1 # Mantle upwelling at Afar triple junction shaped by overriding plate

2 # dynamics

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20 **Mantle upwellings drive large-scale surface volcanism and facilitate continental breakup**

21 **and ocean basin formation. However, the spatial characteristics and internal composition**

22 **of these upwellings and how they are modified by plate tectonics are poorly resolved. Afar,**

23 **East Africa, is a classic triple junction comprising three rifts at various stages of evolution**

24 **thought to be underlain by a mantle upwelling or plume, allowing examination of the**

25 **controls on the mantle upwelling. Here, we present geochemical data from >130 samples**

26 **of "young" volcanoes spanning the triple junction to show that the underlying mantle**

27 **comprises a single, asymmetric upwelling. Using statistical modelling to integrate our**

28 **data with existing geochemical and geophysical constraints, we suggest that Afar is fed by**

29 **a spatially and chemically heterogeneous upwelling, which controls the composition and**

30 **relative abundance of melt in all three rift arms. We identify repetitive signatures in**

31 **mantle compositions in rift regions, whose variability is a longer wavelength in faster-**

32 **extending rift arms. This suggests more rapid channelised mantle flow occurs where**

33 **rifting rates are higher and the plate is thinner, aiding flow of the upwelling towards the**

34 **faster spreading Red Sea Rift. Our findings demonstrate how the evolution of mantle**

35 **upwellings are influenced by the dynamics of overriding plates.**

36 The role of mantle upwellings, sometimes interpreted as mantle plumes, in driving volcanism

37 during continental breakup has long been debated (e.g. [1-4]). Moreover, our understanding of

38 rift-plume interactions remains incomplete because only a small fraction of Earth's upwellings

39 are situated under continents [5] and there are a limited number of upwellings associated with

40 ongoing continental rifting [6]. The Afar triple junction—where the Arabian, Nubian, and

41 Somalian tectonic plates intersect—is a "classic" example of magma-assisted continental

42 rifting. Here, rifting occurred diachronously with the onset of the Gulf of Aden Rift (GoA) at

43 ~35 Ma [7], the Red Sea Rift (RSR) at ~23 Ma [8] and the Main Ethiopian Rift (MER) at ~11

44 Ma [9]. Both intraplate stresses tied to the slab pull effect of Neo-Tethys subduction [10], and

45 thermal weakening by a mantle upwelling, are thought to have driven rifting [11]. The

46 diachronous onset has led to each rift (GoA, RSR and MER) being in a different phase of

47 maturity (that is, ocean formation, proto-oceanic formation, and mature continental rifting,

48 respectively), and all three rifts are currently volcanically and tectonically active [12], making

49   it an ideal location to study the interactions between mantle upwelling and rifting, and how

50   these coevolve.

51   The driver of melt production in Afar is debated, with some models suggesting decompression

52   melting with minimal plume involvement [13], whereas others propose the upwelling of hot,

53   deep mantle [14-17], or indeed multiple upwellings [18, 19]. Whilst several discrete segments

54   of the RSR have been studied in terms of magma petrogenesis (e.g., [16, 20]), a paucity of

55   high-precision geochemical data has hampered evaluation of the spatial characteristics of

56   upwelling across the broader region and rigorously test existing models of the links between

57   tectonics and upwellings.

58   Here, we implement a comprehensive sampling strategy, targeting evolutionarily young

59   volcanoes spanning the three rifts (Fig. 1). We analyse rocks that are Quaternary in age (i.e.,

60   less than 2.58 million years (Myr) old), and from volcanoes that have been active during the

61   Holocene, which began 11.7 thousand years ago (ka) [21]. By targeting younger rocks, we

62   make a direct comparison with geophysical data across the region, enabling an integrated

63   exploration of mantle petrogenesis and dynamics. Our approach utilises statistical methods

64   including semi-parametric regression using splines and K-means cluster analysis to integrate

65   and analyse these geophysical and geochemical data to explore models of upwelling that can

66   explain our data.

67   **Characteristics of Mantle Upwellings**

68   Mantle upwellings that originate between depths of 1,000 and 2,800 km are anomalously hot

69   zones and/or zones of an enriched composition that reduce the solidus temperature of the

70   mantle, enabling increased partial melting [22]. Mantle upwellings are widely accepted to

71   contain a variety of domains of differing proportions (e.g., HIMU, EMI, EMII, C and FOZO

72   [e.g., 5, 22-25]). Such domains typically exhibit an isotopically distinct and enriched

73   composition (that is, generally low $^{87}Sr/^{86}Sr$, high $^{143}Nd/^{144}Nd$, and high $^{206}Pb/^{204}Pb$ [24])

74   relative to those of bulk silicate Earth (BSE [5]). Trace element ratios such as Ce/Pb and ΔNb

75   have previously been used to indicate enriched upwellings (> 30 [26], >0 [27] respectively),

76   and La/Sm to suggest the melt fraction relative to the study region with a lower-than-average

77   value suggesting an elevated melt fraction [19]. Mantle upwellings are also commonly

78   associated with reduced (i.e., lower) seismic velocities (i.e., S waves [Vs] and P waves [Vp])

79   [28, 29] that are caused by elevated temperatures and/or the presence of fluids and partial melt

80   [30].

81   Crustal assimilation, where crust components are incorporated into the magma, can obscure

82   these geochemical indicators of a deep mantle plume. However, within the Afar region, crustal

83   contamination has played a relatively minor role in recent magmatism [14] compared to earlier

84   stages of rifting [14, 26], due to the thinning of the present-day crust and that it has been

85   extensively intruded by mafic melts along the length of the rift axes. Seismicity analysis

86   indicates that recent magmatic activity beneath the rift axes in Afar is transient [31] and, in

87   turn, that magmas are unlikely to reside in crustal reservoirs for long enough to extensively

88   assimilate crustal lithologies.

89   **Probing the Presence of Mantle Upwelling(s) in Afar**

90   Our study includes over 130 rock samples, with many from previously unstudied volcanoes,

91   roughly doubling the number of high-quality analyses from the area (Fig. 1). The 79 Afar

92   samples included in our study were carefully selected from a repository covering the broader

93   Afar region (see Methods for details). These were supplemented by 52 additional samples

94   collected during fieldwork in the MER. To examine spatial trends in the geochemistry of

95   surface volcanism, we analysed all samples for major and trace elements alongside radiogenic

96   isotopes (Sr, Nd, Pb; see Methods). We also integrated data for 93 rock samples from the open-

97   source GEOROC data repository (https://georoc.eu/ (ref.[32]); see Methods for selection

98   criteria), as well as the classic GoA catalogue from ref.[19]. Additionally, we leverage recent

99   spatial compilations of geophysical variables, such as the depth of the Mohorovičić

100   Discontinuity (Moho) [31] (see Methods) and shear-wave velocities at regularly spaced depths

101   (i.e., 40, 60, 80, 100, and 120 km [30]) across the region. These variables provide well-

102   established proxies for the boundary between the crust and mantle, and for the presence and

103   abundance of melt within the lithosphere and asthenosphere [30]. Collectively, this information

104   allows us to infer details about the depth, compositional characteristics and relative abundance

105   of partial melts distributed across all three rifts.

106   Based on these samples, we infer wide geochemical variability across the study region (Fig. 1).

107   Delta Niobium ranges from -0.26 to 0.94 and La/Sm ratio ranges from 0.4 to 4.6. The

108   radiogenic isotopes $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$, $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ also display

109   a large range (Fig. 2, Extended Data Table 1), with enrichments relative to BSE occurring in

110   all three rifts. Local variability in these radiogenic isotopes is observed within some volcanoes,

111   e.g., Boset Bericha; however, this variability is smaller than the regional range determined for

112   Afar (Fig. 1).

113   Across the study region, the depth of the Moho varies, being shallowest in the RSR (~16 km)

114   and deepest in the MER (31 km). Like the geochemical data, the shear-wave velocities (Vs) at

115   40, 60, 80, 100 and 120 km depths show regional variability: 3.81-4.05, 4.06-4.17, 4.00-4.15,

116   3.97-4.10, 4.02-4.10, respectively (Extended Data Fig. 1). All rifts show zones of high and low

117   Vs (relative to ref.[30]) in the mantle which vary laterally and in depth.

118   To evaluate the potential influence of crustal assimilation—considered minor in the Afar region

119   [14]—on mantle composition and upwelling, we assess the correlation between key

120   geochemical and geophysical indicators (Fig. 4a) and the depth to the Moho. The Moho, the

121 boundary between the crust and mantle, serves as a proxy for crustal thickness, which is widely

122 thought to influence the degree of assimilation [26] (Methods). We found that most indicators,

123 including Pb isotopes—a reliable indicator of crustal assimilation [34]—exhibit only a weak,

124 but statistically significant, correlation with Moho depth (Fig. 4a). Further, Ce/Pb exhibits a

125 strong negative correlation (i.e., Pearson correlation coefficient of -0.7), indicating that where

126 the crust is thin, the Ce/Pb values are high, and vice versa. This trend can be attributed to

127 minimal crustal assimilation across most of the Afar region, though the degree of assimilation

128 increases as the crust thickens within the MER.

129 Overall, our dataset shows geochemical and geophysical variability across the study area,

130 which are consistent with the presence of an upwelling across all three rifts. The spatial trends

131 observed in all variables implicate an underlying complexity to the location of partial melts.

Models of the Afar Upwelling

133 We used our data to test multiple conceptual models of mantle upwelling dynamics. The initial

134 conceptual model we considered is a simple, homogeneous mantle upwelling at the triple

135 junction (e.g., ref.[19]). This model expects variables (geochemical and geophysical) that

136 indicate deep upwelling to change radially with distance from the upwelling centre (C1C – 1

137 centre, concentric; Fig. 3, Extended Data Table 2). Therefore, this model assumes that variables

138 change linearly from the upwelling centre due to lateral spreading. Extending this model, we

139 then allow the upwelling to be spatially and temporally heterogeneous, as reported for the

140 Hawaiian [35] and Canary Island [36] volcanoes. This mechanism yields a similar pattern to

141 the linear C1C model but accommodates compositional fluctuations over the radial distance

142 corresponding to a chemically pulsed upwelling (Fig. 3). This model fits a single spline per

143 parameter for all data against distance from the upwelling centre (spline C1C). The optimum

144 spline allows for regional variations to be accounted for, whilst minimising noise (i.e., optimal

145   smoothing). This approach of both linear and spline fits is applied to all further models

146   described in this section allowing for homogenous and heterogeneous upwelling(s),

147   respectively. Note the starting composition of the upwelling is not constrained within the model

148   parameters.

149   We additionally tested whether the spatial geochemical and geophysical variations observed

150   (Fig. 1 and Extended Data Fig. 1) are best explained through the presence of three small-scale

151   upwellings, which have been proposed based on geophysics and numerical models (e.g.

152   ref.[37], C3C – 3 centres, concentric; Fig. 3; Extended Data Table 1). We tested this model

153   using three upwellings: one centred on the triple junction, one in the northern RSR, and one in

154   the southern MER, with the positions of these loci informed by previous models and

155   observations (Methods). This model fits one linear/spline regression per variable (against

156   distance) from the nearest upwelling centre and assumes that the upwellings are

157   compositionally identical and from the same deep source.

158   It is plausible that the variable tectonic regime (e.g., extension rate, crustal thickness) between

159   the three rifts [12] introduces further complexity to the geochemical and geophysical signals.

160   Accordingly, we introduce three further models, C1D, C3D, and C3X (Fig. 3, Extended Data

161   Table 2; Methods) to account for these regional differences. Models C1D (1 centre, different

162   spreading) and C3D (3 centres, different spreading) consider one upwelling and three small-

163   scale upwellings, respectively, while allowing for distinct distance-dependent patterns for each

164   rift, thereby modelling the distribution of variables across each rift independently. Unlike the

165   other models, C3X (3 independent centres, different spreading) allows each small-scale

166   upwelling to have a distinct signature, as well as permitting an independent distribution along

167   each rift (Methods).

168   **Spatial Characteristics of Afar Mantle Upwelling**

169   To test these models (Fig 3, Extended Data Table 2), we identify 14 key geochemical and

170   geophysical variables (for descriptions, see Extended Table 2) and calculate the distance, using

171   the spherical cosine law (Methods), between the purported upwelling centre [15, 19, 38] and

172   each observation site (Methods). We then apply two-deep cross validation (100 iterations) to

173   find the optimum linear fit (that is, representing a homogeneous upwelling) and penalised B-

174   spline fit (that is, representing a heterogeneous upwelling) to each of the variables, using all

175   data points, over a radial distance of 500 km—the radial limit of samples considered within our

176   study (Fig. 4b and Extended Data Fig. 2). The predictive performance of each fit is then

177   assessed by calculating the mean standardised root-mean squared error of prediction (RMSEP),

178   where a value of 1 indicates a lack of predictive capability, and 0 a perfect predictive ability

179   (Fig. 4c).

180   For all models, we observe the B-spline fit (i.e., a class of polynomial function; Methods) to

181   have the best predictive performance, compared to a linear fit (Fig. 4c). This indicates that a

182   compositionally heterogeneous upwelling in Afar is most probable (Figs. 4b and 4c).

183   The analysis indicates that the overall best predictive model is the B-spline fit of model C1D,

184   wherein a single, heterogeneous mantle upwelling is present, albeit with differing distributions

185   of geochemical and geophysical variables between rift-arms (Fig. 3; Extended Data Table 2).

186   This model yields a mean standardised RMSEP of 0.59 (Fig. 4c), lower than that of the other

187   models. To further validate our results, we carried out sensitivity analysis, varying the

188   geochemical and geophysical data about their known uncertainties (see Methods). The results

189   confirm that model C1D remains the most accurate predictive model (Fig. 4c).

190   Whilst the RSR and MER have a high sample density, there is limited sample availability from

191   the GoA due to poor access. When excluding the GoA from our analyses, the overall trend

192   between the models remains effectively the same (Extended Data Fig. 3b). Although the Afar

193   rifts share a single, compositionally heterogenous upwelling, they appear to behave

194   independently, implying that some feature of their tectonic regime modulates the observed

195   signals.

Interplay Between Upwelling and Segmentation

197   Many of the optimum splines for each rift display distance-dependent sinusoidal patterns (Fig.

198   4b; Extended Data Fig. 2). Importantly, our analysis indicates that the variability observed for

199   some variables within the MER exhibit greater amplitude and shorter periodicity with distance

200   from the centre of the upwelling compared to those of the RSR (Fig. 4b; Extended Data Fig.

201   2). Further, the observed variation in Pb isotopes within the RSR suggests that the upwelling

202   may be chemically heterogeneous for some elements, whereas others show a narrower range

203   in composition (e.g., $^{87}Sr/^{86}Sr$ is more heterogeneous than $^{143}Nd/^{144}Nd$; Fig 1; Extended Data

204   Fig 1). Although ΔNb values are almost consistently positive (>0) across the region (except

205   around Boset-Bericha Volcano), we identify small-scale differences in La/Sm and Vs at 100

206   km depth, within the likely melt-rich zone of the asthenosphere [26], with distance to upwelling

207   centre in each rift (Fig. 4b; Extended Data Fig. 2). These small-scale differences indicate locally

208   variable degrees of melting across the study region, agreeing with previous studies that reported

209   low velocity areas [e.g., 37, 39]. This raises the question: do the zones of locally higher melt

210   fraction, low Vs, and variable geochemistry observed in one rift correspond, spatially and

211   compositionally, to those observed in the other two rifts? If so, this could indicate a shared melt

212   source.

213   To address the spatial heterogeneity patterns observed and investigate the potential shared melt

214   source, we carried out principal component analysis (PCA) and K-means cluster analysis using

215   all variables post-standardisation (Methods). Across all variables, the K-means cluster analysis

216   algorithm seeks to group similar observations whilst minimising the within-cluster total sum

217   of squares for a pre-specified number of clusters. Our K-means cluster analysis shows a higher

218   number of clusters that are smaller in geographic size for the MER (50-100 km length scale; 4

219   clusters) compared to the RSR (150-200 km length scale; 3 clusters) (Fig. 5; Methods). Several

220   clusters (clusters 1-3) are found to co-exist in different rift-arms. For example, samples

221   assigned to cluster 3 are observed in the distal section of the RSR, as well as in locations closer

222   to the MER rift centre (Fig. 5). The three clusters (1-3) observed across the RSR match the

223   initial ~200 km clustering sequence observed across the MER. This sequential repeated

224   clustering may indicate that they are derived from a shared source melt. However, the sequence

225   of these melts—as indicated by clusters—within the MER occurs over a shorter distance

226   compared to that of the RSR.

