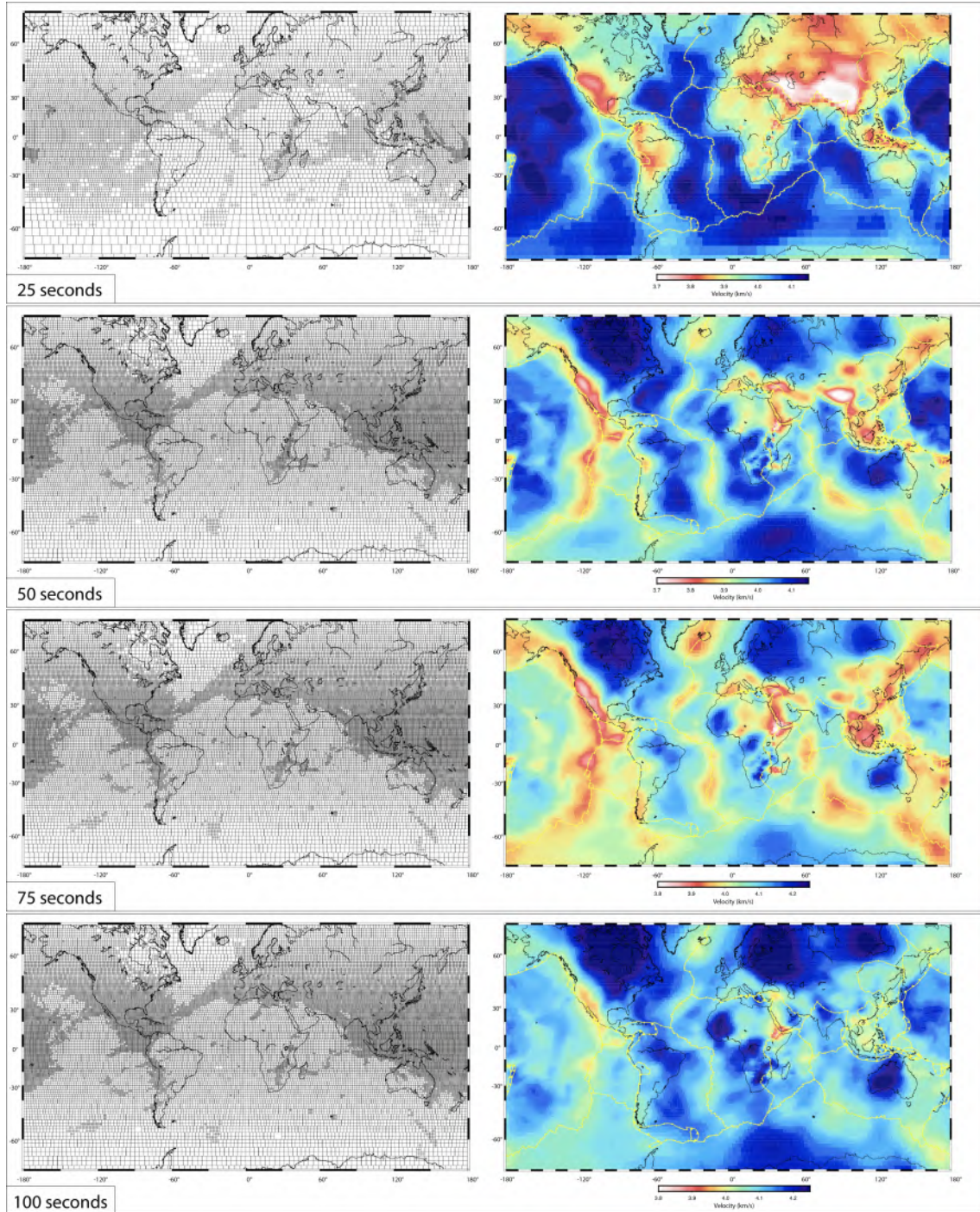


Figure 9. 2D Rayleigh wave phase velocity maps at 25, 50, 75 and 100 s. Plate boundaries from Bird (2003).

273 **4.2.1 The East African Rift System**

274 On previous global studies, the main visible feature of Africa was the Afar low-velocity
275 anomaly, suggesting the presence of a mantle plume under the Afar triple junction (Ekström,
276 2011; Auer et al., 2014). Recent studies (Emry et al., 2019; Celli et al., 2020) show an
277 improved resolution over the area: the Main Ethiopian Rift and a low-velocity anomaly
278 beneath the Eastern Branch are identified. The regional study of Emry et al. (2019) even
279 displays a low-velocity feature beneath the Kivu-Virunga Volcanic Province.

280 In our images (fig. 10 and 11b), we can better constrain these low-velocity anomalies.
281 The lowest velocities are located in the Main Ethiopian Rift and western Afar depression,
282 where the active volcano-tectonic segments and recent volcanoes are found (Ebinger &
283 Casey, 2001). This low velocity feature is clearly visible as far as below the south-western
284 Yemen and western Gulf of Aden volcanic margins, southern Red Sea, and the Afar region
285 (Ahmed et al., 2013; Korostelev et al., 2014; Stab et al., 2016), where Tertiary volcanism
286 can be found (fig. 1).

287 Further south, we do not observe a continuous low-velocity anomaly along the EARS,
288 but several low-velocity zones. On the eastern branch, east of Lake Victoria, a first low-
289 velocity zone is imaged from 10 to 75 s. This anomaly is located beneath the central graben
290 of Kenya Rift, under a dozen of Quaternary volcanoes that are aligned along the Kenya
291 rift valley. These volcanoes are known as the ‘Quaternary Volcanic Province of central
292 Kenya’ (KQVP, fig. 12b) (B. Baker, 1987). KQVP probably represents the most recent
293 activity in the most voluminous and extensive alkaline igneous province (Mechie et al.,
294 1994). Tertiary and Quaternary volcanoes are shown in figures 1 and 12. The low-velocity
295 anomaly is centered on recent volcanism in the area of the frequently erupting Greater Olka-
296 ria Volcanic Complex (Marshall et al., 2009) and Longonot volcano (fig. 12b), active this
297 last millenium (last eruption in 1770 and 1863 respectively, according to Global Volcanism
298 Program (2013)). The southern end of the low-velocity anomaly lies beneath three active
299 volcanoes of the North Tanzanian divergence zone: Ol Doinyo Lengai, the famous unique
300 low-temperature carbonatitic volcano in the world, Meru and Chyulu Hills volcanic field
301 (fig. 12b). The low-velocity anomaly extends until Mount Kenya in the east.

302 The western branch is characterized by two low-velocity anomalies, located beneath the
303 Kivu-Virunga and Rungwe Volcanic Province (respectively noted KVVP and RVP in fig.
304 12a).

