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# 1 Uppermost mantle velocity from Pn tomography in the 2 Gulf of Aden

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## 22 **ABSTRACT**

23 We determine the lateral variations in seismic velocity of the lithospheric mantle beneath the  
24 Gulf of Aden and its margins by inversion of Pn travel times. Data for this study was collected by  
25 several temporary seismic networks and from the global catalogue. A least-squares tomographic

26 algorithm is used to solve for velocity variations in the mantle lithosphere. In order to separate  
27 shallow and deeper structures, we use separate inversions for shorter and longer ray path data. High  
28 Pn velocities (8.2 to 8.4 km/s) are observed in the uppermost mantle beneath Yemen that may be  
29 related to the presence of magmatic underplating of the volcanic margins of Aden and Red Sea.  
30 Zones of low velocity (7.7 km/s) are present in the shallow upper mantle beneath Sana'a, Aden,  
31 Afar, and along the Gulf of Aden that are likely related to melt transport through the lithosphere  
32 feeding active volcanism. Deeper within the upper mantle, beneath the Oman margin, a low  
33 velocity zone (7.8 km/s) suggests a deep zone of melt accumulation. Our results provide evidence  
34 that the asthenosphere undergoes channelized flow from the Afar hotspot towards the east along the  
35 Aden and Sheba Ridges.

## 36 **INTRODUCTION**

37 The Afar triple junction separates the Arabian Plate from the African Plate. This triple  
38 junction is characterized by abundant magmatic activity due to the presence of elevated  
39 temperatures associated with the Afar mantle plume, suggested to have played an important role in  
40 the continental break-up that led to the opening of the Red Sea and the Gulf of Aden rifts (Bellahsen  
41 et al., 2003). Deformation within the region is largely localized along these two rifts (Leroy et al.,  
42 2010). Seismic imaging studies carried out in this region have led to a better understanding of the  
43 lithospheric structure and the role played by the Afar plume in the volcanic activity and continental  
44 break-up. Shear wave velocity variations studied by Park et al. (2008) indicate the presence of low  
45 velocity regions at depths greater than 150 km beneath the Red Sea coast and the volcanic structures  
46 in Saudi Arabia. These velocity anomalies may be the result of hot material from the Afar plume  
47 flowing north beneath Arabia and along the Red Sea rift (e.g. Chang and Van der Lee, 2011).  
48 Continental margins in the western Gulf of Aden are volcanic while eastern margins are non-  
49 volcanic. The gravity study of Hébert et al. (2001) suggests the influence of the Afar plume is  
50 limited to the western part of the gulf. They found that the oceanic crustal thicknesses obtained from

51 inversion of mantle Bouguer anomaly east of 45°E are typical of a normal crust generated outside  
52 any hot spot influence. However, several subsequent studies have pointed out the presence of low  
53 velocity anomalies associated with partial melting in Oman (Basuyau et al., 2010), off-axis  
54 volcanism near the Sheba ridge (d'Acremont et al., 2010) and magmatic activity within the mantle  
55 beneath the entire Gulf of Aden (e.g. compilation of several investigations: electromagnetism,  
56 geochemistry, heat flow, see for a review Leroy et al., 2010). On the basis of geophysical  
57 measurements and teleseismic body-wave tomography, Leroy et al. (2010) and Chang and Van der  
58 Lee (2011) suggested that hot mantle material from the Afar plume may be flowing eastward along  
59 the inverted channel at the base of the lithosphere created by the Gulf of Aden ridges. In order to  
60 test this hypothesis we need robust constraints on the wavespeed of the uppermost mantle,  
61 constraints which are lacking from the previous regional and global studies which could not place  
62 constraints on mantle structure above 75 km depth (Park et al., 2007; Park et al., 2008; Chang and  
63 Van der Lee, 2011; Debayle et al., 2001; Phillips et al., 2007).