227   The spatial distribution of clusters reflects spatial variations in the composition and abundance

228   of melt, which shares some cursory similarities to the magmatic segments observed at the

229   surface (Fig. 5). However, when inspected in detail we observe clear differences. For example,

230   volcanic systems both within magmatic segments and the adjacent rift flanks are commonly

231   allocated to single clusters, and the boundaries between clusters and known magmatic segments

232   are typically mismatched (Fig. 5). In Afar, the length of the region containing clusters is longer

233   than that of magmatic segments. We therefore infer that the compositional variability of mantle

234   upwelling is unlikely to be related to the along-axis segmentation of crustal subvolcanic

235   plumbing systems.

236   **Tectonic Control on Flow of Upwelling**

237   Taken together, our data can be explained through a single upwelling model with internal

238   heterogeneity between rifts (e.g., refs.[31, 35, 40, 41]), as shown by the spline model. Crucially,

239   the K-means cluster analysis indicates the signatures of geochemical variability (i.e., clusters)

240   are repeated across rifts, implicating pulses of upwelling from the same source, as inferred for

241 other mantle plumes (e.g., refs.[36, 40, 41]). Rifts act as natural channels for upwelling melt

242 from deeper mantle sources [42]. Considering the high extension rate in the RSR (10.5-19.5

243 mm/yr; [43]) compared to that of the MER (~5.2 mm/yr; [43]), it is plausible that a mantle

244 flow rate is impeded by the narrowing of the rift in the MER. This process would lead to a

245 'bottleneck' effect [42, 44, 45], which in turn may result in a different length scale of mantle

246 heterogeneity (Fig. 4; Extended Data Fig. 2) between the RSR and MER (Fig. 5). Further, a

247 contrast in crustal thickness is evident between the rifts, with the MER crust being thicker (25-

248 33 km [46]) than that of RSR (16-25 km [47]; Extended Data Fig. 1). Assuming a correlation

249 between crustal and overall plate thickness, this effect is expected to introduce differences in

250 mantle flow rate along each rift in Afar. A progressive thickening of the overlying lithosphere

251 away from the upwelling centre in the MER should reduce the volume capacity for melt,

252 impeding mantle flow. Consequently, the heterogeneous nature of the pulsed upwelling would

253 exhibit a more condensed spatial pattern within the MER compared to RSR, as we observe

254 (Fig. 5).

255 We conclude that variations in melt composition and abundance in and around Afar is best

256 explained by a heterogeneous pulsing mantle upwelling that is not symmetrical (Fig. 5) but is

257 instead shaped by both variable lithospheric thinning and extension rates within each rift (Fig.

258 6). Whilst this model principally investigates the likelihood of a singular or three-small-scale

259 upwelling scenario, our results demonstrate that for either option, a single heterogeneous

260 upwelling provides the best match to observations in the region. The detected variations in melt

261 composition and abundance between the MER and RSR imply that the length scale of

262 heterogeneities within magma-assisted rifting environments may be controlled not only by the

263 upwelling itself, but by the extension rate and plate thickness. If this model is correct, it

264 demonstrates that the evolution of a mantle upwelling can be influenced and shaped by the

265 dynamics of the overriding plates.

277 **Author Contributions**

278 E.J.W. conceived the idea, processed the data, and prepared the manuscript. T.M.G and D.K.

279 advised on the work and assisted with sampling and interpretation. P.J. wrote the code for the

280 statistical modelling and assisted with interpretation. T.K.H advised on the statistical analysis.

281 E.J.W., R.R., M.S., M.J.C., A.M., J.A.M., and R.N.T analysed the samples and processed the

282 geochemical data. E.L.C processed the geophysical data for the sample locations. E.J.W.,

283 T.M.G., and D.K. wrote the manuscript with input from all co-authors.

284 **Competing Interests Statement**

285 The authors declare no competing interests.

286   **Figure Captions**

287   *Fig. 1: Variation in geochemical and geophysical properties around the Afar Triangle; (a)

288   Map showing the Gulf of Aden Rift (GoA), Red Sea Rift (RSR) and the Main Ethiopian Rift

289   (MER) axes (dashed lines) and associated rifting rates indicated by arrows (from refs. [43,48]).

290   The three hypothesised [19, 37, 38] upwelling locations (yellow stars) and Holocene volcanoes

291   (red triangles) are shown. Hexmap colours show the density of samples within the hexagons'

292   area, with purple representing >12 and yellow showing 1-2. Location of maps shown on global

293   inset (black rectangle). (b) Hexmap showing the $^{206}Pb/^{204}Pb$ variations across the study region

294   (dark blue = low $^{206}Pb/^{204}Pb$ - minimal upwelling signature, yellow = high $^{206}Pb/^{204}Pb$). (c)

295   Hexmap showing La/Sm variations across the study region (yellow = high La/Sm – low melt

296   fraction, dark blue = low La/Sm – high melt fraction). (d) Hexmap showing the $^{143}Nd/^{144}Nd$

297   variations across the study region. Yellow indicates a high $^{143}Nd/^{144}Nd$. The topography shown

298   is from the 1 arc-sec (~30 m resolution) Shuttle Radar Topography Mission (SRTM) Digital

299   Elevation Model (DEM) [50].

300   *Fig. 2: Radiogenic isotope compositions of samples across Afar.* (a) $^{206}Pb/^{204}Pb$ versus

301    $^{208}Pb/^{204}Pb$; (b) $^{143}Nd/^{144}Nd$ versus $^{87}Sr/^{86}Sr$. Samples are classified by their rift position,

302   indicated by their symbol colour and shape (RSR = blue circles, MER = green squares, GoA =

303   yellow diamonds). Error bars show the uncertainty associated. Black error bars are the average

304   uncertainty of the dataset, grey are the maximum uncertainty. Uncertainty for datapoints in (a)

305   are smaller than the symbols. The global mantle endmember compositions are shown as fields

306   behind from refs.[5, 49]. The histograms show the distribution of all data analysed in our study,

307   including our >130 data points.

308   *Fig. 3: Conceptual models of mantle upwellings beneath Afar tested in this study.* Schematic

309   diagram of the upwelling scenarios for Afar tested in this study. The diagrams (left) are labelled

310   with the code associated with each model (see Extended Data Table 2 and the Statistical

311   Analysis section within Methods for further details). The location of the purported mantle

312   upwellings are shown by the star symbol. The number of lines shown on the schematic graphs

313   equals the number of models that must be fitted for that model variant (linear = dashed, spline

314   = continuous), where R = Rift and U = upwelling. Note that each model variant has been

315   illustrated with an indicator that decreases with a reduction in upwelling proportion.

316   ***Fig. 4: Statistical analysis of rifting models for the RSR, GoA and MER. (a)*** *Pearson*

317   correlation coefficient of each of the selected 13 variables with Moho depth. Error bars show

318   the 95-percentile error of the coefficient (n = 250) with the squares representing the mean. Red

319   squares indicate where the correlation is significant (p < 0.05) and blue squares indicate that

320   the correlations are not deemed significant (p > 0.05). **(b)** Splines (a smooth, flexible

321   polynomial curve) of the best overall model—that is, C1C—for selected variables. Symbols

322   show the data within the study (locations denoted by symbols shown). 95% confidence

323   intervals are indicated by the shaded background. The number of data observations (n) for

324   La/Sm, ^{143}Nd/^{144}Nd, ^{206}Pb/^{204}Pb and Shear velocity at 100km depth are 269, 218, 185, and 184

325   respectively. Uncertainty in data values have been shown by error bars (average in black, max

326   in grey). (**c**) The mean standardised root means square error of prediction (RMSEP) for each

327   of the models tested. Individual linear model results are shown by red squares and the mean of

328   those results are displayed by the red line. Individual spline results are shown by blue circles

329   and the mean of those results are shown by a blue line. All models were run for 100 iterations

330   to capture the probable uncertainty distribution, as shown by the data points. Mean (dotted line)

331   and 95% confidence interval (shaded) of results using perturbed data (within the uncertainty of

332   each datapoint) are also shown (300 perturbation runs each using 100 iterations).

333   ***Fig. 5: Map of the segments and cluster assignment within the study region.*** Segments are

334   shown in blue from north to south: Erta Ale Volcanic Segment (EAVS), Tat'Ale Volcanic

335 Segment (TAVS), Alayta Volcanic Segment (AVS), Dabbahu Volcanic Segment (DVS),

336 Gabillema Volcanic Segment (GVS), Adda'do Magmatic Segment (AMS), Fentale-Dofen

337 Magmatic Segment (FDMS), Boset Magmatic Segment (BMS), Aluto-Gedamsa Magmatic

338 Segment (AGMS), Corbetti Magmatic Segment (CMS). Rift axis (dotted line) is shown. (b)

339 and (c) are enlarged maps of the boxes shown in (a). (d) & (e) Principal component (PC)

340 analysis bi-plot (PC1 vs PC2) when considering the six isotopic systems (see Extended Data

341 Table 3) showing the samples and their component scores relative to those of the mantle

342 endmembers. Values used for the mantle endmembers, that is, Pan-African Lithosphere (PAL),

343 Enriched Mantle 1 & 2 (EM1, EM2, respectively), Depleted MORB Mantle (DMM) and

344 HiMU, are shown in Extended Table 3. The topography shown is from the 1 arc-sec ($\sim$30 m

345 resolution) Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) [50].

346 *Fig. 6: Spatially heterogeneous nature of the mantle upwelling beneath Afar.* (**a**) Box

347 diagram showing the rifts across Afar and the mantle upwelling being channelised by the rift.

348 The lines of section X-Y-Z are those shown in panel (**c**). Volcanic segments are shown and

349 labelled: Erta Ale Volcanic Segment (EAVS), Tat'Ale Volcanic Segment (TAVS), Alayta

350 Volcanic Segment (AVS), Dabbahu Volcanic Segment (DVS), Gabillema Volcanic Segment

351 (GVS), Adda'do Magmatic Segment (AMS), Fentale-Dofen Magmatic Segment (FDMS). (**b**)

352 Schematic of the Afar upwelling showing the dimensions of channelised flow along the three

353 rifts (dashed lines). (**c**) Schematic cross sections along the Red Sea Rift (line section X-Y) and

354 MER (Y-Z) showing the distribution of chemical heterogeneities within the upwelling and how

355 those map to the clusters shown in Fig. 5. Note that the depths of distinct features including the

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516   **Methods**

517   *Sample Selection and Processing*

518   All samples and previously published data used in this study must originate from a volcano

519   that has been active within the Holocene [21] (Fig. 1), with the age of the sample estimated to

520   be of Quaternary age (i.e., < 2.58 Ma). An essential criterion was that all samples have a

521   precisely known location with accurate coordinates.

522   *Obtaining Previously Published Data*

523   Previously published geochemical data were obtained from GeoROC [19, 32]. Once

524   downloaded the data-files were filtered to only include data within Ethiopia (including the

525   Main Ethiopian Rift and Afar). These data were further filtered using the following criteria:

526   1. The values for the sample must relate to whole rock geochemistry, as opposed to

527   mineral separates.

528   2. The individual sample must have major element, trace element, $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$,

529        $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ isotope values available.

530   *3.* The coordinates must be specific to the individual sample's location rather than

531   providing an average coordinate for a broader study area.

532   *Sampling and Sample Preparation*

533   Ninety-three lavas, eleven welded tuffs and one pumice sample, from various volcanoes in

534   Afar (Erta Ale Volcanic Segment, Ayelu, Abida, Yangudi, Dama Ali, Kerub, Ela, Didoli,

535   Abbahu, Afdera, Tat Ali and Manda Hararo) were selected for geochemical analysis [see

536   refs.51-53]. The samples were collected during the CNR/CNRS projects in Afar during the

537   1960s [54] and stored in the Afar Repository at the University of Pisa, Italy,

538   (http://repositories.dst.unipi.it/index.php/home-afar). A further 52 samples from the Boset-

539   Bericha Volcanic Complex (BBVC) were collected during three field seasons [ref.55], in

540   November 2012, April-May 2015 [ref.56], and February 2017 [ref.57].

541   Sample preparation, for major, trace and isotope analyses, was carried out at the University of

542   Southampton. Samples were cut with a saw to remove any weathered sections, and any cut

543   surfaces ground down to reduce any potential contamination by metals from the saw blade.

544   Rock samples were then crushed using a fly press and placed in double-layered plastic bags

545   prior to crushing to minimise metal contamination during the crushing process.

546   The crushed material was separated into three size fractions (>1 mm, 0.5 mm to 1 mm, <0.5

547   mm) using Teflon sieves, retaining the middle fraction (0.5 - 1 mm) for analysis. The selected

548   fraction was cleaned by ultrasonicating in Milli-Q water then dried overnight in an oven at

549   85ºC. The cleaned rock chips were then hand-picked under a microscope, to remove any

550   extraneous (non-rock) material. An aliquot of cleaned chips was used for Pb isotope analysis.

551   For major element, trace element, and $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ isotope analysis, the

552   remaining rock chips were ground to a fine powder using an agate mortar and pestle, again to

553   minimise contamination with metals.

554   *Trace Element Analysis*

555   Samples were prepared for whole-rock trace element analysis using 0.05 g (for BBVC

556   samples) or 0.075 g (for all other samples) powdered sample. The powdered samples were

557   digested in sealed Savillex Teflon vials with 15 drops concentrated HNO_3 and 2 ml HF on a

558   hotplate at 130 °C for 24 hours (for all samples excluding those from the BBVC), or with 50

559   drops HF and 0.2 ml HNO_3 on a hotplate at 130 °C for 24 hours (for BBVC samples only).

560   The HNO_3/HF was evaporated off, and the samples were refluxed in 6M HCl for another 24

561   hours on a hotplate at 130 °C. The 6M HCl was evaporated off, and the samples were

562   redissolved in 6M HCl. Mother solutions were prepared by adding 6M HCl and Milli-Q

563   water (total 30 ml) to the dissolved samples. Daughter solutions were prepared using 0.5 ml

564   of mother solution, diluted to 5 ml with 3% HNO_3 (containing the internal standards 5 ppb In/

565   5 ppb Re/ 20 ppb Be), resulting in an overall dilution factor of c. 4000.

566   Trace element analyses of the daughter samples were undertaken on the Thermo Scientific X

567   Series 2 quadrupole inductively coupled plasma mass spectrometer (ICP-MS) at the

568   University of Southampton. Samples and standards were spiked with internal standard

569   elements and corrected for interferences and the blank and then calibrated using a suite of

570   international rock standards. Accuracy was monitored using reference materials JA-2, BCR-

571   2, JB-2 (see Supplementary Tables 1 and 2).

572   *Pb Isotopic Analysis*

573   For Pb isotope analysis, 0.3 g of cleaned, picked rock chips (0.5 mm to 1 mm) were weighed

574   into Pb Savillex Teflon vials and leached on a hotplate with 4 ml 6M HCl for one hour (15

575   minutes for obsidian and pumice samples, to avoid full dissolution of the sample). Samples

576   were rinsed several times in Milli-Q water, then 0.5 ml concentrated HNO_3, before adding 3-

577   4 ml of concentrated HF. Samples were digested, following the same procedure as for trace

578   elements, and refluxed on a hotplate at 130 °C for 24 hours, before being evaporated to

579   dryness. 0.5 ml concentrated HCl was added, and the sample evaporated to dryness. Then 0.5

580   ml concentrated HNO_3 was added and again evaporated to dryness. The final residue was

581   reconstituted in 0.5 ml HBr and refluxed for an hour. The samples were cooled and

582   centrifuged for 5 minutes. Pb was isolated using a single-stage HCl anion-exchange

583   chromatographic resin separation method [58], with AGX-1x8, 200 – 400 mesh resin.

584   Following this, the Pb isolate was dried down, redissolved in HNO_3, and analysed using the

585   double spike method of ref.[59]. The samples were subsequently analysed on a Thermo

586   Scientific Neptune Multi-collector inductively coupled plasma mass spectrometer (MC-

587   ICPMS) at the University of Southampton (UK) achieving a NBS SRM 981 reproducibility

588   of $^{206}Pb/^{204}Pb$ = 16.9404 ± 24 (142 ppm), $^{207}Pb/^{204}Pb$ = 15.4969 ± 26 (168 ppm), $^{208}Pb/^{204}Pb$

589   = 36.7149 ± 66 (180 ppm) (2sd; n=44). Pb isotope measurements of the standard are within

590   error of the accepted values ($^{206}Pb/^{204}Pb$ = 16.9412, $^{207}Pb/^{204}Pb$ = 15.4988, $^{208}Pb/^{204}Pb$ =

591   36.7233). Accuracy was 47 ppm for $^{206}Pb/^{204}Pb$, 123 ppm for $^{207}Pb/^{204}Pb$, and 174 ppm for

592     $^{208}Pb/^{204}Pb$.