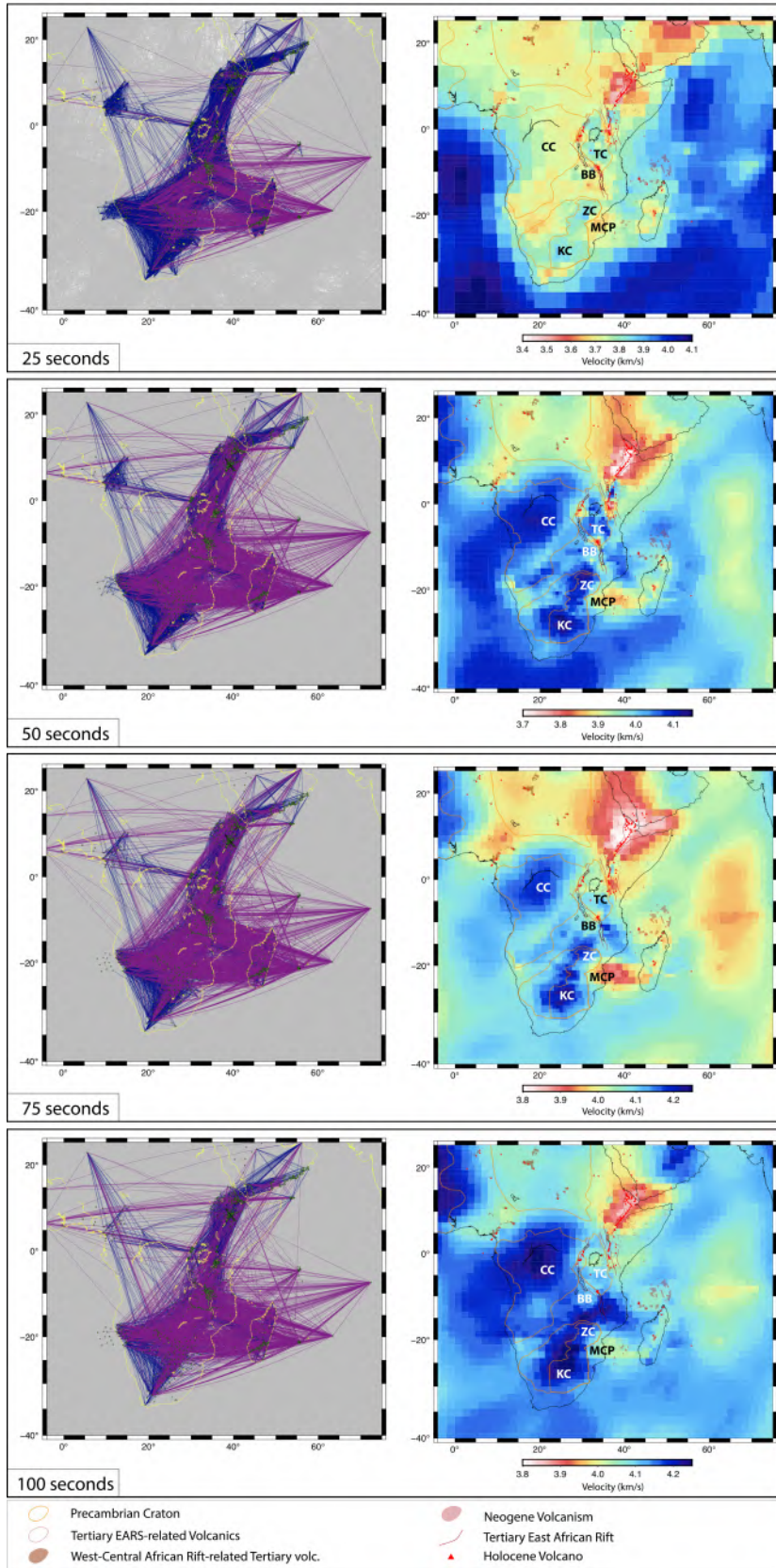


Figure 10. Left panels: ray-paths from regional dataset. Ray-paths from global dataset (Ekström, 2011) are shown in grey, ray-paths from ambient noise are shown in blue, ray-paths from teleseisms are shown in purple. Right panels: 2D Rayleigh wave phase velocity maps at 25, 50, 75 and 100 s. Abbreviations: BB Bangweulu Block, CC Congo Craton, KC Kaapval Craton,

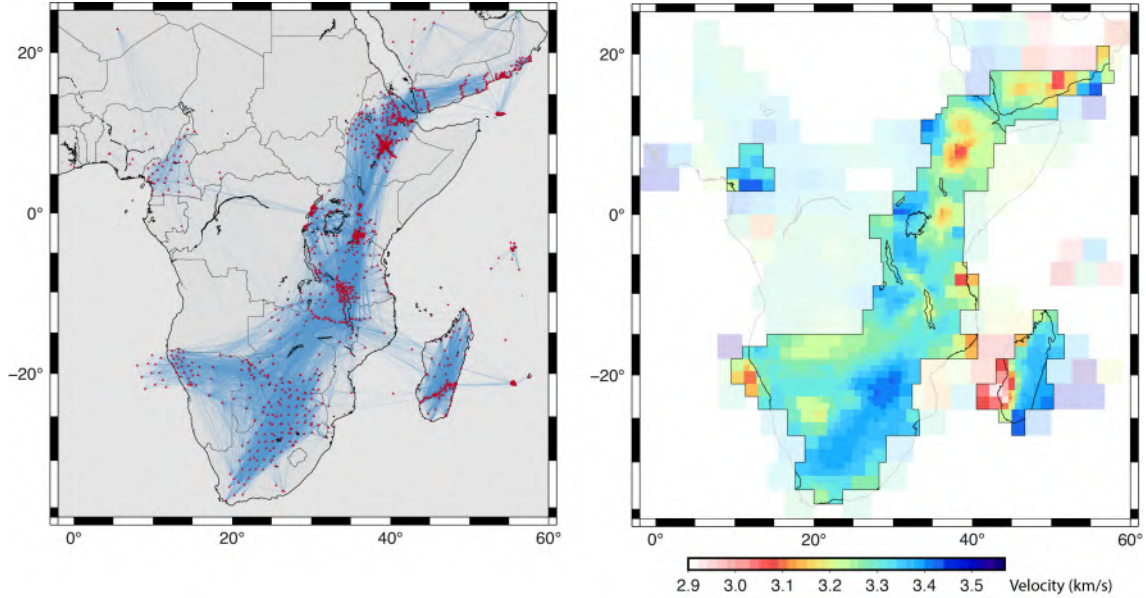


Figure 11. a. Ray-paths from regional ambient seismic noise dataset at 10 s. Sensors are shown in red. b. 2D Rayleigh wave phase velocity map at 10 s.