64 Here we describe the first regional study of lithospheric mantle P-wave velocities ( $P_n$ ) along the  
65 Gulf of Aden.  $P_n$  are high-frequency compressional waves that are refracted in the lithospheric  
66 mantle at about 8 km/s (Beghoul et al., 1993).  $P_n$  tomography studies can be used to interpret the  
67 rheology and the physical characteristics of the Mohorovicic discontinuity and the uppermost  
68 mantle (Bannister et al., 1991). Wave propagation velocities provide constraints on temperature,  
69 pressure, and compositional variations within the mantle (Perry et al., 2006). They are also used to  
70 study the spatial distribution of mantle upwelling and partial melting (Dunn et al., 2001). For this  
71 study we use the inversion method of Hearn (1996) to analyze  $P_n$  arrival times in data from  
72 networks of seismometers temporarily deployed in the region.  $P_n$  tomography allows us to image  
73 variations of wave propagation speed within the lithospheric mantle beneath the Gulf of Aden.  
74 These velocity variations are then interpreted within the context of regional geodynamics.

75 The aim of this work is to image the mantle structure of the entire Gulf of Aden and the triple

76 junction of the Red-Sea – Gulf of Aden – East-African rifts. In doing so, we can test models that  
77 explain the origin and distribution of volcanism along the Gulf of Aden.

## 78 **DATA**

79 The data consist of Pn first arrival times recorded by local networks deployed in Oman, Yemen and  
80 Socotra Island (Fig. 1) from April 2009 to May 2011 during the YOCMAL project: 23 stations were  
81 deployed in Oman, 60 stations arranged in 3 profiles in Yemen, and 24 stations on Socotra Island.  
82 Data collected from 2003 to 2007 by existing networks in Oman and Socotra were included in the  
83 study (Dhofar Seismic Experiment network, Fig. 1). We also used data from networks in Djibouti  
84 (2009 to 2011), Ethiopia (2007 to 2010, Afar Rift Consortium, Afar0911 and IRIS-PASSCAL  
85 networks) and Saudi Arabia (2009 to 2010, permanent station RAYN) (Fig. 1).

86 Pn waves are compressional head waves which travel along or below the Moho discontinuity, and  
87 are recorded at regional-scale distances (about 200 km to 1600 km). We used Pn arrival times for  
88 seismic events occurring at epicentral distances of  $1.8^\circ$  to  $16^\circ$  from each receiver, and we precisely  
89 hand-picked 13530 Pn arrival times. We combine our data with data from the ISC global catalogue  
90 in order to improve the data set and tomography model resolution (comparisons of the resolution  
91 between ISC data only and the combined data set with hand-picked Pn are provided in the  
92 Supplemental File, Figures DR1 and DR2). From the ISC catalogue we selected 65985 arrival times  
93 that are identified as Pn waves from events that occurred from 1990 to 2010 within a 2000 km  
94 diameter zone centered at  $17^\circ\text{N}$ ,  $54^\circ\text{E}$ . Several selection criteria were used to improve the data set  
95 quality. Only earthquakes with depths less than 35 km were selected. Each station was required to  
96 record five or more events and each event had to be recorded by at least five stations. To minimize  
97 location errors the following criteria were used: event locations calculated with a minimum of 8  
98 stations; azimuth gap  $< 200^\circ$ ; rms residuals  $< 3$  s; nearest station used in the calculation  $< 800$  km.  
99 All travel times selected were then plotted as a function of distance (Fig. 2) and only data with  
100 travel time residuals of 4 seconds or less relative to the mean mantle velocity were retained. We

101 found 52947 arrival times from 3778 events and 352 stations that satisfied the above criteria (Fig.  
102 3).

103 The distribution of seismic stations is not evenly spread over the entire study area. There is a high  
104 density of stations along the northern coast of the Gulf of Aden and in the Afar hotspot region.  
105 There are only a few stations across the rest of the Arabian plate and no stations in Somalia. The  
106 greatest number of seismic events occurred in the Zagros mountain belt and along the Aden Ridge.  
107 Figure 4 shows the ray path density for the selected arrival times and for the tomographic model.  
108 Regions with the highest density of Pn ray paths ( $> 64$  rays by cell) occur near the Afar triple  
109 junction, the northern coast of Gulf of Aden and an area between the western Gulf of Aden and  
110 Socotra Island. Intrusions of dyke swarms in the Afar region have triggered seismic episodes of a  
111 large number of highly-localized,  $< M5$  seismic events over a period of a few days or weeks (e.g.  
112 Wright et al., 2006; Ebinger et al., 2010; Grandin et al., 2011; Keir et al., 2011; Nobile et al., 2012)  
113 leading to high data density in the Afar region. At the time of the study, the most recent such swarm  
114 was located east of Djibouti, at  $44^{\circ}E$ , in November 2010 (Ahmed et al., 2013a; Shuler and Nettles,  
115 2012; Ebinger et al., 2013). One hundred seismic events were recorded over a period of two days,  
116 principally from the Socotra Island network. This episode is one of the largest observed from an  
117 oceanic spreading centre (Shuler and Nettles, 2012; Ahmed et al., 2013a). Areas with Pn arrivals  
118 numbering between 4 and 64 predominate in the rest of the study area. Data coverage is very good  
119 in the Afar region and on the northern margin of the Gulf of Aden, where most of the stations are  
120 located. Data coverage is poorest in the southern Saudi Arabia, the easternmost part of the Gulf of  
121 Aden and the southern margin.