593   *$^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ Isotopic Analysis*

594   For Sr and Nd analysis, the remaining mother solutions from the preparation of trace element

595   solutions (see above) were used for all samples except those of the BBVC. An aliquot of each

596   mother solution was used, to give a volume of liquid containing at least 1 μg Sr and 200 ng

597   Nd and evaporated to dryness in Savillex Teflon vials on a hotplate at 130ºC. Sample

598   residues were reconstituted in 200 μl 1.75M HCl. For the BBVC samples, rock chips were

599   leached in 4 ml 6M HCl or 30 minutes in Savillex Teflon vials (obsidian samples for only 15

600   minutes, to avoid full dissolution of the sample). The samples were then rinsed with Milli-Q

601   water and HNO$_3$, and then the same digestion procedure as for trace element analysis (above)

602   was followed. The final mother solutions were prepared using HCl and Milli-Q water to 30

603   ml for felsic samples and 20 ml for mafic samples.

604   All samples were then passed through ion exchange column chemistry, using a AG50-X8

605   200-400 mesh resin cation column to separate the Sr and Nd fractions. The sample fractions

606   were subsequently evaporated to dryness, ready for further column chemistry.

607   Sr was further isolated through Sr-spec resin columns, following the methodology of ref.[60].

608   Samples were then evaporated to dryness, dissolved in 1.5 ml 1M HCl and loaded onto

609   outgassed tantalum filaments with 1 μl of Ta-activator. Sr isotopic analysis was performed on

610   a Thermal Ionisation Mass Spectrometer (TIMS) Thermo Scientific Triton Plus at the

611   University of Southampton. Reference material SRM NIST987 ($^{87}Sr/^{86}Sr = 0.710258$;

612   GeoREM) was used to monitor accuracy and gave average $^{87}Sr/^{86}Sr$ values of 0.710243. All

613   samples were normalised to NBS SRM-987 $^{87}Sr/^{86}Sr = 0.710248$ [61], while reproducibility

614   was ± 0.000020 (28.2 ppm, 2sd; n=464). Accuracy was 21 ppm.

615   The Nd aliquot from the cation column was followed by an Ln-spec resin (50-100 μm) [60].

616   The samples were then evaporated to dryness and 3% HNO_3 was added to produce a solution

617   of 50 ppb. $^{143}Nd/^{144}Nd$ analyses were undertaken on the ThermoScientific Neptune multi-

618   collector inductively coupled plasma mass spectrometer (MC-ICP-MS) at the University of

619   Southampton. Corrected Nd isotopic compositions were obtained using a method based on

620   ref.[62] through adjustment to a $^{146}Nd/^{144}Nd$ ratio of 0.7219 and a secondary normalisation to

621    $^{142}Nd/^{144}Nd = 1.141876$. Reference material JNdi-1 was measured as an unknown

622   ($^{143}Nd/^{144}Nd$ of 0.512124, 2sd; [63]) achieving an average $^{143}Nd/^{144}Nd$ of 0.512115 with an

623   external reproducibility of ±0.000008 (2sd, 15.2 ppm) across 6 analysis sessions over 2 years.

624   The total column blanks (i.e., when blank acid is run through the column procedure) were

625   negligible (<20 pg) compared to the total amounts analysed (1 μg and 200 μg) for Sr and Nd,

626   respectively.

627   ***Shear Velocity Mapping from Joint Inversion***

628   We use the shear wave velocity model of ref.[30] for inclusion in our analysis. The 3D

629   velocity model is created through a joint inversion of Rayleigh-wave phase-velocities from

630   ambient noise and teleseisms [30, 33]. The shear velocity model is parameterised every 5 km

631   vertically with 0.1° x 0.1° pixel size for the upper 50 km. For deeper depths, an irregular

632   spacing was used, increasing from 10 – 50 km spacings to match that of ref.[39]. For further

633   details on the creation of the velocity model, the reader is directed to refs.[30, 33] and

634   references therein.

635   For the analysis in this paper, the shear velocity model was interpolated to 1 km depth using a

636   linear interpolation; we then extracted 1D columns of velocity with depth at the same

637   resolution as our pixel size (0.1° x 0.1°).

Moho Depths

639   The gridded Moho depth map was produced from the Vs maps of ref.[33], described above.

640   The Vs model was interpolated to a vertical grid spacing of 1 km. A velocity slice at the 3.75

641   km/s contour was extracted, which mapped best to previous receiver function measurements

642   [65-69], active source experiments (e.g., ref.[70]) and previous S-wave models (e.g.,

643   ref.[71]).

Statistical Models Considered

645   As described in the text, five models were considered (see Extended Data Table 2), with each

646   model being tested using a linear fit and a spline fit (Fig. 3). We note that a spline fit to itself

647   can be linear if that is the best-fitting line.

648   Empirical models are estimated for the variation of each of 14 geochemical quantities (each

649   of which is represented generically by random variable Y) as a function of distance $d \in [0,$

650    $1800]$ km for the five different models. Models are specified that explore the variation of Y

651   with d in increasing complexity. The simplest model (C1C) assumes the existence of a single

652   upwelling centre (at 11.192 ºN 41.784 ºE; see Figs. 1 & 3), with respect to which d is defined

653   for all three rifts. The variation of Y with d is assumed common to all rifts. Model C3C

654   assumes the existence of three upwelling centres (at 11.192 ºN 41.784 ºE, 14.008 ºN 40.458

655   ºE & 6.626 ºN 37.948 ºE; see Fig. 1) based on ref.[37]; observations are allocated to the

656   nearest upwelling centre, facilitating calculation of a single d for each observation. Like

657   model C1C, the variation of Y with d is assumed common to all rifts, regardless of upwelling

658   allocation. Model C1D assumes one upwelling centre (like C1C) for calculation of d, but now

659   the variation of *Y* with *d* is assumed to be different across rifts. Model C3D duplicates C3C

660   for estimation of *d*, but variation of *Y* with *d* is assumed to be different across rifts. Finally, in

661   model C3X, we consider the presence of three upwelling centres, with different variation of *Y*

662   with *d* for each combination of upwelling and rift.

663   ***Data Pre-Processing***

664   For models C1C and C1D, the distance between each sample and the upwelling locus centred

665   on Lake Abhe (11.192170 ºN, 41.783750 ºE) is calculated. For models C3C, C3D and C3X,

666   the distance between each sample and each of the three upwelling locations (Figs. 1 & 3) is

667   measured, and then each sample is assigned to its nearest upwelling centre. The distance (*d*)

668   between two locations (i.e., upwelling and sample) is calculated using the spherical cosine

669   law:

670     $d \ = \ R(\cos^{-1}(\cos(a)\cos(b) \ + \ \sin(a)\sin(b)\cos(C))$ (Eq. 5)

671   where *a* is the angle (in radians) from the North Pole to the sample location, *b* is the angle (in

672   radians) from the North Pole to the upwelling location, *C* is the difference in radians between

673   the longitude values of the sample and upwelling, and *R* is the radius of the earth in metres

674   (6371×10^3).

675   ***Penalised B-splines***

676   For each model, the variation of *Y* with *d* is described using a penalised B-spline (e.g.,

677   refs.[72-73]), the characteristics of which are selected to provide optimal predictive

678   performance. First, for a large index set of locations equally spaced on the domain of

679   distance, we calculate a B-spline basis matrix, *B* (e.g., ref.[74]) consisting of *p* equally spaced

680   cubic spline basis functions. Then the value of *Y* on the index set is given by the vector *Bβ*,

681   for spline coefficient vector *β* to be estimated. The value of *p* is specified to be sufficiently

682   large to provide a good description of a highly variable *Y*. For a given data set, we penalise

683   the difference between consecutive values in β using a roughness penalty, such that the

684   penalised spline exhibits optimal roughness, providing optimal predictive performance.

685   ***Estimating Optimal Spline Roughness and Predictive Performance***

686   For a sample of n_1 training data, consisting of vectors of geochemical and geophysical

687   quantities (y_1) and distances (d_1), we first allocate each element of d_1 to its nearest

688   neighbour in the index set, and hence construct the appropriate spline basis matrix B_1 for the

689   sample. We then assume that $y_1 = B_1\beta + \varepsilon$, where the elements of ε are independently and

690   identically distributed zero-mean Gaussian random variables. We penalise the roughness of β

691   using a first-different penalty $\lambda\beta'P\beta$, where $P = D'D$ and D is a first difference matrix (with

692   elements $D_{ij} = -1$ if $i = j$; $= 1$ if $j = i + 1$; and $= 0$ otherwise (e.g., ref.[75]). For a

693   given choice of λ, we then find the optimal value of β by minimising lack of fit:

694     $\beta^*(\lambda) = \underset{\beta}{argmin} \{(y_1 - B_1\beta)'(y_1 - B_1\beta) + \lambda\beta'P\beta\}$ (Eq. 6)

695     $= (B_1'B_1 + \lambda P)^{-1}B_1'y_1$ (Eq. 7)

696   We can evaluate the predictive performance of the resulting spline description using a tuning

697   set of n_2 observations (independent of the training set) represented by vectors y_2 and d_2. We

698   again start by finding the appropriate spline basis matrix B_2 for this sample. Then we can

699   calculate the predictive mean square error for the tuning sample:

700     $\text{MSE}_{Tune}(\lambda) = \frac{1}{n_2}\left(y_2 - B_2\beta^*(\lambda)\right)'\left(y_2 - B_2\beta^*(\lambda)\right)$ (Eq. 8)

701   for each of a set of representative choices of values for λ. We can then select the optimal

702   value of λ using

703     $\lambda^* = \underset{\lambda}{argmin} \{\text{MSE}_{Tune}(\lambda)\}$ (Eq. 9)

704   The value $\text{MSE}_{Tune}(\lambda^*)$ is a biased estimate of predictive performance since the value of λ^*

705   was tuned to minimise its value. We can obtain an unbiased estimate for the predictive

706   performance of the spline model using a test set of n_3 observations (independent of the

707   training and tuning sets) represented by vectors y_3 and d_3 (and corresponding spline basis

708   matrix B_3). Then the predictive performance is estimated using:

709      $$MSE_{Test} = \frac{1}{n_3}\left(y_3 - B_3\beta^*(\lambda^*)\right)'\left(y_3 - B_3\beta^*(\lambda^*)\right) \qquad \text{(Eq. 10)}$$

710   ***Cross-Validation and Model Comparison***

711   We exploit cross-validation to evaluate MSE_{Test}, by partitioning the full sample of data into

712      $k > 2$ groups at random, withholding one group for tuning, another group for testing, and

713   retaining the remaining $k - 2$ groups for training. We then loop exhaustively over all

714   possible combinations of choice of train, tune, and test groups, evaluating overall predictive

715   performance on the test data over all iterations, noting that each observation occurs exactly

716   once in the test set. For models requiring separate model fits to subsets of data (that is, C1D,

717   C3D, C3X), MSE_{Test} is estimated using predictions from optimal predictive models for each

718   subset. Further, we can repeat the analysis for different initial random partitioning of

719   observations into k groups, to assess the sensitivity of overall predictive performance to this

720   choice. We are careful to use the same cross-validation partitions to evaluate each of the five

721   models, so that predictive performances can be compared fairly.

722   To quantify model performance over all 13 geochemical quantities ($j = 1,2,\ldots,13$), we

723   define the overall standardised MSE_{Test}

724      $$\text{SMSE} = \sum_{j=1}^{13} \frac{\text{MSE}_{Test,j}}{s_j^2} \qquad \text{(Eq. 11)}$$

725   where $\text{MSE}_{Test,j}$ is the predictive performance for the jth geochemical indicator, and s_j^2 is the

726   sample estimate for the variance of that quantity. The estimation of the splines and the testing

727   of their predictive performance was repeated over 100 iterations. Results from each iteration

728   and the mean of the SMSE is shown in Fig. 4.

729   ***Linear Regression***

730   For comparison, we also evaluate linear regression models for the variation of *Y* with *d*. In the

731   current notation, these can be thought of as simple models with basis matrix *B = [1 d]*, where

732   *1* is a vector of appropriate length with each element *= 1*. *B* in this case is a 2-vector with

733   elements corresponding to intercept and slope coefficients. Linear regression is approached

734   using penalised B-spline models as the roughness coefficient $\lambda \rightarrow \infty$. That is, linear regression

735   corresponds to a penalised B-spline model with very large λ. Therefore, a penalised B-spline

736   model is guaranteed to perform at least as well as linear regression.

737   ***Uncertainty of Model Performance***

738   To explore the effect of uncertainty on model performance, a perturbation analysis was

739   undertaken. This analysis required the generation and modelling of n_{Pert} new data samples.

740   Each of these data samples corresponded to a perturbation of the original data sample. A

741   value of $n_{Pert} = 300$ was selected to ensure that 95% uncertainty bands for predictive

742   performance on perturbed data could be estimated with confidence.

743   In perturbed sample q, $q = 1, 2, ..., n_{Pert}$, the value y_{ijq}^* of the *i*th observation for variable *j*

744   was obtained by perturbing the corresponding value y_{ij} in the original data sample, using

745   additive Gaussian noise e_{ijq}, the standard deviation σ_{ij} of which was informed by the known

746   value of measurement uncertainty for that observation of the variable. Mathematically:

747    $$y_{ijq}^* = y_{ij} + e_{ijq} \tag{Eq. 12}$$

748   The complete modelling procedure was then applied to each perturbed data sample in turn.

749   The predictive performance of different models was assessed over the n_{Pert} perturbations, as

750   illustrated in Fig. 4, in terms of 95% uncertainty bands. The figure indicates that model C1D

751   provides best predictive performance on perturbed data, as well as for the original

752   unperturbed sample. Note that, since noise has been added to observations in the perturbation

753   analysis, the overall performance of models on perturbed data is poorer than on the original

754   sample, as expected.

Testing the Influence of Crustal Assimilation

756   We tested the influence of crustal assimilation further by excluding cases where Ce/Pb values

757   fall below 20 and which could feasibly be associated with crustal assimilation [26, 34]. Using

758   additional analysis, we confirm that excluding cases in which Ce/Pb < 20 does not affect our

759   overall results (see Extended Data Fig. 3a), suggesting that primary mantle compositional

760   fluctuations (i.e., relative proportions of compositional mantle endmembers) exert the first-

761   order control on eruptive compositions at the surface.

Principal Component Analysis

763   Principal component analysis (PCA) requires each sample or object to have the same number

764   of values for each variable and so the dataset was reduced to 94 samples. PCA is only carried

765   out on radiogenic isotope compositions of the samples where data are available for the mantle

766   endmembers investigated (i.e., Afar plume, Pan-African Lithosphere, Depleted Mantle,

767   Enriched Mantle 1, Enriched Mantle 2, HiMU; Fig. 5; Extended Data Table 3). While other

768   purely geochemical studies on Afar (e.g., refs.[14, 38]) have included sub-crustal components

769   such as the sub continental lithospheric mantle (SCLM), we decided not to include this

770   endmember as it can sometimes be indistinguishable from certain mantle endmembers (i.e.,

771   EM1), especially in cases where the SCLM is metasomatized. Values used for the

772   endmembers in our models are provided in Extended Data Table 3. Each object is

773   standardised before being included in the PCA:

774 $\qquad y_{\text{std}\,j} = \dfrac{y_j - \bar{y}_j}{\sigma_j}$ (Eq. 13)

775 where $\bar{y}_j$ is the mean of variable j, and σ_j is the standard deviation of the variable j:

776 $\qquad \sigma_j = \sqrt{\dfrac{\Sigma\left\{\left(y_j - \bar{y}_j\right)\right\}^2}{N_j}}$ (Eq. 14)

777 where N_j is the number of objects within variable j.

778 Approximately 90.5% of the variance is explained within the plane of the first two

779 eigenvectors, increasing to 95.5% when including the third eigenvector. The first principal

780 component (PC-1) is most influenced by $^{207}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$, whereas the second

781 principal component (PC-2) is dominantly influenced by $^{206}Pb/^{204}Pb$ and $^{87}Sr/^{86}Sr$. The third

782 principal component (PC-3) is dominated by $^{207}Pb/^{204}Pb$ and $^{143}Nd/^{144}Nd$ (Supplementary

783 Table 3).

784 ***K-means Cluster Analysis***

785 K-means cluster analysis [76] was carried out on the samples using the 13 standardised

786 variables (Extended Data Table 1). The K-means algorithm assigns each object to a singular

787 cluster that does not overlap with another (i.e., partitional clustering), minimising the total

788 sum of squared error (SSE) from the centre point of each cluster, known as the centroid, to

789 each data point.

790 To find the optimum number of clusters (k)—which reduces the within-cluster total sum of

791 squares error with the lowest number of clusters—we run the K-means algorithm specifying k

792 to be 1:20, over 1000 iterations for each k (Supplementary Fig. 1). We then select eight

793 clusters based on $k=8$, reducing the within-cluster total sum of squares by 75% from $k=1$, and

794 the range over the 1,000 iterations being minimised when $k \geq 8$. The cluster assignments for

795 each object, out of the 1,000 iterations, are selected by finding the iteration number that is

796   closest to the mean within-cluster total sum of squares of that k value (shown by the blue line

797   in Supplementary Fig. 1).

798   **Data Availability**

799   The datasets analysed for the current project are available as Supplementary Material. Some

800   data were obtained from GeoROC [19,32,51]; these data are clearly marked in the datafile.