305 The Kivu-Virunga Volcanic Province (KVVP, fig. 12a) is located to the north of
 306 lake Kivu, in a transfer zone between two segments of the Western Branch of the EARS
 307 (Chorowicz, 2005). Moreover, the KVVP is located in the centre of the Kivu dome, a re-
 308 gional topographic uplift, which is thought to be related either to melting and lithospheric
 309 process in the underlying mantle (Chorowicz, 2005; Schmeling & Wallner, 2012) or to a
 310 local effect of mantle upwelling located beneath the nearby Tanzanian craton (Furman &
 311 Graham, 1999). Our maps display a relatively weak low-velocity anomaly from 25 to 75 s
 312 (~ 3.9 km/s at 50 s) under this area (fig. 10 and 12a), although active volcanism is present
 313 since 10 Ma (Pasteels et al., 1989). Two of the most active volcanoes of Africa are even
 314 located in KVVP: Nyamuragira and Nyiragongo (fig. 12b) that hosts a semi-permanent
 315 lava lake (Samsonov & d’Oreye, 2012). The small amplitude of the retrieved anomaly could
 316 be due to relatively scarce data coverage in this region, which is centered on the edge of the
 317 temporary networks installed in the area (fig. 10 and 11).

318 The southernmost volcanic province in the Western Branch is the Rungwe Volcanic
 319 Province (RVP, fig. 12a), active from Miocene (Ebinger, 1989; O’Connor et al., 2019) and
 320 located at the northern tip of Malawi rift. This province is characterized by three large
 321 active volcanoes: Ngozi, Rungwe, and Kyejo (fig. 12b). In our maps, RVP is associated

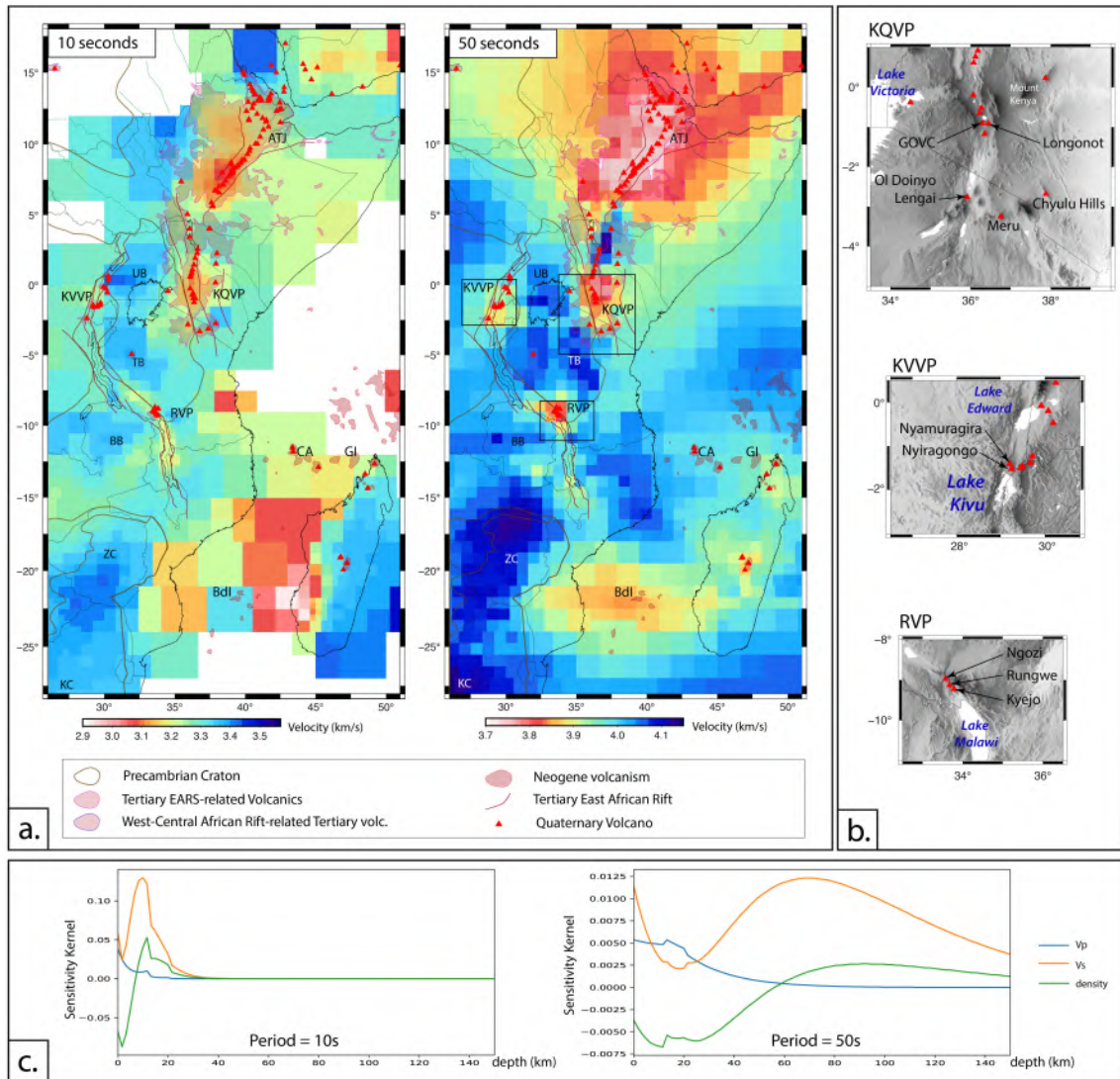


Figure 12. a. Rayleigh-wave phase-velocity map at 10 and 50 s. Abbreviations: ATJ Afar Triple Junction, BB Bangweulu Block, CA Comores Archipelago, BdI Bassas da India, KC Kaapval Craton, KQVP Kenya Quaternary Volcanic Province, KVVP Kivu-Virunga Volcanic Province, RVP Rungwe Volcanic Province, TB Tanzanian Block, UB Uganda Block, ZC Zimbabwe Craton. Structures are from Globig et al. (2016), volcanoes modified from Global Volcanism Program (2013). b. Zoom over the volcanic provinces. c. Sensitivity kernels at 10 and 50 s. At 10 s, best sensitivity is achieved between the surface and 20 km, which means that we can image crustal structures. At 50 s, best sensitivity is achieved between 40 and 100 km. We thus can image the structures of the crust and uppermost mantle. Kernels were calculated via Keurfon Luu's "disba" Python package.

322 with a pronounced low-velocity zone (~ 3.83 km/s at 50 s, as seen in fig. 10) in the mantle
 323 from 25 to 75 s.

324 Finally, we observe the discontinuous nature of the EARS from north to south. Whereas
 325 the Afar Triple Junction appears as a large low-velocity mantle zone, the southern part of
 326 EARS is characterized by several patches of low-velocities in localized points. There, Qua-
 327 ternary volcanism occurred: Kivu-Virunga Volcanic Province, Kenya Quaternary Volcanic
 328 Province and Rungwe Volcanic Province are the three main volcanic area.