## 122 **METHOD**

123 The Pn data inversion method for velocity was developed and described by Hearn (1996). Pn rays  
124 are sensitive to lateral propagation velocity variations in the upper mantle, to crustal thickness  
125 variations, and to crustal propagation velocity variations (Hearn and Ni, 1994). Following the

126 method of Hearn (1996) our investigation focuses on the Pn velocity variations assuming an  
127 isotropic medium and a ray path divided into three straight segments: (1) the focus-mantle path, (2)  
128 the mantle path and (3) the mantle–station path, which are then adjusted for the curvature of the  
129 Earth. For the inversion, the uppermost layer of the mantle is divided into a set of two dimensional  
130 cells. The slowness (inverse of velocity) is determined for each cell by solving the Pn total travel  
131 time equation:

$$132 \quad T_{ij} = a_i + b_j + \sum d_{ijk} * S_k$$

133 where  $T_{ij}$  is the travel time along the ray path from event  $j$  to station  $i$ ,  $a_i$  is the travel time for the  
134 mantle-station path arriving at station  $i$ ,  $b_j$  is the travel time for the focus-mantle path for event  $j$ ,  
135  $d_{ijk}$  is the distance traveled by ray  $ij$  in mantle cell  $k$  and  $S_k$  is the slowness perturbation (inverse of  
136 velocity) for cell  $k$ . The travel time equation is solved for each cell and for each event–station ray  
137 path using a conditional least squares (LSQR) algorithm (Paige and Saunders, 1982; Hearn, 1996)  
138 to obtain the slowness of the lithospheric mantle. An iteration number of 500 was used to reach  
139 LSQR inversion convergence. A number of analyses were performed to select optimum cell size.  
140 The best solutions of the travel time equation were obtained using a cell size of  $0.25^\circ$  by  $0.25^\circ$ . The  
141 Laplace damping equation was used during the inversion to control the smoothness of the solution.  
142 After a series of tests, we chose a damping parameter of 500. This value was found to best balance  
143 error reduction and model resolution. Damping values of less than 200 were found to produce  
144 spurious velocity anomalies, while values larger than 800 significantly reduced our model  
145 resolution. When the LSQR algorithm initialization occurs, mean mantle velocity is calculated from  
146 the slope of the linear trend line of the arrival time versus distance plot.

## 147 **RESOLUTION AND ERROR ANALYSIS**

148 The estimated standard error for the Pn inversion in the method of Hearn (1996) is typically on the  
149 order of one second, indicating the presence of weak noise that comes from event location errors  
150 (Hearn et al., 2004; Calvert et al., 2000). We find a consistent value in our model inversion of 0.87

151 seconds. Standard errors for velocity were calculated using the bootstrap method for 50 iterations  
152 (Hearn and Ni, 1994). The resulting average velocity error is 0.05 km/s. Velocity errors are less than  
153 0.17 km/s, much smaller than the amplitude of anomalies interpreted. Synthetic tests were used to  
154 determine the resolution of the inversion model for the study area, and to quantify the ability of the  
155 inversion model to distinguish small-scale features. Checkerboard test models were used with cell  
156 sizes of 2° by 2° and 4° by 4° (Fig. 5) with a random Gaussian noise of 1s to simulate travel time  
157 estimation errors. Input velocity anomalies alternate between +0.25 km/s and -0.25 km/s. For the 4°  
158 by 4° checkerboard test (Fig. 5c), the resolution is very good on the northern margin and along the  
159 Gulf of Aden. The lack of seismological stations and of seismic events on the southern Gulf of Aden  
160 result in poor resolution on the southern margin, the eastern Sheba Ridge, and areas near the edge of  
161 the study area. For the 2° by 2° checkerboard test, high resolution areas are located at the junction  
162 of Red Sea and the Gulf of Aden and along the northern margin of the Gulf of Aden. Small-scale  
163 features of about 2° by 2° can be interpreted in these areas.