801   The data is freely available on FigShare at https://doi.org/10.6084/m9.figshare.28769105 (ref

802   83)

803   **Code Availability**

804   The input data, code and output within this study is openly available and can be found at

805   https://github.com/ygraigarw/AfarPlume.git (ref. 84)

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1 # Mantle upwelling at Afar triple junction shaped by overriding plate

2 # dynamics

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20 **Mantle upwellings drive large-scale surface volcanism and facilitate continental breakup**

21 **and ocean basin formation. However, the spatial characteristics and internal composition**

22 **of these upwellings and how they are modified by plate tectonics are poorly resolved. Afar,**

23 **East Africa, is a classic triple junction comprising three rifts at various stages of evolution**

24 **thought to be underlain by a mantle upwelling or plume, allowing examination of the**

25 **controls on the mantle upwelling. Here, we present geochemical data from >130 samples**

26 **of "young" volcanoes spanning the triple junction to show that the underlying mantle**

27 **comprises a single, asymmetric upwelling. Using statistical modelling to integrate our**

28 **data with existing geochemical and geophysical constraints, we suggest that Afar is fed by**

29 **a spatially and chemically heterogeneous upwelling, which controls the composition and**

30 **relative abundance of melt in all three rift arms. We identify repetitive signatures in**

31 **mantle compositions in rift regions, whose variability is a longer wavelength in faster-**

32 **extending rift arms. This suggests more rapid channelised mantle flow occurs where**

33 **rifting rates are higher and the plate is thinner, aiding flow of the upwelling towards the**

34 **faster spreading Red Sea Rift. Our findings demonstrate how the evolution of mantle**

35 **upwellings are influenced by the dynamics of overriding plates.**

36 The role of mantle upwellings, sometimes interpreted as mantle plumes, in driving volcanism

37 during continental breakup has long been debated (e.g. [1-4]). Moreover, our understanding of

38 rift-plume interactions remains incomplete because only a small fraction of Earth's upwellings

39 are situated under continents [5] and there are a limited number of upwellings associated with

40 ongoing continental rifting [6]. The Afar triple junction—where the Arabian, Nubian, and

41 Somalian tectonic plates intersect—is a "classic" example of magma-assisted continental

42 rifting. Here, rifting occurred diachronously with the onset of the Gulf of Aden Rift (GoA) at

43 ~35 Ma [7], the Red Sea Rift (RSR) at ~23 Ma [8] and the Main Ethiopian Rift (MER) at ~11

44 Ma [9]. Both intraplate stresses tied to the slab pull effect of Neo-Tethys subduction [10], and

45 thermal weakening by a mantle upwelling, are thought to have driven rifting [11]. The

46 diachronous onset has led to each rift (GoA, RSR and MER) being in a different phase of

47 maturity (that is, ocean formation, proto-oceanic formation, and mature continental rifting,

48 respectively), and all three rifts are currently volcanically and tectonically active [12], making

49   it an ideal location to study the interactions between mantle upwelling and rifting, and how

50   these coevolve.

51   The driver of melt production in Afar is debated, with some models suggesting decompression

52   melting with minimal plume involvement [13], whereas others propose the upwelling of hot,

53   deep mantle [14-17], or indeed multiple upwellings [18, 19]. Whilst several discrete segments

54   of the RSR have been studied in terms of magma petrogenesis (e.g., [16, 20]), a paucity of

55   high-precision geochemical data has hampered evaluation of the spatial characteristics of

56   upwelling across the broader region and rigorously test existing models of the links between

57   tectonics and upwellings.

58   Here, we implement a comprehensive sampling strategy, targeting evolutionarily young

59   volcanoes spanning the three rifts (Fig. 1). We analyse rocks that are Quaternary in age (i.e.,

60   less than 2.58 million years (Myr) old), and from volcanoes that have been active during the

61   Holocene, which began 11.7 thousand years ago (ka) [21]. By targeting younger rocks, we

62   make a direct comparison with geophysical data across the region, enabling an integrated

63   exploration of mantle petrogenesis and dynamics. Our approach utilises statistical methods

64   including semi-parametric regression using splines and K-means cluster analysis to integrate

65   and analyse these geophysical and geochemical data to explore models of upwelling that can

66   explain our data.

67   **Characteristics of Mantle Upwellings**

68   Mantle upwellings that originate between depths of 1,000 and 2,800 km are anomalously hot

69   zones and/or zones of an enriched composition that reduce the solidus temperature of the

70   mantle, enabling increased partial melting [22]. Mantle upwellings are widely accepted to

71   contain a variety of domains of differing proportions (e.g., HIMU, EMI, EMII, C and FOZO

72   [e.g., 5, 22-25]). Such domains typically exhibit an isotopically distinct and enriched

73   composition (that is, generally low $^{87}Sr/^{86}Sr$, high $^{143}Nd/^{144}Nd$, and high $^{206}Pb/^{204}Pb$ [24])

74   relative to those of bulk silicate Earth (BSE [5]). Trace element ratios such as Ce/Pb and ΔNb

75   have previously been used to indicate enriched upwellings (> 30 [26], >0 [27] respectively),

76   and La/Sm to suggest the melt fraction relative to the study region with a lower-than-average

77   value suggesting an elevated melt fraction [19]. Mantle upwellings are also commonly

78   associated with reduced (i.e., lower) seismic velocities (i.e., S waves [Vs] and P waves [Vp])

79   [28, 29] that are caused by elevated temperatures and/or the presence of fluids and partial melt

80   [30].

81   Crustal assimilation, where crust components are incorporated into the magma, can obscure

82   these geochemical indicators of a deep mantle plume. However, within the Afar region, crustal

83   contamination has played a relatively minor role in recent magmatism [14] compared to earlier

84   stages of rifting [14, 26], due to the thinning of the present-day crust and that it has been

85   extensively intruded by mafic melts along the length of the rift axes. Seismicity analysis

86   indicates that recent magmatic activity beneath the rift axes in Afar is transient [31] and, in

87   turn, that magmas are unlikely to reside in crustal reservoirs for long enough to extensively

88   assimilate crustal lithologies.

89   **Probing the Presence of Mantle Upwelling(s) in Afar**

90   Our study includes over 130 rock samples, with many from previously unstudied volcanoes,

91   roughly doubling the number of high-quality analyses from the area (Fig. 1). The 79 Afar

92   samples included in our study were carefully selected from a repository covering the broader

93   Afar region (see Methods for details). These were supplemented by 52 additional samples

94   collected during fieldwork in the MER. To examine spatial trends in the geochemistry of

95   surface volcanism, we analysed all samples for major and trace elements alongside radiogenic

96   isotopes (Sr, Nd, Pb; see Methods). We also integrated data for 93 rock samples from the open-

97   source GEOROC data repository (https://georoc.eu/ (ref.[32]); see Methods for selection

98   criteria), as well as the classic GoA catalogue from ref.[19]. Additionally, we leverage recent

99   spatial compilations of geophysical variables, such as the depth of the Mohorovičić

100   Discontinuity (Moho) [31] (see Methods) and shear-wave velocities at regularly spaced depths

101   (i.e., 40, 60, 80, 100, and 120 km [30]) across the region. These variables provide well-

102   established proxies for the boundary between the crust and mantle, and for the presence and

103   abundance of melt within the lithosphere and asthenosphere [30]. Collectively, this information

104   allows us to infer details about the depth, compositional characteristics and relative abundance

105   of partial melts distributed across all three rifts.

106   Based on these samples, we infer wide geochemical variability across the study region (Fig. 1).

107   Delta Niobium ranges from -0.26 to 0.94 and La/Sm ratio ranges from 0.4 to 4.6. The

108   radiogenic isotopes $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$, $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ also display

109   a large range (Fig. 2, Extended Data Table 1), with enrichments relative to BSE occurring in

110   all three rifts. Local variability in these radiogenic isotopes is observed within some volcanoes,

111   e.g., Boset Bericha; however, this variability is smaller than the regional range determined for

112   Afar (Fig. 1).

113   Across the study region, the depth of the Moho varies, being shallowest in the RSR (~16 km)

114   and deepest in the MER (31 km). Like the geochemical data, the shear-wave velocities (Vs) at

115   40, 60, 80, 100 and 120 km depths show regional variability: 3.81-4.05, 4.06-4.17, 4.00-4.15,

116   3.97-4.10, 4.02-4.10, respectively (Extended Data Fig. 1). All rifts show zones of high and low

117   Vs (relative to ref.[30]) in the mantle which vary laterally and in depth.

118   To evaluate the potential influence of crustal assimilation—considered minor in the Afar region

119   [14]—on mantle composition and upwelling, we assess the correlation between key

120   geochemical and geophysical indicators (Fig. 4a) and the depth to the Moho. The Moho, the

121   boundary between the crust and mantle, serves as a proxy for crustal thickness, which is widely

122   thought to influence the degree of assimilation [26] (Methods). We found that most indicators,

123   including Pb isotopes—a reliable indicator of crustal assimilation [34]—exhibit only a weak,

124   but statistically significant, correlation with Moho depth (Fig. 4a). Further, Ce/Pb exhibits a

125   strong negative correlation (i.e., Pearson correlation coefficient of -0.7), indicating that where

126   the crust is thin, the Ce/Pb values are high, and vice versa. This trend can be attributed to

127   minimal crustal assimilation across most of the Afar region, though the degree of assimilation

128   increases as the crust thickens within the MER.

129   Overall, our dataset shows geochemical and geophysical variability across the study area,

130   which are consistent with the presence of an upwelling across all three rifts. The spatial trends

131   observed in all variables implicate an underlying complexity to the location of partial melts.

132   **Models of the Afar Upwelling**

133   We used our data to test multiple conceptual models of mantle upwelling dynamics. The initial

134   conceptual model we considered is a simple, homogeneous mantle upwelling at the triple

135   junction (e.g., ref.[19]). This model expects variables (geochemical and geophysical) that

136   indicate deep upwelling to change radially with distance from the upwelling centre (C1C – 1

137   centre, concentric; Fig. 3, Extended Data Table 2). Therefore, this model assumes that variables

138   change linearly from the upwelling centre due to lateral spreading. Extending this model, we

139   then allow the upwelling to be spatially and temporally heterogeneous, as reported for the

140   Hawaiian [35] and Canary Island [36] volcanoes. This mechanism yields a similar pattern to

141   the linear C1C model but accommodates compositional fluctuations over the radial distance

142   corresponding to a chemically pulsed upwelling (Fig. 3). This model fits a single spline per

143   parameter for all data against distance from the upwelling centre (spline C1C). The optimum

144   spline allows for regional variations to be accounted for, whilst minimising noise (i.e., optimal

145   smoothing). This approach of both linear and spline fits is applied to all further models

146   described in this section allowing for homogenous and heterogeneous upwelling(s),

147   respectively. Note the starting composition of the upwelling is not constrained within the model

148   parameters.

149   We additionally tested whether the spatial geochemical and geophysical variations observed

150   (Fig. 1 and Extended Data Fig. 1) are best explained through the presence of three small-scale

151   upwellings, which have been proposed based on geophysics and numerical models (e.g.

152   ref.[37], C3C – 3 centres, concentric; Fig. 3; Extended Data Table 1). We tested this model

153   using three upwellings: one centred on the triple junction, one in the northern RSR, and one in

154   the southern MER, with the positions of these loci informed by previous models and

155   observations (Methods). This model fits one linear/spline regression per variable (against

156   distance) from the nearest upwelling centre and assumes that the upwellings are

157   compositionally identical and from the same deep source.

158   It is plausible that the variable tectonic regime (e.g., extension rate, crustal thickness) between

159   the three rifts [12] introduces further complexity to the geochemical and geophysical signals.

160   Accordingly, we introduce three further models, C1D, C3D, and C3X (Fig. 3, Extended Data

161   Table 2; Methods) to account for these regional differences. Models C1D (1 centre, different

162   spreading) and C3D (3 centres, different spreading) consider one upwelling and three small-

163   scale upwellings, respectively, while allowing for distinct distance-dependent patterns for each

164   rift, thereby modelling the distribution of variables across each rift independently. Unlike the

165   other models, C3X (3 independent centres, different spreading) allows each small-scale

166   upwelling to have a distinct signature, as well as permitting an independent distribution along

167   each rift (Methods).

168   **Spatial Characteristics of Afar Mantle Upwelling**

169   To test these models (Fig 3, Extended Data Table 2), we identify 14 key geochemical and

170   geophysical variables (for descriptions, see Extended Table 2) and calculate the distance, using

171   the spherical cosine law (Methods), between the purported upwelling centre [15, 19, 38] and

172   each observation site (Methods). We then apply two-deep cross validation (100 iterations) to

173   find the optimum linear fit (that is, representing a homogeneous upwelling) and penalised B-

174   spline fit (that is, representing a heterogeneous upwelling) to each of the variables, using all

175   data points, over a radial distance of 500 km—the radial limit of samples considered within our

176   study (Fig. 4b and Extended Data Fig. 2). The predictive performance of each fit is then

177   assessed by calculating the mean standardised root-mean squared error of prediction (RMSEP),

178   where a value of 1 indicates a lack of predictive capability, and 0 a perfect predictive ability

179   (Fig. 4c).

180   For all models, we observe the B-spline fit (i.e., a class of polynomial function; Methods) to

181   have the best predictive performance, compared to a linear fit (Fig. 4c). This indicates that a

182   compositionally heterogeneous upwelling in Afar is most probable (Figs. 4b and 4c).

183   The analysis indicates that the overall best predictive model is the B-spline fit of model C1D,

184   wherein a single, heterogeneous mantle upwelling is present, albeit with differing distributions

185   of geochemical and geophysical variables between rift-arms (Fig. 3; Extended Data Table 2).

186   This model yields a mean standardised RMSEP of 0.59 (Fig. 4c), lower than that of the other

187   models. To further validate our results, we carried out sensitivity analysis, varying the

188   geochemical and geophysical data about their known uncertainties (see Methods). The results

189   confirm that model C1D remains the most accurate predictive model (Fig. 4c).

190   Whilst the RSR and MER have a high sample density, there is limited sample availability from

191   the GoA due to poor access. When excluding the GoA from our analyses, the overall trend

192   between the models remains effectively the same (Extended Data Fig. 3b). Although the Afar

193   rifts share a single, compositionally heterogenous upwelling, they appear to behave

194   independently, implying that some feature of their tectonic regime modulates the observed

195   signals.

Interplay Between Upwelling and Segmentation

197   Many of the optimum splines for each rift display distance-dependent sinusoidal patterns (Fig.

198   4b; Extended Data Fig. 2). Importantly, our analysis indicates that the variability observed for

199   some variables within the MER exhibit greater amplitude and shorter periodicity with distance

200   from the centre of the upwelling compared to those of the RSR (Fig. 4b; Extended Data Fig.

201   2). Further, the observed variation in Pb isotopes within the RSR suggests that the upwelling

202   may be chemically heterogeneous for some elements, whereas others show a narrower range

203   in composition (e.g., $^{87}Sr/^{86}Sr$ is more heterogeneous than $^{143}Nd/^{144}Nd$; Fig 1; Extended Data

204   Fig 1). Although ΔNb values are almost consistently positive (>0) across the region (except

205   around Boset-Bericha Volcano), we identify small-scale differences in La/Sm and Vs at 100

206   km depth, within the likely melt-rich zone of the asthenosphere [26], with distance to upwelling

207   centre in each rift (Fig. 4b; Extended Data Fig. 2). These small-scale differences indicate locally

208   variable degrees of melting across the study region, agreeing with previous studies that reported

209   low velocity areas [e.g., 37, 39]. This raises the question: do the zones of locally higher melt

210   fraction, low Vs, and variable geochemistry observed in one rift correspond, spatially and

211   compositionally, to those observed in the other two rifts? If so, this could indicate a shared melt

212   source.

213   To address the spatial heterogeneity patterns observed and investigate the potential shared melt

214   source, we carried out principal component analysis (PCA) and K-means cluster analysis using

215   all variables post-standardisation (Methods). Across all variables, the K-means cluster analysis

216   algorithm seeks to group similar observations whilst minimising the within-cluster total sum

217   of squares for a pre-specified number of clusters. Our K-means cluster analysis shows a higher

218   number of clusters that are smaller in geographic size for the MER (50-100 km length scale; 4

219   clusters) compared to the RSR (150-200 km length scale; 3 clusters) (Fig. 5; Methods). Several

220   clusters (clusters 1-3) are found to co-exist in different rift-arms. For example, samples

221   assigned to cluster 3 are observed in the distal section of the RSR, as well as in locations closer

222   to the MER rift centre (Fig. 5). The three clusters (1-3) observed across the RSR match the

223   initial ~200 km clustering sequence observed across the MER. This sequential repeated

224   clustering may indicate that they are derived from a shared source melt. However, the sequence

225   of these melts—as indicated by clusters—within the MER occurs over a shorter distance

226   compared to that of the RSR.