329 *4.2.2 Mozambique Channel and Madagascar: the southern end of EARS?*

330 Our Rayleigh-wave velocity maps highlight some interesting features beside the EARS
 331 and African cratons. Among them is a marked low-velocity anomaly in the Central Mozam-
 332 bique channel (BdI in fig. 12a). This low-velocity anomaly corresponds to a cluster of
 333 seamounts (some of the Eparses Islands): Europa platform, Bassas da India atoll, and
 334 Jaguar and Hall Banks. These islands and banks are tropical isolated shallow-water car-
 335 bonate platforms (Courgeon et al., 2016). Morphology of crater and cones in the area
 336 suggests a volcanic origin, and dredgings have demonstrated the volcanic nature of these
 337 seamounts (Courgeon et al., 2016). However, no low-velocity anomaly have been imaged so
 338 far under the area. Our maps thus provide for the first time an evidence for the presence of
 339 hot mantellic material under the area, from 50 to 100 s. The Central Mozambique Channel
 340 is located in a diffuse zone of the southern EARS (Kusky et al., 2010), and the Bassas da
 341 India low-velocity is located in the direct continuity of the southern EARS onshore Africa.
 342 Moreover, as described in Torsvik and Cocks (2012, 2013), this part of the Mozambique
 343 Channel is located above the edges of the African large low shear-wave velocity province
 344 (LLSVP, in the deep mantle). The edges of the LLSVP are the plume generation zones,
 345 where the majority of plumes are generated (Torsvik & Cocks, 2012, 2013).

346 Northern part of Mozambique Channel hosts the Comoro Archipelago (CA in fig. 12a),
 347 composed of four volcanic islands (from west to east: Grande Comore, Mohély, Anjouan and
 348 Mayotte). Magmatism initiated ~ 20 Ma ago in Mayotte (Emerick & Duncan, 1982; Michon,
 349 2016) and is now giving birth to a new large submarine volcano located east of Mayotte
 350 (Lemoine et al., 2020; Feuillet et al., 2021). To the north-west, the Glorieuses Island (GI in
 351 fig. 12a) is the same kind of isolated carbonate platform with a volcanic origin (Courgeon

et al., 2016). Our maps image at 75 s a weak low-velocity anomaly under these clusters of islands and seamounts, centered on Glorieuses Islands (fig. 10).

Onshore Madagascar, the three small Quaternary volcanic regions are located in the northernmost tip of the island, its center and in the southwest. The northernmost volcanics seems to be aligned with the Comoro Archipelago and Glorieuses island volcanics. Our maps display a low velocity anomaly beneath this whole area, from 25 to 75 s. Another low-velocity anomaly lies beneath the center Madagascar volcanics from 25 to 75 s. And finally, the southwestern Madagascar volcanics are highlighted by the large Bassas da India low-velocity zone (BdI in fig. 12a) from 10 to 100 s (fig. 10 and 11b). Madagascar island has been rapidly uplifted since 30-40 Ma and seems to be maintained by mantle processes, in link with high asthenosphere temperatures and magmatism (Stephenson et al., 2021). These two low-velocity anomalies coincide with a zone of thinned lithosphere (Stephenson et al., 2021).

4.2.3 *The African cratons*

Global models show a clear correlation between fast velocities and the cratonic portions of the continents (e.g., Ekström, 2011). In our maps, fast velocities appear in the location of Archean cratonic lithosphere. These fast velocities are clearly distinct from 25 to 100 s. We thus observe that our study provides images of the distinct African cratons (Congo, Tanzanian, Zimbabwe and Kaapval cratons). It even seems possible to individualize some of the Archean blocks that were accreted during the life of the cratons.

The Tanzanian Craton (TC in fig. 12a) is composed of two smaller Archean fragments: the Uganda Block to the north and the Tanzanian Block to the south (Globig et al., 2016). The Tanzanian Craton is visible on our maps from 10 to 50 s for its northern part, and seems to be underlined by a weak low-velocity anomaly (visible at 75 and 100 s beneath Lake Victoria), also imaged in the study of Celli et al. (2020). In its southern part, fast velocities are observed at all periods, though they are less distinct from the velocities in the surrounding areas. In other studies (e.g. Weeraratne et al., 2003; Adams et al., 2018), a similar decrease in the amplitude of fast anomalies has been noted. Our image at 50 s suggests the presence of three different cratonic blocks within the Tanzanian Craton, located respectively under Lake Victoria (Uganda Block, UB in fig. 12a), in southwest and in southeast Tanzania Block (TB in fig. 12a). The northern block seems to be lying above

383 a weak low-velocity anomaly (at 75 and 100 s, fig. 10), whereas the two southern blocks
 384 display fast velocities until 100 s. This could mean that the northern block has a shallower
 385 lithospheric keel, which may reflect the thermal effect of nearby Kenya rift plume material
 386 (e.g. Nyblade et al., 2000; Weeraratne et al., 2003). The Archean Tanzanian Block seems
 387 to be composed of two smaller blocks. These blocks have deeper keels as they display faster
 388 velocities at 75 and 100 s. They are located further from plume or small-scale upwellings,
 389 and may therefore have undergone less cratonic carving.

390 To the west, the Bangweulu Block (BB in fig. 12a) is a cratonic feature proposed to
 391 be an Archean terrain (De Waele et al., 2006; O’Donnell et al., 2013). Here it appears
 392 as a fast-velocity zone from 10 to 50 s, but seems to do not have a cratonic root. This
 393 is consistent with previous studies (O’Donnell et al., 2013; Celli et al., 2020). The Congo
 394 Craton is characterized by a large fast-velocity anomaly in our maps from 50 to 100 s under
 395 the Congo Basin (fig. 10). At 25 s, resolution may be too poor to image its structure.

396 The southernmost craton of Africa is the Zimbabwe-Kaapval Craton. It displays the
 397 fastest velocities of all cratons on our maps (up to ~ 4.2 km/s at 50 s and ~ 4.3 km/s
 at
 398 100 s). At 10, 25, 50 and 75 s, our map show clearly the two different blocks: Zimbabwe
 399 Craton to the north (ZC in fig. 10 and 12a) and Kaapval Craton to the south (KC in fig.
 400 10 and 12).

401 **5 Conclusions**

402 In this study, we downloaded publicly-available seismograms from 54 seismic networks
 403 and processed them to obtain dispersion curves, using both ambient noise and earthquakes.
 404 We additionally take advantage of a global-scale, relatively long period database of surface-
 405 wave dispersion measurements (Ekström, 2011). The compilation of data from earthquake
 406 events and seismic noise, and of regional and global data provides us with a good data
 407 coverage, maximizing data density in the EARS. We translated the dispersion curves into
 408 phase velocity maps using a linearized inversion based on the ray theory. Owing to the
 409 adaptive parameterization criterion, we obtained enhanced resolution in comparison to pre-
 410 vious studies. Our joint inversion of the numerous regional networks together with a global
 411 dataset gave us new maps that highlight the discontinuous nature of magmatic activity
 412 along the EARS. We found high velocities in correspondence of the African cratons (Tan-
 413 zanian, Congo, Zimbabwe and Kaapval Cratons). Our detailed maps show several smaller

414 high-velocity anomalies within these cratons, which we interpret as Archean blocks within
415 them. Besides the Afar triple junction and Main Ethiopian Rift, we image low velocities in
416 correspondence of three active volcanic provinces: the Kivu-Kirunga, Kenya and Rungwe
417 Volcanic Provinces. Other low-velocity anomalies are found beneath Comores Archipelago
418 and Madagascar, which we interpret as higher temperature mantle and/or melt in active
419 volcanic areas. Interestingly, we also found low velocities in correspondence of the Mozam-
420 bique channel beneath Bassas da India Islands and seamounts. This feature is expected
421 upon consideration of the geology of the region, but was not shown in previous studies. A
422 future 3D study based on a larger regional dataset will lead to localize more precisely
423 these low velocity features in depth and better understand the magmatic plumbing system
424 in the Mozambique Channel.

425 **Acknowledgments**

426 F elicie Korostelev was supported by a grant from the PAMELA project (2020-2021) and from
427 Sorbonne Universit e. The PAMELA project (PASSive Margin Exploration Laboratories) is
428 a scientific project led by Ifremer and TOTAL in collaboration with Universit e de Bretagne
429 Occidentale, Universit e Rennes 1, Sorbonne Universit e, CNRS and IFPEN. Fabrizio Magrini
430 was funded by the Deutsche Forschungsgemeinschaft (DFG - German Research Foundation)
431 under the Individual Research Project: SI 1748/4-1. We acknowledge the Incorporated
432 Research Institutions for Seismology - IRIS (<http://www.iris.edu>), the GEOFON Global
433 Seismic Network (<https://geofon.gfz-potsdam.de>), RESIF (<https://www.resif.fr>), and IPGP
434 (<http://www.ipgp.fr>) which provided the data used in this study. The maps were imple-
435 mented with the Generic Mapping Tools (GMT, Wessel et al. 2013). The data for the
436 following networks are provided by the Incorporated Research Institutions for Seismology
437 (IRIS) Data Management Center (<http://www.iris.edu>):

438 1C (https://doi.org/10.7914/SN/1C_2011),
439 2H (https://doi.org/10.7914/SN/2H_2009),
440 4H (https://doi.org/10.7914/SN/4H_2011),
441 5H (https://doi.org/10.7914/SN/5H_2011),
442 8A (https://doi.org/10.7914/SN/8A_2015),
443 AF (<https://doi.org/10.7914/SN/AF>),
444 BX (Botswana Seismological Network),
445 DW (<https://doi.org/10.7914/SN/DW>),

446 G (<https://doi.org/10.18715/GEOSCOPE.G>),
 447 GT (<https://doi.org/10.7914/SN/GT>),
 448 II (<https://doi.org/10.7914/SN/II>),
 449 IU (<https://doi.org/10.7914/SN/IU>),
 450 MR (Mauritius Seismic Network),
 451 NJ (<https://doi.org/10.7914/SN/NJ>),
 452 NR (<https://doi.org/10.7914/SN/NR>),
 453 XA (https://doi.org/10.7914/SN/XA_1997),
 454 XB (https://doi.org/10.7914/SN/XB_2005),
 455 XD (https://doi.org/10.7914/SN/XD_1994),
 456 XI (https://doi.org/10.7914/SN/XI_1995;
 457 https://doi.org/10.7914/SN/XI_2000),
 458 XJ (https://doi.org/10.7914/SN/XJ_2013),
 459 XK (https://doi.org/10.7914/SN/XK_2012),
 460 XM (Ethiopia-Afar Geoscientific Lithospheric Experiment 6TD Passive Array),
 461 XV (https://doi.org/10.7914/SN/XV_2011),
 462 XW (https://doi.org/10.7914/SN/XW_2009),
 463 XZ (https://doi.org/10.7914/SN/XZ_2003),
 464 YH (https://doi.org/10.7914/SN/YH_2010),
 465 YJ (Ethiopia-Afar Geoscientific Lithospheric Experiment),
 466 YQ (https://doi.org/10.7914/SN/YQ_2013),
 467 YR (<https://doi.org/10.15778/RESIF.YR1999>; DhoFar Seismic Experiment II),
 468 YY (https://doi.org/10.7914/SN/YY_2013),
 469 ZE (https://doi.org/10.7914/SN/ZE_2007),
 470 ZF (Afar Consortium Network),
 471 ZK (https://doi.org/10.7914/SN/ZK_2009),
 472 ZP (https://doi.org/10.7914/SN/ZP_2007),
 473 ZT (https://doi.org/10.7914/SN/ZT_2015),
 474 and ZV (https://doi.org/10.7914/SN/ZV_2014).
 475 The data for the following networks are hosted by GEOFON (<https://geofon.gfz-potsdam.de/>):
 476 1B (Uganda project),
 477 6A (<https://doi.org/10.14470/1N134371>),
 478 GE (<https://doi.org/10.14470/TR560404>),

479 XC (<https://doi.org/10.14470/KP6443475642>),
 480 and ZE (<https://doi.org/10.14470/MR7567431421>).

481 The data for the following networks are hosted by RESIF (<https://seismology.resif.fr/>):
 482 7C (<https://doi.org/10.15778/RESIF.7C2009>),
 483 PF (<https://doi.org/10.18715/REUNION.PF>),
 484 YA (https://doi.org/10.7914/SN/YA_2012),
 485 YV (<https://doi.org/10.15778/RESIF.YV2011>),
 486 and ZS (<https://doi.org/10.15778/RESIF.ZS2007>).

487

488 References

- 489 Adams, A., Miller, J., & Accardo, N. (2018). Relationships between lithospheric structures
 490 and rifting in the East African Rift System: A Rayleigh wave tomography study.
 491 *Geochemistry, Geophysics, Geosystems*, *19*(10), 3793–3810.
- 492 Ahmed, A., Tiberi, C., Leroy, S., Stuart, G. W., Keir, D., Sholan, J., . . . Basuyau, C. (2013).
 493 Crustal structure of the rifted volcanic margins and uplifted plateau of Western Yemen
 494 from receiver function analysis. *Geophysical Journal International*, *193*(3), 1673–1690.
- 495 Auer, L., Boschi, L., Becker, T., Nissen-Meyer, T., & Giardini, D. (2014). Savani: A
 496 variable resolution whole-mantle model of anisotropic shear velocity variations based
 497 on multiple data sets. *Journal of Geophysical Research: Solid Earth*, *119*(4), 3006–
 498 3034.
- 499 Baker, B. (1987). Outline of the petrology of the Kenya rift alkaline province. *Geological*
 500 *Society, London, Special Publications*, *30*(1), 293–311.
- 501 Baker, B. H., Mohr, P. A., & Williams, L. A. J. (1972). Geology of the eastern rift system
 502 of Africa. *Geological Society of America Special Papers*.
- 503 Bastow, I., Nyblade, A., Stuart, G., Rooney, T., & Benoit, M. (2008). Upper mantle
 504 seismic structure beneath the Ethiopian hot spot: Rifting at the edge of the African
 505 low-velocity anomaly. *Geochem. Geophys. Geosyst.*, *9*(12), Q12022.
- 506 Bastow, I., Stuart, G., Kendall, J., Ebinger, C., et al. (2005). Upper-mantle seismic structure
 507 in a region of incipient continental breakup: Northern Ethiopian Rift. *Geophysical*
 508 *Journal International*, *162*(2), 479–493.
- 509 Bell, K., & Dodson, M. (1981). The geochronology of the Tanzanian Shield. *The Journal*
 510 *of Geology*, *89*(1), 109–128.