227   The spatial distribution of clusters reflects spatial variations in the composition and abundance

228   of melt, which shares some cursory similarities to the magmatic segments observed at the

229   surface (Fig. 5). However, when inspected in detail we observe clear differences. For example,

230   volcanic systems both within magmatic segments and the adjacent rift flanks are commonly

231   allocated to single clusters, and the boundaries between clusters and known magmatic segments

232   are typically mismatched (Fig. 5). In Afar, the length of the region containing clusters is longer

233   than that of magmatic segments. We therefore infer that the compositional variability of mantle

234   upwelling is unlikely to be related to the along-axis segmentation of crustal subvolcanic

235   plumbing systems.

236   **Tectonic Control on Flow of Upwelling**

237   Taken together, our data can be explained through a single upwelling model with internal

238   heterogeneity between rifts (e.g., refs.[31, 35, 40, 41]), as shown by the spline model. Crucially,

239   the K-means cluster analysis indicates the signatures of geochemical variability (i.e., clusters)

240   are repeated across rifts, implicating pulses of upwelling from the same source, as inferred for

241   other mantle plumes (e.g., refs.[36, 40, 41]). Rifts act as natural channels for upwelling melt

242   from deeper mantle sources [42]. Considering the high extension rate in the RSR (10.5-19.5

243   mm/yr; [43]) compared to that of the MER (∼5.2 mm/yr; [43]), it is plausible that a mantle

244   flow rate is impeded by the narrowing of the rift in the MER. This process would lead to a

245   'bottleneck' effect [42, 44, 45], which in turn may result in a different length scale of mantle

246   heterogeneity (Fig. 4; Extended Data Fig. 2) between the RSR and MER (Fig. 5). Further, a

247   contrast in crustal thickness is evident between the rifts, with the MER crust being thicker (25-

248   33 km [46]) than that of RSR (16-25 km [47]; Extended Data Fig. 1). Assuming a correlation

249   between crustal and overall plate thickness, this effect is expected to introduce differences in

250   mantle flow rate along each rift in Afar. A progressive thickening of the overlying lithosphere

251   away from the upwelling centre in the MER should reduce the volume capacity for melt,

252   impeding mantle flow. Consequently, the heterogeneous nature of the pulsed upwelling would

253   exhibit a more condensed spatial pattern within the MER compared to RSR, as we observe

254   (Fig. 5).

255   We conclude that variations in melt composition and abundance in and around Afar is best

256   explained by a heterogeneous pulsing mantle upwelling that is not symmetrical (Fig. 5) but is

257   instead shaped by both variable lithospheric thinning and extension rates within each rift (Fig.

258   6). Whilst this model principally investigates the likelihood of a singular or three-small-scale

259   upwelling scenario, our results demonstrate that for either option, a single heterogeneous

260   upwelling provides the best match to observations in the region. The detected variations in melt

261   composition and abundance between the MER and RSR imply that the length scale of

262   heterogeneities within magma-assisted rifting environments may be controlled not only by the

263   upwelling itself, but by the extension rate and plate thickness. If this model is correct, it

264   demonstrates that the evolution of a mantle upwelling can be influenced and shaped by the

265   dynamics of the overriding plates.

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Author Contributions

E.J.W. conceived the idea, processed the data, and prepared the manuscript. T.M.G and D.K. advised on the work and assisted with sampling and interpretation. P.J. wrote the code for the statistical modelling and assisted with interpretation. T.K.H advised on the statistical analysis. E.J.W., R.R., M.S., M.J.C., A.M., J.A.M., and R.N.T analysed the samples and processed the geochemical data. E.L.C processed the geophysical data for the sample locations. E.J.W., T.M.G., and D.K. wrote the manuscript with input from all co-authors.

Competing Interests Statement

The authors declare no competing interests.

Figure Captions

Fig. 1: Variation in geochemical and geophysical properties around the Afar Triangle; (a) Map showing the Gulf of Aden Rift (GoA), Red Sea Rift (RSR) and the Main Ethiopian Rift (MER) axes (dashed lines) and associated rifting rates indicated by arrows (from refs. [43,48]). The three hypothesised [19, 37, 38] upwelling locations (yellow stars) and Holocene volcanoes (red triangles) are shown. Hexmap colours show the density of samples within the hexagons' area, with purple representing >12 and yellow showing 1-2. Location of maps shown on global inset (black rectangle). (b) Hexmap showing the $^{206}Pb/^{204}Pb$ variations across the study region (dark blue = low $^{206}Pb/^{204}Pb$ - minimal upwelling signature, yellow = high $^{206}Pb/^{204}Pb$). (c) Hexmap showing La/Sm variations across the study region (yellow = high La/Sm – low melt fraction, dark blue = low La/Sm – high melt fraction). (d) Hexmap showing the $^{143}Nd/^{144}Nd$ variations across the study region. Yellow indicates a high $^{143}Nd/^{144}Nd$. The topography shown is from the 1 arc-sec (~30 m resolution) Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) [50].

Fig. 2: Radiogenic isotope compositions of samples across Afar. (a) $^{206}Pb/^{204}Pb$ versus $^{208}Pb/^{204}Pb$; (b) $^{143}Nd/^{144}Nd$ versus $^{87}Sr/^{86}Sr$. Samples are classified by their rift position, indicated by their symbol colour and shape (RSR = blue circles, MER = green squares, GoA = yellow diamonds). Error bars show the uncertainty associated. Black error bars are the average uncertainty of the dataset, grey are the maximum uncertainty. Uncertainty for datapoints in (a) are smaller than the symbols. The global mantle endmember compositions are shown as fields behind from refs.[5, 49]. The histograms show the distribution of all data analysed in our study, including our >130 data points.

Fig. 3: Conceptual models of mantle upwellings beneath Afar tested in this study. Schematic diagram of the upwelling scenarios for Afar tested in this study. The diagrams (left) are labelled

310 with the code associated with each model (see Extended Data Table 2 and the Statistical

311 Analysis section within Methods for further details). The location of the purported mantle

312 upwellings are shown by the star symbol. The number of lines shown on the schematic graphs

313 equals the number of models that must be fitted for that model variant (linear = dashed, spline

314 = continuous), where R = Rift and U = upwelling. Note that each model variant has been

315 illustrated with an indicator that decreases with a reduction in upwelling proportion.

316 *Fig. 4: Statistical analysis of rifting models for the RSR, GoA and MER. (a)* Pearson

317 correlation coefficient of each of the selected 13 variables with Moho depth. Error bars show

318 the 95-percentile error of the coefficient (n = 250) with the squares representing the mean. Red

319 squares indicate where the correlation is significant ($p < 0.05$) and blue squares indicate that

320 the correlations are not deemed significant ($p > 0.05$). **(b)** Splines (a smooth, flexible

321 polynomial curve) of the best overall model—that is, C1C—for selected variables. Symbols

322 show the data within the study (locations denoted by symbols shown). 95% confidence

323 intervals are indicated by the shaded background. The number of data observations (n) for

324 La/Sm, $^{143}Nd/^{144}Nd$, $^{206}Pb/^{204}Pb$ and Shear velocity at 100km depth are 269, 218, 185, and 184

325 respectively. Uncertainty in data values have been shown by error bars (average in black, max

326 in grey). (**c**) The mean standardised root means square error of prediction (RMSEP) for each

327 of the models tested. Individual linear model results are shown by red squares and the mean of

328 those results are displayed by the red line. Individual spline results are shown by blue circles

329 and the mean of those results are shown by a blue line. All models were run for 100 iterations

330 to capture the probable uncertainty distribution, as shown by the data points. Mean (dotted line)

331 and 95% confidence interval (shaded) of results using perturbed data (within the uncertainty of

332 each datapoint) are also shown (300 perturbation runs each using 100 iterations).

333 *Fig. 5: Map of the segments and cluster assignment within the study region.* Segments are

334 shown in blue from north to south: Erta Ale Volcanic Segment (EAVS), Tat'Ale Volcanic

335   Segment (TAVS), Alayta Volcanic Segment (AVS), Dabbahu Volcanic Segment (DVS),

336   Gabillema Volcanic Segment (GVS), Adda'do Magmatic Segment (AMS), Fentale-Dofen

337   Magmatic Segment (FDMS), Boset Magmatic Segment (BMS), Aluto-Gedamsa Magmatic

338   Segment (AGMS), Corbetti Magmatic Segment (CMS). Rift axis (dotted line) is shown. (b)

339   and (c) are enlarged maps of the boxes shown in (a). (d) & (e) Principal component (PC)

340   analysis bi-plot (PC1 vs PC2) when considering the six isotopic systems (see Extended Data

341   Table 3) showing the samples and their component scores relative to those of the mantle

342   endmembers. Values used for the mantle endmembers, that is, Pan-African Lithosphere (PAL),

343   Enriched Mantle 1 & 2 (EM1, EM2, respectively), Depleted MORB Mantle (DMM) and

344   HiMU, are shown in Extended Table 3. The topography shown is from the 1 arc-sec ($\sim$30 m

345   resolution) Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) [50].

346   *Fig. 6: Spatially heterogeneous nature of the mantle upwelling beneath Afar.* (**a**) Box

347   diagram showing the rifts across Afar and the mantle upwelling being channelised by the rift.

348   The lines of section X-Y-Z are those shown in panel (**c**). Volcanic segments are shown and

349   labelled: Erta Ale Volcanic Segment (EAVS), Tat'Ale Volcanic Segment (TAVS), Alayta

350   Volcanic Segment (AVS), Dabbahu Volcanic Segment (DVS), Gabillema Volcanic Segment

351   (GVS), Adda'do Magmatic Segment (AMS), Fentale-Dofen Magmatic Segment (FDMS). (**b**)

352   Schematic of the Afar upwelling showing the dimensions of channelised flow along the three

353   rifts (dashed lines). (**c**) Schematic cross sections along the Red Sea Rift (line section X-Y) and

354   MER (Y-Z) showing the distribution of chemical heterogeneities within the upwelling and how

355   those map to the clusters shown in Fig. 5. Note that the depths of distinct features including the

356   Lithosphere-Asthenosphere Boundary (LAB) are not shown to scale.

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516   **Methods**

517   *Sample Selection and Processing*

518   All samples and previously published data used in this study must originate from a volcano

519   that has been active within the Holocene [21] (Fig. 1), with the age of the sample estimated to

520   be of Quaternary age (i.e., < 2.58 Ma). An essential criterion was that all samples have a

521   precisely known location with accurate coordinates.

522   *Obtaining Previously Published Data*

523   Previously published geochemical data were obtained from GeoROC [19, 32]. Once

524   downloaded the data-files were filtered to only include data within Ethiopia (including the

525   Main Ethiopian Rift and Afar). These data were further filtered using the following criteria:

526   1. The values for the sample must relate to whole rock geochemistry, as opposed to

527   mineral separates.

528   2. The individual sample must have major element, trace element, $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$,

529        $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ isotope values available.

530   *3.* The coordinates must be specific to the individual sample's location rather than

531   providing an average coordinate for a broader study area.

532   *Sampling and Sample Preparation*

533   Ninety-three lavas, eleven welded tuffs and one pumice sample, from various volcanoes in

534   Afar (Erta Ale Volcanic Segment, Ayelu, Abida, Yangudi, Dama Ali, Kerub, Ela, Didoli,

535   Abbahu, Afdera, Tat Ali and Manda Hararo) were selected for geochemical analysis [see

536   refs.51-53]. The samples were collected during the CNR/CNRS projects in Afar during the

537   1960s [54] and stored in the Afar Repository at the University of Pisa, Italy,

538   (http://repositories.dst.unipi.it/index.php/home-afar). A further 52 samples from the Boset-

24

539   Bericha Volcanic Complex (BBVC) were collected during three field seasons [ref.55], in

540   November 2012, April-May 2015 [ref.56], and February 2017 [ref.57].

541   Sample preparation, for major, trace and isotope analyses, was carried out at the University of

542   Southampton. Samples were cut with a saw to remove any weathered sections, and any cut

543   surfaces ground down to reduce any potential contamination by metals from the saw blade.

544   Rock samples were then crushed using a fly press and placed in double-layered plastic bags

545   prior to crushing to minimise metal contamination during the crushing process.

546   The crushed material was separated into three size fractions (>1 mm, 0.5 mm to 1 mm, <0.5

547   mm) using Teflon sieves, retaining the middle fraction (0.5 - 1 mm) for analysis. The selected

548   fraction was cleaned by ultrasonicating in Milli-Q water then dried overnight in an oven at

549   85ºC. The cleaned rock chips were then hand-picked under a microscope, to remove any

550   extraneous (non-rock) material. An aliquot of cleaned chips was used for Pb isotope analysis.

551   For major element, trace element, and $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ isotope analysis, the

552   remaining rock chips were ground to a fine powder using an agate mortar and pestle, again to

553   minimise contamination with metals.

554   *Trace Element Analysis*

555   Samples were prepared for whole-rock trace element analysis using 0.05 g (for BBVC

556   samples) or 0.075 g (for all other samples) powdered sample. The powdered samples were

557   digested in sealed Savillex Teflon vials with 15 drops concentrated HNO_3 and 2 ml HF on a

558   hotplate at 130 °C for 24 hours (for all samples excluding those from the BBVC), or with 50

559   drops HF and 0.2 ml HNO_3 on a hotplate at 130 °C for 24 hours (for BBVC samples only).

560   The HNO_3/HF was evaporated off, and the samples were refluxed in 6M HCl for another 24

561   hours on a hotplate at 130 °C. The 6M HCl was evaporated off, and the samples were

562   redissolved in 6M HCl. Mother solutions were prepared by adding 6M HCl and Milli-Q

563 water (total 30 ml) to the dissolved samples. Daughter solutions were prepared using 0.5 ml

564 of mother solution, diluted to 5 ml with 3% HNO_3 (containing the internal standards 5 ppb In/

565 5 ppb Re/ 20 ppb Be), resulting in an overall dilution factor of c. 4000.

566 Trace element analyses of the daughter samples were undertaken on the Thermo Scientific X

567 Series 2 quadrupole inductively coupled plasma mass spectrometer (ICP-MS) at the

568 University of Southampton. Samples and standards were spiked with internal standard

569 elements and corrected for interferences and the blank and then calibrated using a suite of

570 international rock standards. Accuracy was monitored using reference materials JA-2, BCR-

571 2, JB-2 (see Supplementary Tables 1 and 2).

572 *Pb Isotopic Analysis*

573 For Pb isotope analysis, 0.3 g of cleaned, picked rock chips (0.5 mm to 1 mm) were weighed

574 into Pb Savillex Teflon vials and leached on a hotplate with 4 ml 6M HCl for one hour (15

575 minutes for obsidian and pumice samples, to avoid full dissolution of the sample). Samples

576 were rinsed several times in Milli-Q water, then 0.5 ml concentrated HNO_3, before adding 3-

577 4 ml of concentrated HF. Samples were digested, following the same procedure as for trace

578 elements, and refluxed on a hotplate at 130 °C for 24 hours, before being evaporated to

579 dryness. 0.5 ml concentrated HCl was added, and the sample evaporated to dryness. Then 0.5

580 ml concentrated HNO_3 was added and again evaporated to dryness. The final residue was

581 reconstituted in 0.5 ml HBr and refluxed for an hour. The samples were cooled and

582 centrifuged for 5 minutes. Pb was isolated using a single-stage HCl anion-exchange

583 chromatographic resin separation method [58], with AGX-1x8, 200 – 400 mesh resin.

584 Following this, the Pb isolate was dried down, redissolved in HNO_3, and analysed using the

585 double spike method of ref.[59]. The samples were subsequently analysed on a Thermo

586 Scientific Neptune Multi-collector inductively coupled plasma mass spectrometer (MC-

587 ICPMS) at the University of Southampton (UK) achieving a NBS SRM 981 reproducibility

588 of $^{206}Pb/^{204}Pb$ = 16.9404 ± 24 (142 ppm), $^{207}Pb/^{204}Pb$ = 15.4969 ± 26 (168 ppm), $^{208}Pb/^{204}Pb$

589 = 36.7149 ± 66 (180 ppm) (2sd; n=44). Pb isotope measurements of the standard are within

590 error of the accepted values ($^{206}Pb/^{204}Pb$ = 16.9412, $^{207}Pb/^{204}Pb$ = 15.4988, $^{208}Pb/^{204}Pb$ =

591 36.7233). Accuracy was 47 ppm for $^{206}Pb/^{204}Pb$, 123 ppm for $^{207}Pb/^{204}Pb$, and 174 ppm for

592 $^{208}Pb/^{204}Pb$.