- 511 Benoit, M., Nyblade, A., & VanDecar, J. (2006). Upper mantle P-wave speed variations
512 beneath Ethiopia and the origin of the Afar hotspot. *Geology*, *34*(5), 329–332.
- 513 Bensen, G., Ritzwoller, M., Barmin, M., Levshin, A., Lin, F., Moschetti, M., . . . Yang,
514 Y. (2007). Processing seismic ambient noise data to obtain reliable broad-band
515 surface wave dispersion measurements. *Geophysical Journal International*, *169*(3),
516 1239–1260.
- 517 Bird, P. (2003). An updated digital model of plate boundaries. *Geochemistry, Geophysics,*
518 *Geosystems*, *4*(3).
- 519 Bodin, T., & Sambridge, M. (2009). Seismic tomography with the reversible jump algorithm.
520 *Geophysical Journal International*, *178*(3), 1411–1436.
- 521 Borrego, D., Nyblade, A. A., Accardo, N. J., Gaherty, J. B., Ebinger, C. J., Shillington,
522 D. J., . . . others (2018). Crustal structure surrounding the northern Malawi rift and
523 beneath the Rungwe Volcanic Province, East Africa. *Geophysical Journal Interna-*
524 *tional*, *215*(2), 1410–1426.
- 525 Boschi, L., & Dziewonski, A. M. (1999). High-and low-resolution images of the Earth’s
526 mantle: Implications of different approaches to tomographic modeling. *Journal of*
527 *Geophysical Research: Solid Earth (1978–2012)*, *104*(B11), 25567–25594.
- 528 Boschi, L., Weemstra, C., Verbeke, J., Ekström, G., Zunino, A., & Giardini, D. (2013).
529 On measuring surface wave phase velocity from station–station cross-correlation of
530 ambient signal. *Geophysical Journal International*, *192*(1), 346–358.
- 531 Celli, N. L., Lebedev, S., Schaeffer, A. J., & Gaina, C. (2020). African cratonic lithosphere
532 carved by mantle plumes. *Nature communications*, *11*(1), 1–10.
- 533 Chang, S., Merino, M., Van der Lee, S., Stein, S., & Stein, C. (2011). Mantle flow beneath
534 Arabia offset from the opening Red Sea. *Geophysical Research Letters*, *38*(4), L04301.
- 535 Chang, S.-J., Kendall, E., Davaille, A., & Ferreira, A. M. (2020). The evolution of man-
536 tle plumes in East Africa. *Journal of Geophysical Research: Solid Earth*, *125*(12),
537 e2020JB019929.
- 538 Chesley, J. T., Rudnick, R. L., & Lee, C.-T. (1999). Re-Os systematics of mantle xenoliths
539 from the East African Rift: Age, structure, and history of the Tanzanian craton.
540 *Geochimica et Cosmochimica Acta*, *63*(7-8), 1203–1217.
- 541 Chorowicz, J. (2005). The east African rift system. *Journal of African Earth Sciences*,
542 *43*(1-3), 379–410.
- 543 Clutier, A., Gautier, S., & Tiberi, C. (2021). Hybrid local and teleseismic P-wave tomog-

- 544 raphy in North Tanzania: role of inherited structures and magmatism on continental
545 rifting. *Geophysical Journal International*, *224*(3), 1588–1606.
- 546 Courgeon, S., Jorry, S., Camoin, G., BouDagher-Fadel, M., Jouet, G., Révillon, S., . . . others
547 (2016). Growth and demise of Cenozoic isolated carbonate platforms: New insights
548 from the Mozambique Channel seamounts (SW Indian Ocean). *Marine Geology*, *380*,
549 90–105.
- 550 Curtis, A., & Snieder, R. (1997). Reconditioning inverse problems using the genetic algo-
551 rithm and revised parameterization. *Geophysics*, *62*(5), 1524–1532.
- 552 Daly, M., Chorowicz, J., & Fairhead, J. (1989). Rift basin evolution in Africa: the influ-
553 ence of reactivated steep basement shear zones. *Geological Society, London, Special
554 Publications*, *44*(1), 309–334.
- 555 Davaille, A., & Romanowicz, B. (2020). Deflating the LLSVPs: Bundles of Mantle
556 Thermochemical Plumes Rather Than Thick Stagnant “Piles”. *Tectonics*, *39*(10),
557 e2020TC006265.
- 558 De Hoop, M. V., & van Der Hilst, R. D. (2005). On sensitivity kernels for ‘wave-
559 equation’ transmission tomography. *Geophysical Journal International*, *160*(2), 621–
560 633.
- 561 De Waele, B., Johnson, S., & Pisarevsky, S. (2008). Palaeoproterozoic to Neoproterozoic
562 growth and evolution of the eastern Congo Craton: its role in the Rodinia puzzle.
563 *Precambrian Research*, *160*(1-2), 127–141.
- 564 De Waele, B., Liégeois, J.-P., Nemchin, A. A., & Tembo, F. (2006). Isotopic and geo-
565 chemical evidence of Proterozoic episodic crustal reworking within the Irumide Belt of
566 south-central Africa, the southern metacratonic boundary of an Archaean Bangweulu
567 Craton. *Precambrian Research*, *148*(3-4), 225–256.
- 568 Dziewonski, A. M., & Anderson, D. L. (1981). Preliminary reference Earth model. *Physics
569 of the earth and planetary interiors*, *25*(4), 297–356.
- 570 Ebinger, C. (1989). Tectonic development of the western branch of the East African rift
571 system. *Geological Society of America Bulletin*.
- 572 Ebinger, C. (2005). Continental break-up: the East African perspective. *Astronomy &
573 Geophysics*, *46*(2), 2–16.
- 574 Ebinger, C., & Casey, M. (2001). Continental breakup in magmatic provinces: An Ethiopian
575 example. *Geology*, *29*(6), 527–530.
- 576 Ekström, G. (2011). A global model of Love and Rayleigh surface wave dispersion and

- 577 anisotropy, 25-250 s. *Geophysical Journal International*, 187(3), 1668–1686.
- 578 Ekström, G., Abers, G. A., & Webb, S. C. (2009). Determination of surface-wave phase
579 velocities across USArray from noise and Aki’s spectral formulation. *Geophysical
580 Research Letters*, 36(18), L18301.
- 581 Emerick, C., & Duncan, R. (1982). Age progressive volcanism in the Comores Archipelago,
582 western indian Ocean and implications for Somali plate tectonics. *Earth and Planetary
583 Science Letters*, 60(3), 415–428.
- 584 Emry, E. L., Shen, Y., Nyblade, A. A., Flinders, A., & Bao, X. (2019). Upper mantle
585 Earth structure in Africa from full-wave ambient noise tomography. *Geochemistry,
586 Geophysics, Geosystems*, 20(1), 120–147.
- 587 Feuillet, N., Jorry, S., Crawford, W., Deplus, C., Thion, I., Jacques, E., . . . others (2021).
588 Birth of a large volcanic edifice through lithosphere-scale dyking offshore Mayotte
589 (Indian Ocean). *Nature Geoscience*.
- 590 Fontijn, K., Williamson, D., Mbede, E., & Ernst, G. G. (2012). The Rungwe volcanic
591 province, Tanzania—a volcanological review. *Journal of African Earth Sciences*, 63,
592 12–31.
- 593 Furman, T., & Graham, D. (1999). Erosion of lithospheric mantle beneath the East African
594 Rift system: geochemical evidence from the Kivu volcanic province. *Developments in
595 Geotectonics*, 24, 237–262.
- 596 Global Volcanism Program. (2013). *Volcanoes of the World. Smithsonian Institution* (Vol.
597 v. 4.9.1 (17 Sep 2020)). Global Volcanism Program. Retrieved 12 oct 2020, from
598 <https://doi.org/10.5479/si.GVP.VOTW4-2013>.
- 599 Globig, J., Fernàndez, M., Torne, M., Vergés, J., Robert, A., & Faccenna, C. (2016).
600 New insights into the crust and lithospheric mantle structure of Africa from elevation,
601 geoid, and thermal analysis. *Journal of Geophysical Research: Solid Earth*, 121(7),
602 5389–5424.
- 603 Hansen, S. E., & Nyblade, A. A. (2013). The deep seismic structure of the Ethiopia/Afar
604 hotspot and the African superplume. *Geophysical Journal International*, 194(1), 118-
605 124.
- 606 Jacobs, J., Pisarevsky, S., Thomas, R. J., & Becker, T. (2008). The Kalahari Craton during
607 the assembly and dispersal of Rodinia. *Precambrian Research*, 160(1-2), 142–158.
- 608 Kästle, E. D., Soomro, R. A., Weemstra, C., Boschi, L., & Meier, T. M. (2016). Two-receiver
609 measurements of phase velocity: cross-validation of ambient-noise and earthquake-

- 610 based observations. *Geophysical Journal International*, 207, 1493–1512.
- 611 Korostelev, F., Basuyau, C., Leroy, S., Tiberi, C., Ahmed, A., Stuart, G. W., ... others
612 (2014). Crustal and upper mantle structure beneath south-western margin of the ara-
613 bian peninsula from teleseismic tomography. *Geochemistry, Geophysics, Geosystems*,
614 15(7), 2850–2864.
- 615 Korostelev, F., Weemstra, C., Leroy, S., Boschi, L., Keir, D., Ren, Y., ... Ayele, A. (2015).
616 Magmatism on rift flanks: insights from Ambient-Noise Phase-velocity in Afar region.
617 *Geophys. Res. Lett.*
- 618 Kusky, T. M., Toraman, E., Raharimahefa, T., & Rasoazanamparany, C. (2010). Active
619 tectonics of the Alaotra–Ankay Graben System, Madagascar: possible extension of
620 Somalian–African diffusive plate boundary? *Gondwana Research*, 18(2-3), 274–294.
- 621 Laó-Dávila, D. A., Al-Salmi, H. S., Abdelsalam, M. G., & Atekwana, E. A. (2015). Hi-
622 erarchical segmentation of the Malawi Rift: The influence of inherited lithospheric
623 heterogeneity and kinematics in the evolution of continental rifts. *Tectonics*, 34(12),
624 2399–2417.
- 625 Lemoine, A., Briole, P., Bertil, D., Roullé, A., Foumelis, M., Thinon, I., ... Hoste Colomer,
626 R. (2020). The 2018–2019 seismo-volcanic crisis east of Mayotte, Comoros islands:
627 seismicity and ground deformation markers of an exceptional submarine eruption.
628 *Geophysical Journal International*, 223(1), 22–44.
- 629 Lu, Y., Stehly, L., Paul, A., & Group, A. W. (2018). High-resolution surface wave to-
630 mography of the European crust and uppermost mantle from ambient seismic noise.
631 *Geophysical Journal International*, 214(2), 1136–1150.
- 632 Luo, Y., Yang, Y., Xu, Y., Xu, H., Zhao, K., & Wang, K. (2015). On the limitations of in-
633 terstation distances in ambient noise tomography. *Geophysical Journal International*,
634 201(2), 652–661.
- 635 Magrini, F., Diaferia, G., Boschi, L., & Cammarano, F. (2020). Arrival-angle effects on two-
636 receiver measurements of phase velocity. *Geophysical Journal International*, 220(3),
637 1838–1844.
- 638 Many, S. (2011). Nd-isotopic mapping of the Archaean–Proterozoic boundary in southwest-
639 ern Tanzania: Implication for the size of the Archaean Tanzania Craton. *Gondwana*
640 *Research*, 20(2-3), 325–334.
- 641 Marshall, A., Macdonald, R., Rogers, N., Fitton, J., Tindle, A., Nejbirt, K., & Hinton,
642 R. (2009). Fractionation of peralkaline silicic magmas: The greater olkaria volcanic