593 *$^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ Isotopic Analysis*

594 For Sr and Nd analysis, the remaining mother solutions from the preparation of trace element

595 solutions (see above) were used for all samples except those of the BBVC. An aliquot of each

596 mother solution was used, to give a volume of liquid containing at least 1 μg Sr and 200 ng

597 Nd and evaporated to dryness in Savillex Teflon vials on a hotplate at 130ºC. Sample

598 residues were reconstituted in 200 μl 1.75M HCl. For the BBVC samples, rock chips were

599 leached in 4 ml 6M HCl or 30 minutes in Savillex Teflon vials (obsidian samples for only 15

600 minutes, to avoid full dissolution of the sample). The samples were then rinsed with Milli-Q

601 water and HNO_3, and then the same digestion procedure as for trace element analysis (above)

602 was followed. The final mother solutions were prepared using HCl and Milli-Q water to 30

603 ml for felsic samples and 20 ml for mafic samples.

604 All samples were then passed through ion exchange column chemistry, using a AG50-X8

605 200-400 mesh resin cation column to separate the Sr and Nd fractions. The sample fractions

606 were subsequently evaporated to dryness, ready for further column chemistry.

607 Sr was further isolated through Sr-spec resin columns, following the methodology of ref.[60].

608 Samples were then evaporated to dryness, dissolved in 1.5 ml 1M HCl and loaded onto

609 outgassed tantalum filaments with 1 μl of Ta-activator. Sr isotopic analysis was performed on

610 a Thermal Ionisation Mass Spectrometer (TIMS) Thermo Scientific Triton Plus at the

611   University of Southampton. Reference material SRM NIST987 ($^{87}Sr/^{86}Sr$ = 0.710258;

612   GeoREM) was used to monitor accuracy and gave average $^{87}Sr/^{86}Sr$ values of 0.710243. All

613   samples were normalised to NBS SRM-987 $^{87}Sr/^{86}Sr$ = 0.710248 [61], while reproducibility

614   was ± 0.000020 (28.2 ppm, 2sd; n=464). Accuracy was 21 ppm.

615   The Nd aliquot from the cation column was followed by an Ln-spec resin (50-100 μm) [60].

616   The samples were then evaporated to dryness and 3% HNO_3 was added to produce a solution

617   of 50 ppb. $^{143}Nd/^{144}Nd$ analyses were undertaken on the ThermoScientific Neptune multi-

618   collector inductively coupled plasma mass spectrometer (MC-ICP-MS) at the University of

619   Southampton. Corrected Nd isotopic compositions were obtained using a method based on

620   ref.[62] through adjustment to a $^{146}Nd/^{144}Nd$ ratio of 0.7219 and a secondary normalisation to

621    $^{142}Nd/^{144}Nd$ = 1.141876. Reference material JNdi-1 was measured as an unknown

622   ($^{143}Nd/^{144}Nd$ of 0.512124, 2sd; [63]) achieving an average $^{143}Nd/^{144}Nd$ of 0.512115 with an

623   external reproducibility of ±0.000008 (2sd, 15.2 ppm) across 6 analysis sessions over 2 years.

624   The total column blanks (i.e., when blank acid is run through the column procedure) were

625   negligible (<20 pg) compared to the total amounts analysed (1 μg and 200 μg) for Sr and Nd,

626   respectively.

627   ***Shear Velocity Mapping from Joint Inversion***

628   We use the shear wave velocity model of ref.[30] for inclusion in our analysis. The 3D

629   velocity model is created through a joint inversion of Rayleigh-wave phase-velocities from

630   ambient noise and teleseisms [30, 33]. The shear velocity model is parameterised every 5 km

631   vertically with 0.1° x 0.1° pixel size for the upper 50 km. For deeper depths, an irregular

632   spacing was used, increasing from 10 – 50 km spacings to match that of ref.[39]. For further

633   details on the creation of the velocity model, the reader is directed to refs.[30, 33] and

634   references therein.

635   For the analysis in this paper, the shear velocity model was interpolated to 1 km depth using a

636   linear interpolation; we then extracted 1D columns of velocity with depth at the same

637   resolution as our pixel size (0.1° x 0.1°).

Moho Depths

639   The gridded Moho depth map was produced from the Vs maps of ref.[33], described above.

640   The Vs model was interpolated to a vertical grid spacing of 1 km. A velocity slice at the 3.75

641   km/s contour was extracted, which mapped best to previous receiver function measurements

642   [65-69], active source experiments (e.g., ref.[70]) and previous S-wave models (e.g.,

643   ref.[71]).

Statistical Models Considered

645   As described in the text, five models were considered (see Extended Data Table 2), with each

646   model being tested using a linear fit and a spline fit (Fig. 3). We note that a spline fit to itself

647   can be linear if that is the best-fitting line.

648   Empirical models are estimated for the variation of each of 14 geochemical quantities (each

649   of which is represented generically by random variable Y) as a function of distance $d \in [0,$

650   1800] km for the five different models. Models are specified that explore the variation of Y

651   with d in increasing complexity. The simplest model (C1C) assumes the existence of a single

652   upwelling centre (at 11.192 ºN 41.784 ºE; see Figs. 1 & 3), with respect to which d is defined

653   for all three rifts. The variation of Y with d is assumed common to all rifts. Model C3C

654   assumes the existence of three upwelling centres (at 11.192 ºN 41.784 ºE, 14.008 ºN 40.458

655   ºE & 6.626 ºN 37.948 ºE; see Fig. 1) based on ref.[37]; observations are allocated to the

656   nearest upwelling centre, facilitating calculation of a single d for each observation. Like

657   model C1C, the variation of Y with d is assumed common to all rifts, regardless of upwelling

658   allocation. Model C1D assumes one upwelling centre (like C1C) for calculation of d, but now

659 the variation of *Y* with *d* is assumed to be different across rifts. Model C3D duplicates C3C

660 for estimation of *d*, but variation of *Y* with *d* is assumed to be different across rifts. Finally, in

661 model C3X, we consider the presence of three upwelling centres, with different variation of *Y*

662 with *d* for each combination of upwelling and rift.

663 ***Data Pre-Processing***

664 For models C1C and C1D, the distance between each sample and the upwelling locus centred

665 on Lake Abhe (11.192170 ºN, 41.783750 ºE) is calculated. For models C3C, C3D and C3X,

666 the distance between each sample and each of the three upwelling locations (Figs. 1 & 3) is

667 measured, and then each sample is assigned to its nearest upwelling centre. The distance (*d*)

668 between two locations (i.e., upwelling and sample) is calculated using the spherical cosine

669 law:

670 $$d = R(\cos^{-1}(\cos(a)\cos(b) + \sin(a)\sin(b)\cos(C)) \qquad \text{(Eq. 5)}$$

671 where *a* is the angle (in radians) from the North Pole to the sample location, *b* is the angle (in

672 radians) from the North Pole to the upwelling location, *C* is the difference in radians between

673 the longitude values of the sample and upwelling, and *R* is the radius of the earth in metres

674 (6371×10^3).

675 ***Penalised B-splines***

676 For each model, the variation of *Y* with *d* is described using a penalised B-spline (e.g.,

677 refs.[72-73]), the characteristics of which are selected to provide optimal predictive

678 performance. First, for a large index set of locations equally spaced on the domain of

679 distance, we calculate a B-spline basis matrix, *B* (e.g., ref.[74]) consisting of *p* equally spaced

680 cubic spline basis functions. Then the value of *Y* on the index set is given by the vector *Bβ*,

681 for spline coefficient vector *β* to be estimated. The value of *p* is specified to be sufficiently

682 large to provide a good description of a highly variable *Y*. For a given data set, we penalise

683   the difference between consecutive values in β using a roughness penalty, such that the

684   penalised spline exhibits optimal roughness, providing optimal predictive performance.

685   ***Estimating Optimal Spline Roughness and Predictive Performance***

686   For a sample of n_1 training data, consisting of vectors of geochemical and geophysical

687   quantities (y_1) and distances (d_1), we first allocate each element of d_1 to its nearest

688   neighbour in the index set, and hence construct the appropriate spline basis matrix B_1 for the

689   sample. We then assume that $y_1 = B_1\beta + \varepsilon$, where the elements of ε are independently and

690   identically distributed zero-mean Gaussian random variables. We penalise the roughness of β

691   using a first-different penalty $\lambda\beta'P\beta$, where $P = D'D$ and D is a first difference matrix (with

692   elements $D_{ij} = -1$ if $i = j$; $= 1$ if $j = i + 1$; and $= 0$ otherwise (e.g., ref.[75]). For a

693   given choice of λ, we then find the optimal value of β by minimising lack of fit:

694      $\beta^*(\lambda) = \underset{\beta}{argmin} \{(y_1 - B_1\beta)'(y_1 - B_1\beta) + \lambda\beta'P\beta\}$ (Eq. 6)

695      $\quad\quad = (B_1'B_1 + \lambda P)^{-1}B_1'y_1$ (Eq. 7)

696   We can evaluate the predictive performance of the resulting spline description using a tuning

697   set of n_2 observations (independent of the training set) represented by vectors y_2 and d_2. We

698   again start by finding the appropriate spline basis matrix B_2 for this sample. Then we can

699   calculate the predictive mean square error for the tuning sample:

700      $\text{MSE}_{Tune}(\lambda) = \frac{1}{n_2}\left(y_2 - B_2\beta^*(\lambda)\right)'\left(y_2 - B_2\beta^*(\lambda)\right)$ (Eq. 8)

701   for each of a set of representative choices of values for λ. We can then select the optimal

702   value of λ using

703      $\lambda^* = \underset{\lambda}{argmin} \{\text{MSE}_{Tune}(\lambda)\}$ (Eq. 9)

704   The value $\mathrm{MSE}_{Tune}(\lambda^*)$ is a biased estimate of predictive performance since the value of λ^*

705   was tuned to minimise its value. We can obtain an unbiased estimate for the predictive

706   performance of the spline model using a test set of n_3 observations (independent of the

707   training and tuning sets) represented by vectors y_3 and d_3 (and corresponding spline basis

708   matrix B_3). Then the predictive performance is estimated using:

709     $MSE_{Test} = \frac{1}{n_3}\left(y_3 - B_3\beta^*(\lambda^*)\right)'\left(y_3 - B_3\beta^*(\lambda^*)\right)$ (Eq. 10)

710   ***Cross-Validation and Model Comparison***

711   We exploit cross-validation to evaluate MSE_{Test}, by partitioning the full sample of data into

712     $k > 2$ groups at random, withholding one group for tuning, another group for testing, and

713   retaining the remaining $k - 2$ groups for training. We then loop exhaustively over all

714   possible combinations of choice of train, tune, and test groups, evaluating overall predictive

715   performance on the test data over all iterations, noting that each observation occurs exactly

716   once in the test set. For models requiring separate model fits to subsets of data (that is, C1D,

717   C3D, C3X), MSE_{Test} is estimated using predictions from optimal predictive models for each

718   subset. Further, we can repeat the analysis for different initial random partitioning of

719   observations into k groups, to assess the sensitivity of overall predictive performance to this

720   choice. We are careful to use the same cross-validation partitions to evaluate each of the five

721   models, so that predictive performances can be compared fairly.

722   To quantify model performance over all 13 geochemical quantities ($j = 1, 2, \dots, 13$), we

723   define the overall standardised MSE_{Test}

724     $\mathrm{SMSE} = \sum_{j=1}^{13} \frac{\mathrm{MSE}_{Test,j}}{s_j^2}$ (Eq. 11)

725   where $\mathrm{MSE}_{Test,j}$ is the predictive performance for the jth geochemical indicator, and s_j^2 is the

726   sample estimate for the variance of that quantity. The estimation of the splines and the testing

727   of their predictive performance was repeated over 100 iterations. Results from each iteration

728   and the mean of the SMSE is shown in Fig. 4.

Linear Regression

730   For comparison, we also evaluate linear regression models for the variation of *Y* with *d*. In the

731   current notation, these can be thought of as simple models with basis matrix *B = [1 d]*, where

732   *1* is a vector of appropriate length with each element *= 1*. *B* in this case is a 2-vector with

733   elements corresponding to intercept and slope coefficients. Linear regression is approached

734   using penalised B-spline models as the roughness coefficient $\lambda \rightarrow \infty$. That is, linear regression

735   corresponds to a penalised B-spline model with very large λ. Therefore, a penalised B-spline

736   model is guaranteed to perform at least as well as linear regression.

Uncertainty of Model Performance

738   To explore the effect of uncertainty on model performance, a perturbation analysis was

739   undertaken. This analysis required the generation and modelling of n_{Pert} new data samples.

740   Each of these data samples corresponded to a perturbation of the original data sample. A

741   value of $n_{Pert} = 300$ was selected to ensure that 95% uncertainty bands for predictive

742   performance on perturbed data could be estimated with confidence.

743   In perturbed sample q, $q = 1, 2, \dots, n_{Pert}$, the value y_{ijq}^{*} of the *i*th observation for variable *j*

744   was obtained by perturbing the corresponding value y_{ij} in the original data sample, using

745   additive Gaussian noise e_{ijq}, the standard deviation σ_{ij} of which was informed by the known

746   value of measurement uncertainty for that observation of the variable. Mathematically:

747    $y_{ijq}^{*} = y_{ij} + e_{ijq}$ (Eq. 12)

748   The complete modelling procedure was then applied to each perturbed data sample in turn.

749   The predictive performance of different models was assessed over the n_{Pert} perturbations, as

750   illustrated in Fig. 4, in terms of 95% uncertainty bands. The figure indicates that model C1D

751   provides best predictive performance on perturbed data, as well as for the original

752   unperturbed sample. Note that, since noise has been added to observations in the perturbation

753   analysis, the overall performance of models on perturbed data is poorer than on the original

754   sample, as expected.

Testing the Influence of Crustal Assimilation

756   We tested the influence of crustal assimilation further by excluding cases where Ce/Pb values

757   fall below 20 and which could feasibly be associated with crustal assimilation [26, 34]. Using

758   additional analysis, we confirm that excluding cases in which Ce/Pb < 20 does not affect our

759   overall results (see Extended Data Fig. 3a), suggesting that primary mantle compositional

760   fluctuations (i.e., relative proportions of compositional mantle endmembers) exert the first-

761   order control on eruptive compositions at the surface.

Principal Component Analysis

763   Principal component analysis (PCA) requires each sample or object to have the same number

764   of values for each variable and so the dataset was reduced to 94 samples. PCA is only carried

765   out on radiogenic isotope compositions of the samples where data are available for the mantle

766   endmembers investigated (i.e., Afar plume, Pan-African Lithosphere, Depleted Mantle,

767   Enriched Mantle 1, Enriched Mantle 2, HiMU; Fig. 5; Extended Data Table 3). While other

768   purely geochemical studies on Afar (e.g., refs.[14, 38]) have included sub-crustal components

769   such as the sub continental lithospheric mantle (SCLM), we decided not to include this

770   endmember as it can sometimes be indistinguishable from certain mantle endmembers (i.e.,

771   EM1), especially in cases where the SCLM is metasomatized. Values used for the

772   endmembers in our models are provided in Extended Data Table 3. Each object is

773   standardised before being included in the PCA:

774 $\qquad y_{\text{std}j} = \frac{y_j - \overline{y}_j}{\sigma_j}$ (Eq. 13)

775 where $\overline{y}_j$ is the mean of variable j, and σ_j is the standard deviation of the variable j:

776 $\qquad \sigma_j = \sqrt{\frac{\Sigma\{(y_j - \overline{y}_j)\}^2}{N_j}}$ (Eq. 14)

777 where N_j is the number of objects within variable j.

778 Approximately 90.5% of the variance is explained within the plane of the first two

779 eigenvectors, increasing to 95.5% when including the third eigenvector. The first principal

780 component (PC-1) is most influenced by $^{207}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$, whereas the second

781 principal component (PC-2) is dominantly influenced by $^{206}Pb/^{204}Pb$ and $^{87}Sr/^{86}Sr$. The third

782 principal component (PC-3) is dominated by $^{207}Pb/^{204}Pb$ and $^{143}Nd/^{144}Nd$ (Supplementary

783 Table 3).

K-means Cluster Analysis

785 K-means cluster analysis [76] was carried out on the samples using the 13 standardised

786 variables (Extended Data Table 1). The K-means algorithm assigns each object to a singular

787 cluster that does not overlap with another (i.e., partitional clustering), minimising the total

788 sum of squared error (SSE) from the centre point of each cluster, known as the centroid, to

789 each data point.

790 To find the optimum number of clusters (k)—which reduces the within-cluster total sum of

791 squares error with the lowest number of clusters—we run the K-means algorithm specifying k

792 to be 1:20, over 1000 iterations for each k (Supplementary Fig. 1). We then select eight

793 clusters based on $k=8$, reducing the within-cluster total sum of squares by 75% from $k=1$, and

794 the range over the 1,000 iterations being minimised when $k \geq 8$. The cluster assignments for

795 each object, out of the 1,000 iterations, are selected by finding the iteration number that is

796   closest to the mean within-cluster total sum of squares of that k value (shown by the blue line

797   in Supplementary Fig. 1).

798   **Data Availability**

799   The datasets analysed for the current project are available as Supplementary Material. Some

800   data were obtained from GeoROC [19,32,51]; these data are clearly marked in the datafile.

801   The data is freely available on FigShare at https://doi.org/10.6084/m9.figshare.28769105 (ref

802   83)

803   **Code Availability**

804   The input data, code and output within this study is openly available and can be found at

805   https://github.com/ygraigarw/AfarPlume.git (ref. 84)

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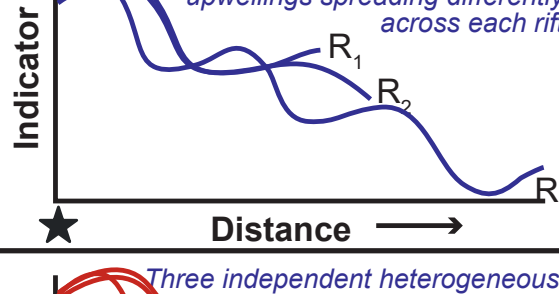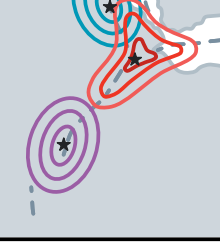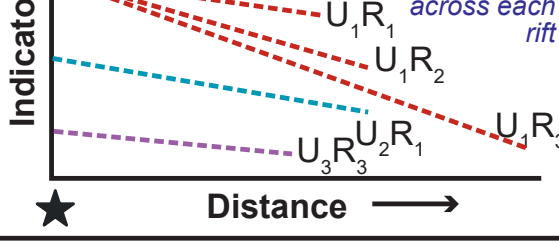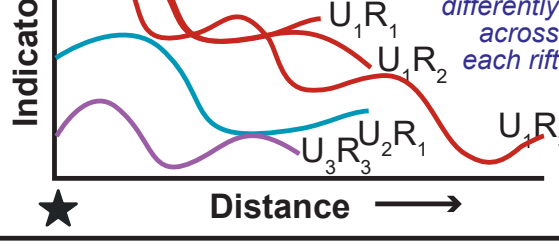
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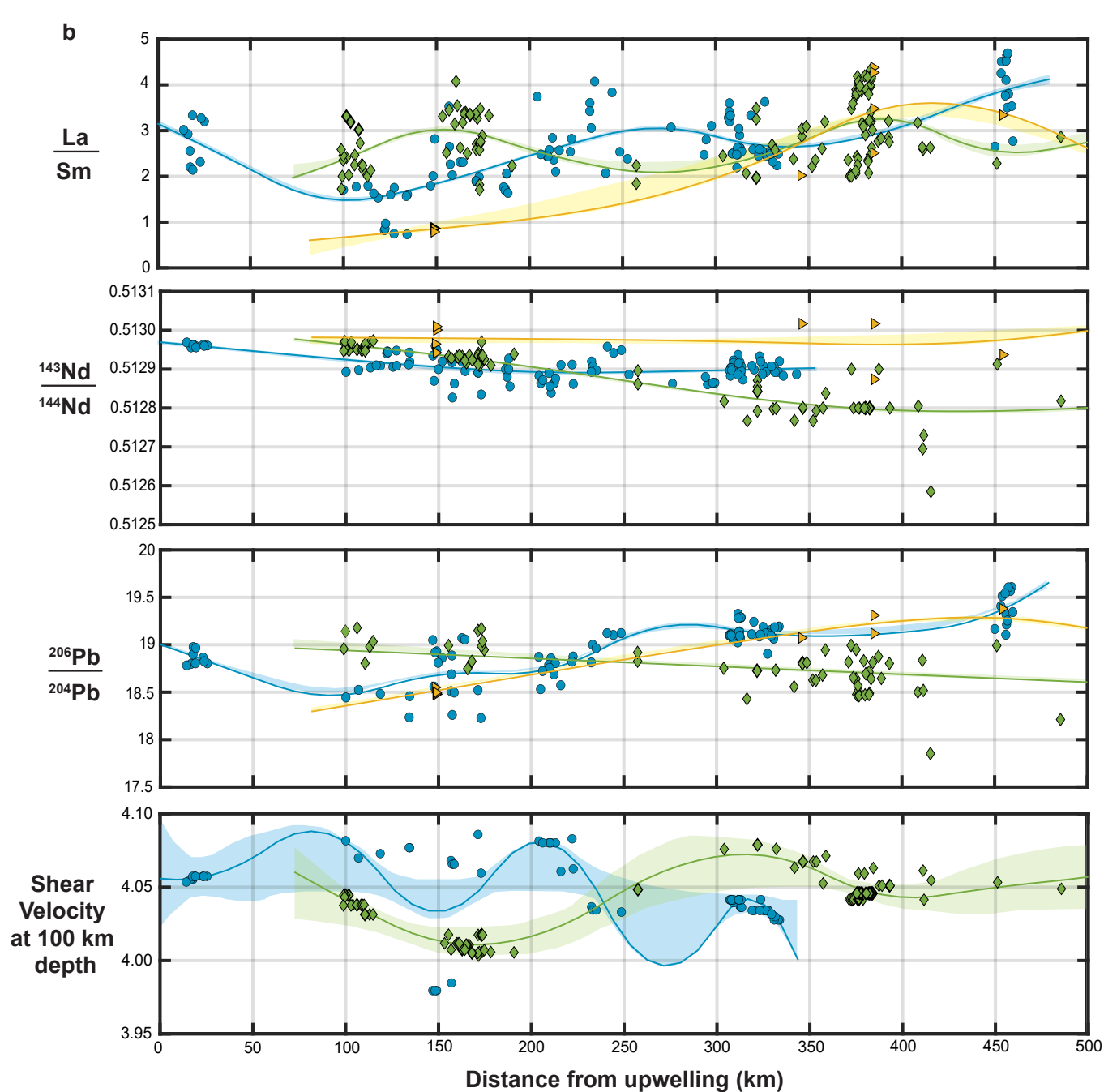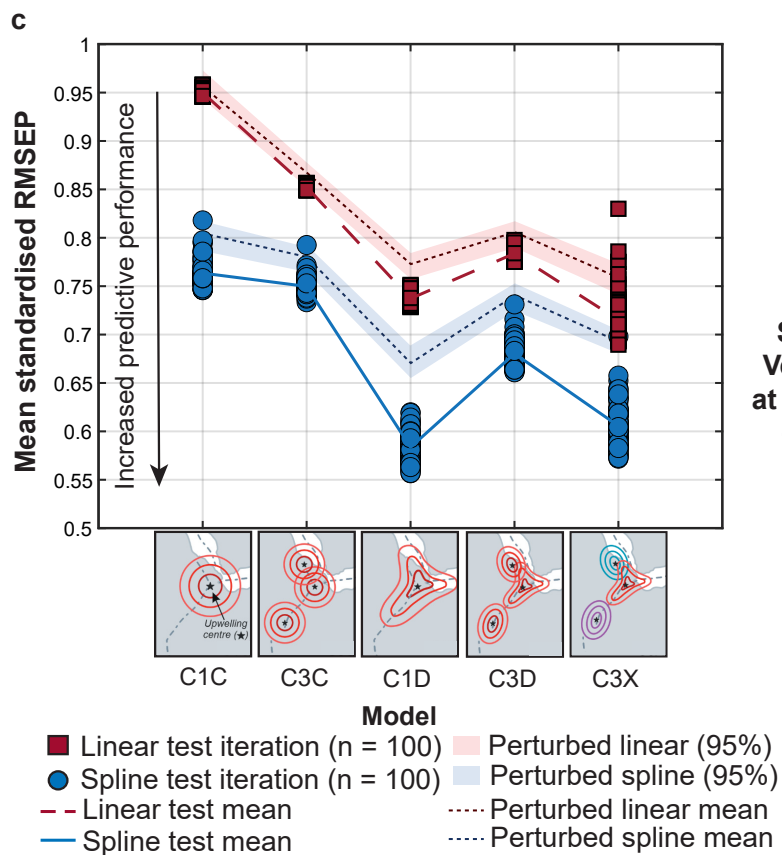
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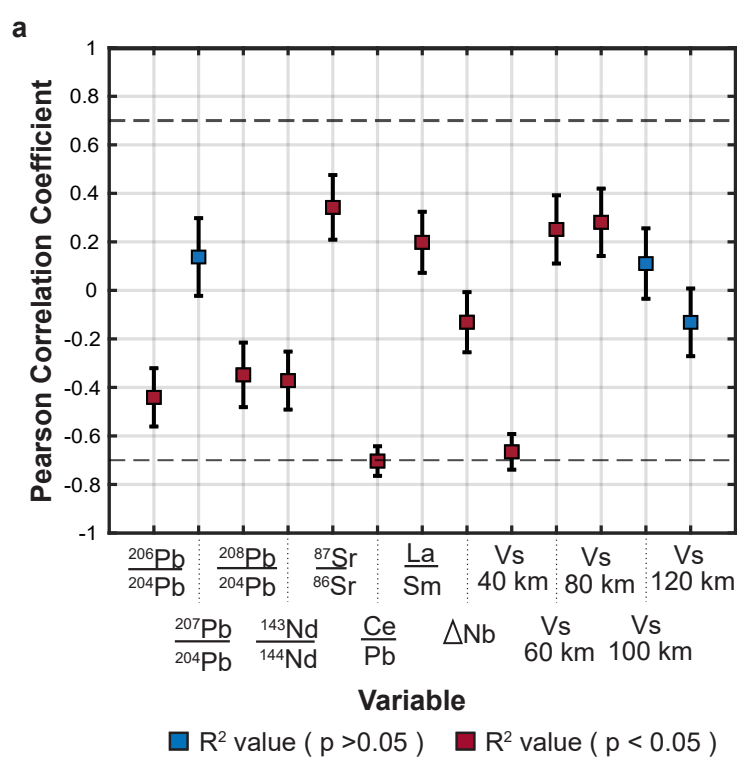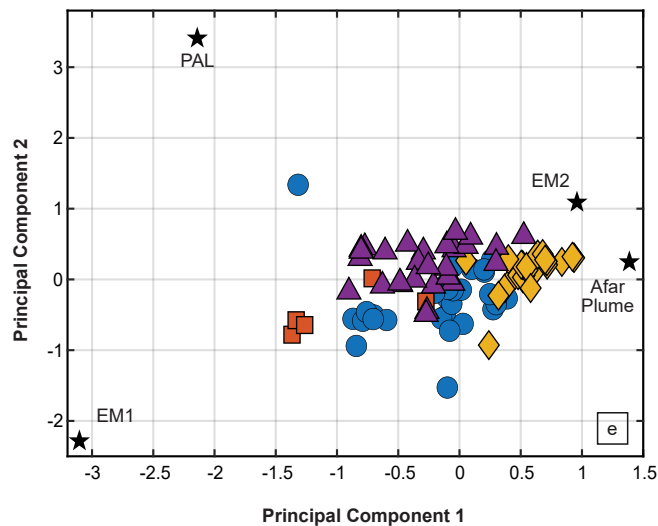
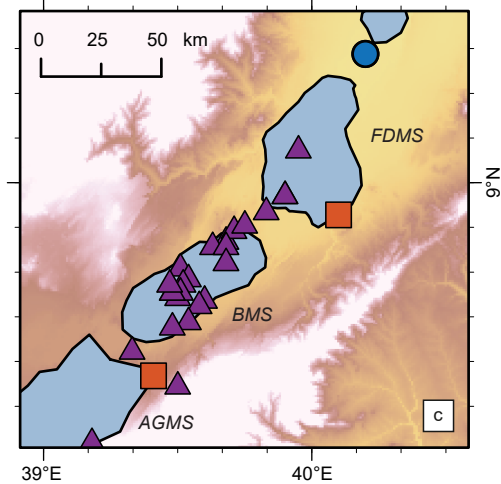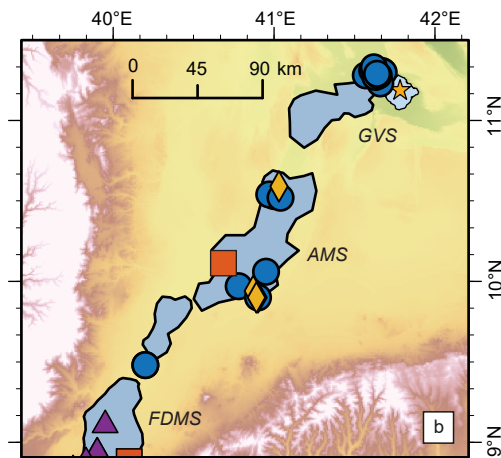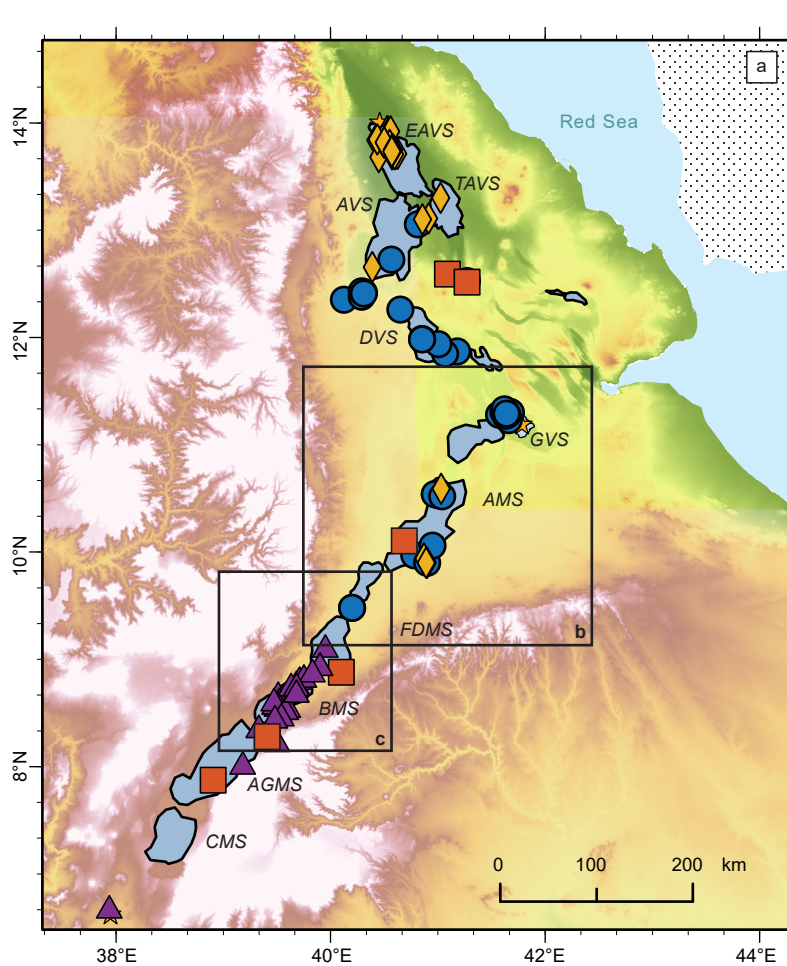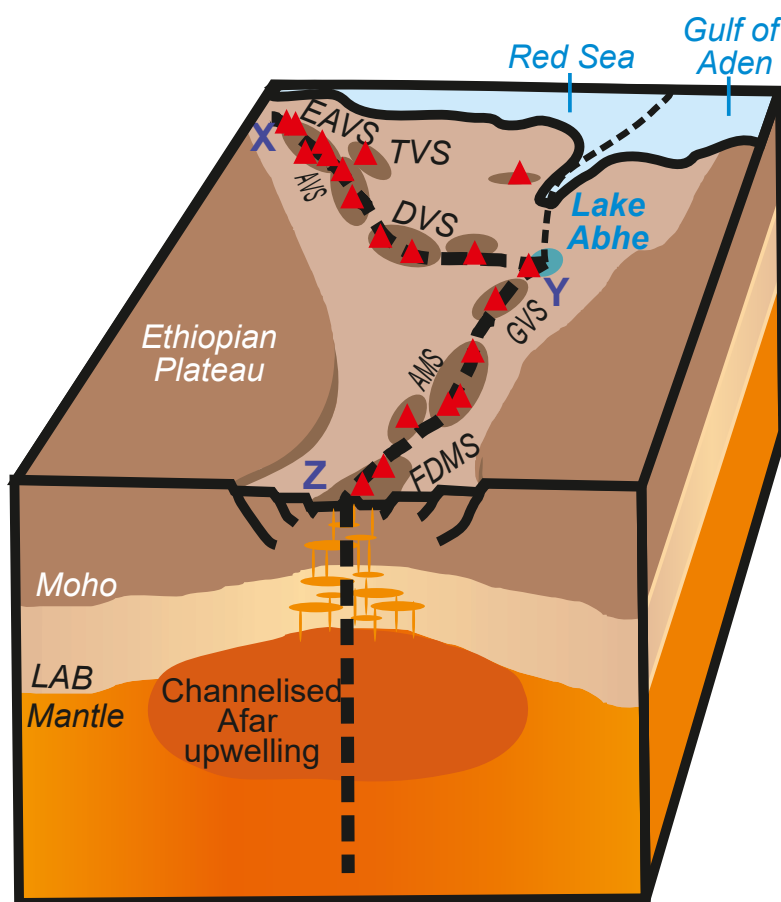| Model name & description	Model sketch	Expected plot for homogenous upwelling (linear model)	Expected plot for heterogeneous upwelling (B-spline model)
C1C (1 upwelling centre, concentric spreading)	*Upwelling centre (★)*	*Homogenous upwelling spreading equally across all three rifts*	*Heterogeneous upwelling spreading equally across all three rifts*
C3C (3 identical upwelling centres, concentric spreading)		*Three similar homogenous upwellings spreading equally with distance*	*Three similar heterogeneous upwellings spreading equally with distance*
C1D (1 upwelling centre, different spreading in each rift)		*One homogenous upwelling spreading differently across each rift* R_1 R_2 R_3	*One heterogeneous upwelling spreading differently across each rift* R_1 R_2 R_3
C3D (3 identical upwelling centres, different spreading in each rift)		*Three similar homogenous upwellings spreading differently across each rift* R_1 R_2 R_3	*Three similar heterogeneous upwellings spreading differently across each rift* R_1 R_2 R_3
C3X (3 different upwelling centres, different spreading in each rift)		*Three independent homogenous upwellings spreading differently across each rift* U_1R_1 U_1R_2 U_1R_3 U_3R_3 U_2R_1	*Three independent heterogeneous upwellings spreading differently across each rift* U_1R_1 U_1R_2 U_1R_3 U_3R_3 U_2R_1

a

Pearson Correlation Coefficient

Variable: $\frac{^{206}Pb}{^{204}Pb}$, $\frac{^{207}Pb}{^{204}Pb}$, $\frac{^{208}Pb}{^{204}Pb}$, $\frac{^{143}Nd}{^{144}Nd}$, $\frac{^{87}Sr}{^{86}Sr}$, $\frac{Ce}{Pb}$, $\frac{La}{Sm}$, ΔNb, Vs 40 km, Vs 60 km, Vs 80 km, Vs 100 km, Vs 120 km