- 643 complex, Kenya Rift Valley. *Journal of Petrology*, 50(2), 323–359.
- 644 McConnell, R. (1972). Geological development of the rift system of eastern Africa. *Geological*
645 *Society of America Bulletin*, 83(9), 2549–2572.
- 646 Mechie, J., Keller, G. R., Prodehl, C., Gaciri, S., Braile, L., Mooney, W. D., ... Sand-
647 meier, K.-J. (1994). Crustal structure beneath the Kenya Rift from axial profile data.
648 *Tectonophysics*, 236(1-4), 179–200.
- 649 Meier, T., Dietrich, K., Stöckhert, B., & Harjes, H.-P. (2004). One-dimensional models
650 of shear wave velocity for the eastern Mediterranean obtained from the inversion of
651 Rayleigh wave phase velocities and tectonic implications. *Geophysical Journal Inter-*
652 *national*, 156(1), 45–58.
- 653 Michon, L. (2016). *The volcanism of the Comoros archipelago integrated at a regional scale*
654 (Vols. 333–344). Springer.
- 655 Mohr, P. (1982). Musings on continental rifts. *Continental and oceanic rifts*, 8, 293–309.
- 656 Nguuri, T., Gore, J., James, D., Webb, S., Wright, C., Zengeni, T., ... Group, K. S.
657 (2001). Crustal structure beneath southern Africa and its implications for the for-
658 mation and evolution of the Kaapvaal and Zimbabwe cratons. *Geophysical Research*
659 *Letters*, 28(13), 2501–2504.
- 660 Nyblade, A., Owens, T., Gurrrola, H., Ritsema, J., & Langston, C. (2000). Seismic evidence
661 for a deep upper mantle thermal anomaly beneath east Africa. *Geology*, 28(7), 599.
- 662 O'Connor, J. M., Jokat, W., Regelous, M., Kuiper, K. F., Miggins, D. P., & Koppers, A. A.
663 (2019). Superplume mantle tracked isotopically the length of Africa from the Indian
664 Ocean to the Red Sea. *Nature communications*, 10(1), 1–13.
- 665 O'Donnell, J., Adams, A., Nyblade, A., Mulibo, G., & Tugume, F. (2013). The uppermost
666 mantle shear wave velocity structure of eastern Africa from Rayleigh wave tomography:
667 Constraints on rift evolution. *Geophysical Journal International*, 194(2), 961–978.
- 668 Paige, C. C., & Saunders, M. A. (1982). LSQR: An algorithm for sparse linear equations
669 and sparse least squares. *ACM Transactions on Mathematical Software (TOMS)*, 8(1),
670 43–71.
- 671 Pasteels, P., Villeneuve, M., De Paepe, P., & Klerkx, J. (1989). Timing of the volcanism of
672 the southern Kivu province: implications for the evolution of the western branch of
673 the East African Rift system. *Earth and Planetary Science Letters*, 94(3-4), 353–363.
- 674 Plasman, M., Hautot, S., Tarits, P., Gautier, S., Tiberi, C., Le Gall, B., ... Gama, R.
675 (2019). Lithospheric structure of a transitional magmatic to amagmatic continental

- 676 rift system—insights from magnetotelluric and local tomography studies in the north
677 Tanzanian divergence, East African rift. *Geosciences*, 9(11), 462.
- 678 Ring, U. (2014). The East African Rift System. *Austrian Journal of Earth Sciences*, 107(1).
- 679 Ring, U., Betzler, C., & Delvaux, D. (1992). Normal vs. strike-slip faulting during rift
680 development in East Africa: the Malawi rift. *Geology*, 20(11), 1015–1018.
- 681 Ritsema, J., Deuss, A., Van Heijst, H., & Woodhouse, J. (2011). S40RTS: a degree-40
682 shear-velocity model for the mantle from new Rayleigh wave dispersion, teleseismic
683 traveltime and normal-mode splitting function measurements. *Geophysical Journal
684 International*, 184(3), 1223–1236.
- 685 Ritsema, J., Heijst, H., & Woodhouse, J. (1999). Complex shear wave velocity structure
686 imaged beneath Africa and Iceland. *Science*, 286(5446), 1925.
- 687 Ruan, Y., Lei, W., Modrak, R., Örsvuran, R., Bozdağ, E., & Tromp, J. (2019). Balanc-
688 ing unevenly distributed data in seismic tomography: a global adjoint tomography
689 example. *Geophysical Journal International*, 219(2), 1225–1236.
- 690 Samsonov, S., & d’Oreye, N. (2012). Multidimensional time-series analysis of ground de-
691 formation from multiple InSAR data sets applied to Virunga Volcanic Province. *Geo-
692 physical Journal International*, 191(3), 1095–1108.
- 693 Schaefer, J., Boschi, L., & Kissling, E. (2011). Adaptively parametrized surface wave to-
694 mography: methodology and a new model of the European upper mantle. *Geophysical
695 Journal International*.
- 696 Schmeling, H., & Wallner, H. (2012). Magmatic lithospheric heating and weakening during
697 continental rifting: A simple scaling law, a 2-D thermomechanical rifting model and
698 the East African Rift System. *Geochemistry, Geophysics, Geosystems*, 13(8).
- 699 Soomro, R., Weidle, C., Cristiano, L., Lebedev, S., Meier, T., & Group, P. W. (2016). Phase
700 velocities of Rayleigh and Love waves in central and northern Europe from automated,
701 broad-band, interstation measurements. *Geophysical Journal International*, 204(1),
702 517–534.
- 703 Stab, M., Bellahsen, N., Pik, R., Quidelleur, X., Ayalew, D., & Leroy, S. (2016). Mode of
704 rifting in magma-rich settings: Tectono-magmatic evolution of Central Afar. *Tecton-
705 ics*, 35(1), 2–38.
- 706 Stephenson, S. N., White, N., Carter, A., Seward, D., Ball, P., & Klöcking, M. (2021).
707 Cenozoic dynamic topography of Madagascar. *Geochemistry, Geophysics, Geosystems*,
708 22(6), e2020GC009624.

- 709 Torsvik, T. H., & Cocks, L. R. M. (2012). From wegener until now: the development of
710 our understanding of earth’s phanerozoic evolution (andré dumont medallist lecture
711 2012). *Geologica belgica*.
- 712 Torsvik, T. H., & Cocks, L. R. M. (2013). Gondwana from top to base in space and time.
713 *Gondwana Research*, 24(3-4), 999–1030.
- 714 Tukey, J. W. (1977). Exploratory data analysis. *Addison-Wesly, PA*, 2.
- 715 Weeraratne, D. S., Forsyth, D. W., Fischer, K. M., & Nyblade, A. A. (2003). Evidence for an
716 upper mantle plume beneath the Tanzanian craton from Rayleigh wave tomography.
717 *Journal of Geophysical Research: Solid Earth (1978–2012)*, 108(B9).
- 718 White-Gaynor, A., Nyblade, A., Durrheim, R., Raveloson, R., van der Meijde, M., Fadel,
719 I., ... others (2020). Lithospheric Boundaries and Upper Mantle Structure Beneath
720 Southern Africa imaged by P and S wave Velocity Models. *Geochemistry, Geophysics,*
721 *Geosystems*, 21(10), e2020GC008925.
- 722 Yao, H., van Der Hilst, R. D., & De Hoop, M. V. (2006). Surface-wave array tomography
723 in SE Tibet from ambient seismic noise and two-station analysis—I. Phase velocity
724 maps. *Geophysical Journal International*, 116(2), 732–744.
- 725 Zhou, L., Xie, J., Shen, W., Zheng, Y., Yang, Y., Shi, H., & Ritzwoller, M. H. (2012). The
726 structure of the crust and uppermost mantle beneath South China from ambient noise
727 and earthquake tomography. *Geophysical Journal International*, 189(3), 1565–1583.