■ R^2 value ($p > 0.05$)   ■ R^2 value ($p < 0.05$)

c

Mean standardised RMSEP

Increased predictive performance

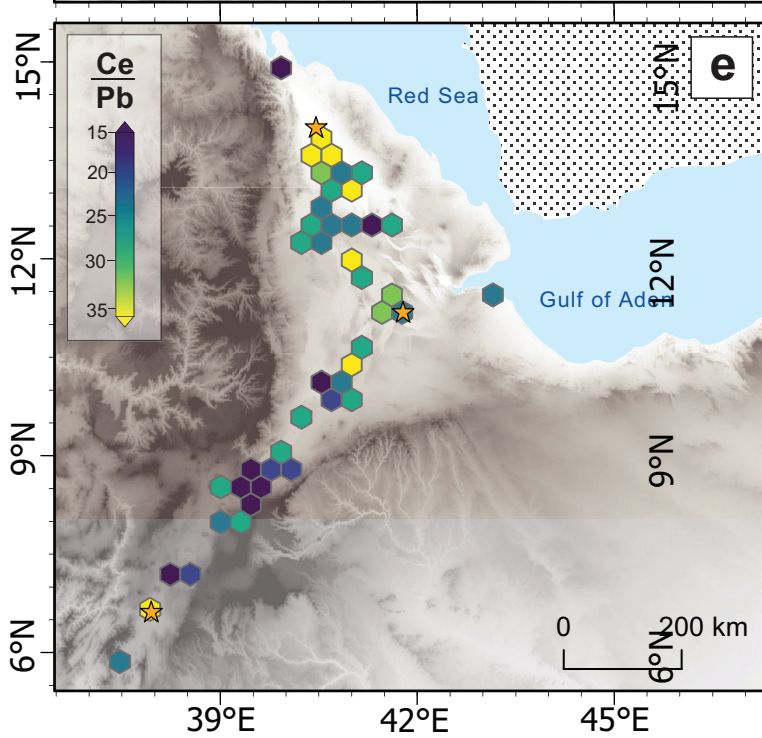Model: C1C, C3C, C1D, C3D, C3X

Upwelling centre (★)

■ Linear test iteration (n = 100)
● Spline test iteration (n = 100)
- - Linear test mean
— Spline test mean
Perturbed linear (95%)
Perturbed spline (95%)
Perturbed linear mean
Perturbed spline mean

b

$\frac{La}{Sm}$

$\frac{^{143}Nd}{^{144}Nd}$

$\frac{^{206}Pb}{^{204}Pb}$

Shear Velocity at 100 km depth

Distance from upwelling (km)

● Red Sea Rift sample
— Red Sea Rift spline
Red Sea Rift spline 95% confidence interval

◆ Main Ethiopian Rift sample
— Main Ethiopian Rift spline
Main Ethiopian Rift spline 95% confidence interval

▶ Gulf of Aden sample
— Gulf of Aden spline
Gulf of Aden spline 95% confidence interval

a

X
EAVS
TVS
AVS
DVS
Red Sea
Gulf of Aden
Lake Abhe
Y
GVS
AMS
FDMS
Z
Ethiopian Plateau
Moho
LAB
Mantle
Channelised Afar upwelling

b

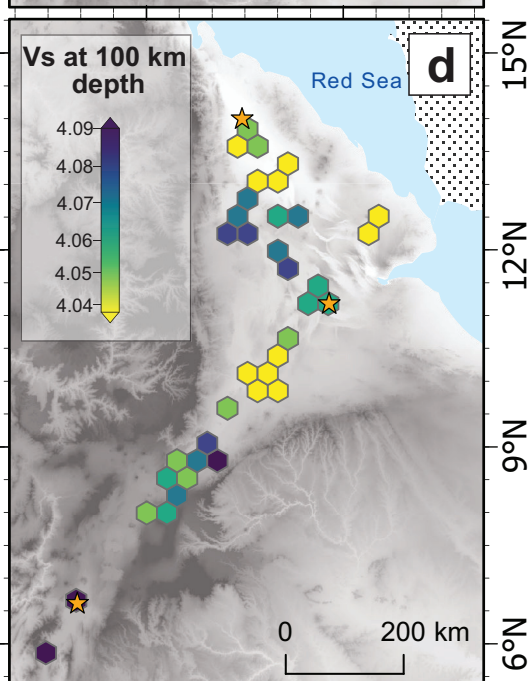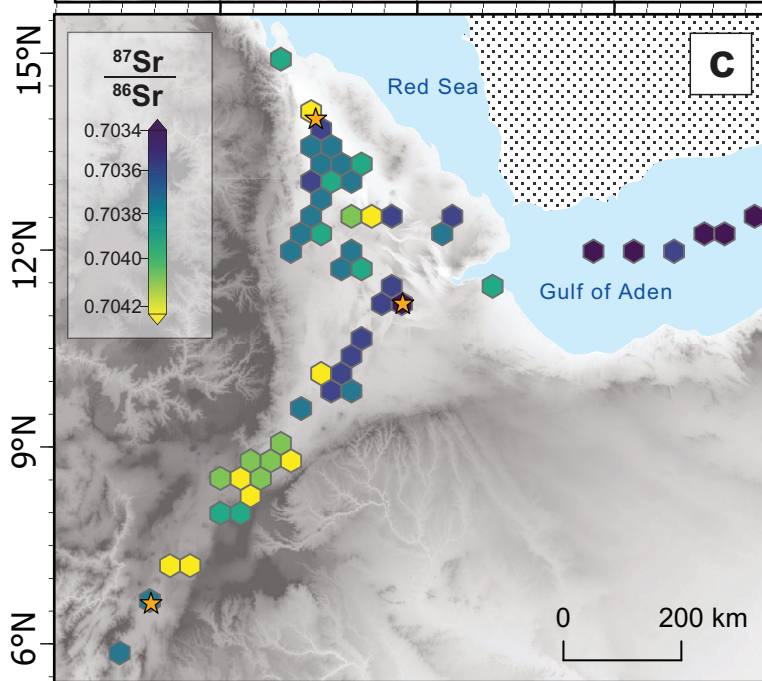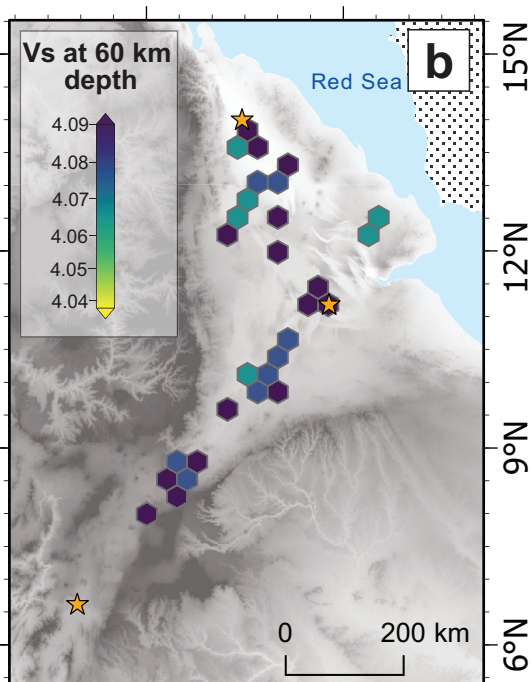*Schematic of Afar upwelling*

GoA
15.5 mm/yr

RSR
14.5 mm/yr

Longer length-scales of mantle heterogenities

MER
5.2 mm/yr

Mantle hetergeneities compressed

Heterogeneous mantle upwelling

c

X — Y

Alid
Alu-Dalafilla
Alayta
Manda Hararo
Dama Ali
Lake Abhe
15 km
Moho
LAB
Heterogeneous Mantle Upwelling
500 km

Y — Z

Lake Abhe
Adwa
Kone
Boset Bericha
Tullu Moye
Aluto
Moho
LAB
Heterogeneous Mantle Upwelling
500 km

24 km
~60 km
120 km
34 km

Clusters

$\dfrac{Ce}{Pb}$

ΔNb

$\dfrac{^{87}Sr}{^{86}Sr}$

$\dfrac{^{208}Pb}{^{204}Pb}$

Shear Velocity at 40 km depth

Shear Velocity at 60 km depth

Distance from upwelling center (km)

● Red Sea Rift sample
◆ Main Ethiopian Rift sample
▶ Gulf of Aden sample

— Red Sea Rift spline
— Main Ethiopian Rift spline
— Gulf of Aden spline

Red Sea Rift spline 95% confidence interval
Main Ethiopian Rift spline 95% confidence interval
Gulf of Aden spline 95% confidence interval

2sd(average,max)

Variable (s)	Observed Range	Details
$^{206}Pb/^{204}Pb$	17.853 to 19.608	$^{206}Pb/^{204}Pb$ >20 is linked to HIMU, $^{206}Pb/^{204}Pb$ ranging from 19.2 to 20.5 indicates a mantle upwelling source (C, FOZO) [77] and $^{206}Pb/^{204}Pb$ <17.8 can be related to a depleted mantle component [78, 79].
$^{207}Pb/^{204}Pb$	15.448 to 15.697	$^{207}Pb/^{204}Pb$ <15.5 is related to a depleted mantle component [77], $^{207}Pb/^{204}Pb$ >15.65 is linked to the HiMU component and $^{207}Pb/^{204}Pb \sim$ 15.6 indicates a mantle upwelling source (C, FOZO). A $^{207}Pb/^{204}Pb$ >15.75 is linked to crustal values [27, 41].
$^{208}Pb/^{204}Pb$	37.984 to 39.420	$^{208}Pb/^{204}Pb$ <38 is related to a depleted mantle component [77], $^{208}Pb/^{204}Pb$ >39.5 is linked to the HiMU component and $^{208}Pb/^{204}Pb$ 39.2 to 39.5 indicates a mantle upwelling source (C, FOZO). A $^{208}Pb/^{204}Pb$ >39.7 is linked to crustal values [27, 41].
$^{143}Nd/^{144}Nd$	0.51259 to 0.51317	A low $^{143}Nd/^{144}Nd$ (<0.5121) indicates continental crust or Pan African Lithosphere. $^{143}Nd/^{144}Nd$ values $\sim$ 0.51285 indicates a HIMU or upwelling related mantle source. Higher $^{143}Nd/^{144}Nd$ values (>0.5131) indicate a depleted mantle source (i.e., DMM) [27, 78-80].
$^{87}Sr/^{86}Sr$	0.70279 to 0.70678	A low $^{87}Sr/^{86}Sr$ (0.7040-0.7045) indicates a mantle component that is either depleted (DMM) or a deeper mantle upwelling (HIMU, C). A higher $^{87}Sr/^{86}Sr$ (<0.705) indicates the potential influence from continental crust [27, 78-80].
Ce/Pb	6.84 to 48.92	A Ce/Pb >30 is commonly attributed to a recycled mantle source that has been depleted in fluid mobile elements (i.e., Pb, Ba, Sr, K) during subduction, therefore resulting in high fluid-immobile-element to fluid-mobile-element ratios (i.e., Ce/Pb). Typical mantle has a Ce/Pb value of 25±5 and crust a value of ~4 [38].
La/Sm	0.4 to 4.7	(La/Sm) >1 indicates LREE enrichment fractionation (e.g., alkali basalts or upwelling), and (La/Sm) <1 indicates LREE depleted (mid-ocean ridge). In general, the higher the La/Sm the lower the melt fraction [23]
ΔNb	-0.26 to 0.95	Differentiates between a depleted mantle (ΔNb <0) and a mantle upwelling (ΔNb >0) [6]. $$\Delta N\,b \quad 1.74 + log\,\frac{N\,b}{Y} - 1.92\,log\,\frac{Z\,r}{Y}$$
Vs @ 40 km	3.81 to 4.06	Shear wave velocities can be sensitive to temperature, grainsize and the presence of fluids. A reduction in Vs can indicate a change in mantle composition or an increased proportion of melt to hydrothermal fluid [31]. Here, we used the velocities from 40 km to 120 km depth.
Vs @ 60 km	4.06 to 4.18	
Vs @ 80 km	4.00 to 4.16	
Vs @ 100 km	3.97 to 4.10	
Vs @ 120 km	4.03 to 4.10	
Moho depth	16-30 km	Depth to the Mohorovičić Discontinuity.

Model Name	Summary	Description
C1C	1 upwelling centre, concentric spreading	A singular upwelling centred at Lake Abhe (11.192 ºN, 41.784 ºE) with each rift (i.e., Red Sea Rift, Gulf of Aden rift and Main Ethiopian Rift) behaving the same (not independently), based on the theory of ref.[23]. This model fits a single line using all the data points from each rift. A linear model is used when assuming the upwelling is homogenous, and a spline is used to allow for heterogeneities in the upwelling.
C3C	3 identical upwelling centres, concentric spreading	Three upwellings centred at Lake Abhe (11.192 ºN, 41.784 ºE), and two other points across the region (14.008 ºN, 40.458 ºE and 6.626 ºN, 37.948 ºE); this model is based on the locations of previously proposed small-scale upwelling locations through numerical modelling [34]. Assumes each rift behaves the same (not independent of each other) and the upwellings are of the same composition.
C1D	1 upwelling centre, different spreading in each rift.	A singular upwelling centred at Lake Abhe (11.192 ºN, 41.784 ºE) with each rift behaving independently. This model fits three lines (i.e., one for each rift) across all data points for the corresponding rift.
C3D	3 identical upwelling centres, different spreading in each rift.	Three small-scale upwellings centred at Lake Abhe (11.192 ºN, 41.784 ºE), and two other points across the region (14.008 ºN, 40.458 ºE and 6.626 ºN, 37.948 ºE) with each rift acting independently. This model assumes that each upwelling is compositionally the same and fits three lines (i.e., one for each rift) across all data points for the corresponding rift.
C3X	3 different upwelling centres, different spreading in each rift.	Three small-scale upwellings centred at Lake Abhe (11.192 ºN, 41.784 ºE), and two other points across the region (14.008 ºN, 40.458 ºE and 6.626 ºN, 37.948 ºE) with each rift and upwelling acting independently. This model plots five lines.

End Member	Afar Plume	Depleted Mantle	Pan African Lithosphere	HiMU	EMI	EMII
$^{206}Pb/^{204}Pb$	19.5	17.5	17.85	22	17.4	19.3
$^{207}Pb/^{204}Pb$	15.6	15.3	15.75	15.84	15.48	15.64
$^{208}Pb/^{204}Pb$	39.2	36.6	39.75	40.75	39.0	39.75
$^{87}Sr/^{86}Sr$	0.512875	0.51335	0.5121	0.51285	0.51235	0.51235
$^{143}Nd/^{144}Nd$	0.7035	0.7022	0.7075	0.7025	0.7055	0.709
References	[41, 51]	[41, 51]	[41, 51]	[82]	[82]	[82]