## 164 **RESULTS**

### 165 **Results of inversion**

166 Figure 6 shows the result of the inversion for 500 iterations. Velocity anomalies are in km/s and are  
167 relative to a mean mantle propagation velocity of 8.16 km/s, calculated by the model with our data  
168 set. A prominent low velocity anomaly (7.7 km/s) is located between Socotra Island and the Omani  
169 margin. Smaller low velocity anomalies are imaged in Afar (7.8 km/s), in the southern Red Sea,  
170 around Sana'a (7.7 km/s) and in the western Gulf of Aden (7.8 km/s). Finally, two small high  
171 velocity anomalies are observed on the western coast of Yemen and in the central Gulf of Aden (8.4  
172 km/s).

### 173 **Variation of mantle velocity with depth**

174 Pn are first arrivals from seismic events that occur about 200 km from the receiver, so that the  
175 waves travel near the crust/mantle interface. Ray paths do not travel strictly along the crust/mantle



176 interface but dive into the lithospheric mantle (Hearn et al., 2004). The greater the distance of the  
177 event from the station, the deeper the waves travel into the lithospheric mantle, such that short and  
178 long ray paths do not travel in the same part of the lithospheric mantle. Quantifying the precise  
179 depth of Pn ray penetration remains challenging. It is possible, however, to separate short ray paths  
180 from long ones. Short ray paths arriving from events that occur at angular distances of  $1.8^\circ$  to  $9.5^\circ$   
181 travel through the shallow lithospheric mantle (SLM) and long ray paths from  $9.5^\circ$  to  $16^\circ$  travel  
182 through the deeper lithospheric mantle (DLM) (Hearn et al., 2004). Travel-time inversion can be  
183 performed for short and long ray paths separately. The reduced data in each inversion results in  
184 reduced model resolution. Nevertheless, the resolution is sufficient to distinguish major structures.  
185 Checkerboard tests models are used for both SLM and DLM and results are presented in Figure 7.  
186 Ray path coverage is denser in the western part of the SLM, yielding resolution of better than  $2^\circ$  by  
187  $2^\circ$  (Fig. 7a). Resolution is  $4^\circ$  by  $4^\circ$  or greater in the eastern SLM (Fig. 7c). It is not possible to  
188 resolve features as small as  $2^\circ$  by  $2^\circ$  in the DLM (Fig. 7b), but  $4^\circ$  by  $4^\circ$  features are resolved for the  
189 eastern part (Fig. 7d). The data set for the DLM has a large number of ray paths from events located  
190 around the Zagros mountain belt. This results in some NE-SW streaking of the checkerboard.  
191 Results of the SLM and DLM inversions are shown in Figures 7e and 7f, respectively. The mean  
192 propagation velocity of waves in the mantle is 8.09 km/s for short ray paths, corresponding to the  
193 SLM, and 8.20 km/s for long ray paths (DLM). We find a velocity gradient between the SLM and  
194 the DLM, as expected in the lithospheric mantle (Hearn et al., 2004). Figure 7e shows velocity  
195 variations of Pn-waves for the SLM. The most visible structures are low velocity anomalies in the  
196 Afar region, the southern Red Sea, around Sana'a, and along the Gulf of Aden (7.7 km/s). High  
197 velocity anomalies appear along the western and southern margins of Yemen (8.2 to 8.4 km/s). For  
198 the DLM (Fig. 7f), low velocity anomalies with high amplitude are situated in southern Oman and  
199 in the north of Socotra Island (7.8 km/s). A high velocity anomaly is located between the southern  
200 Omani margin and the Sheba Ridge. The separation of the data set into short and long ray paths

201 shows the different distribution of velocity anomalies in the SLM and DLM.

## 202 **DISCUSSION AND GEODYNAMIC IMPLICATIONS**

### 203 **Upper mantle structure**

204 Previous tomographic studies at various scales of resolution have been carried out within the Gulf  
205 of Aden. The global Pn tomography study of Phillips et al. (2007) imaged velocity anomalies with a  
206 resolution of 4° to 8°. They found that all of the Red Sea and its borders are marked by a  
207 pronounced low velocity anomaly whereas only a weak low velocity anomaly occurs in the western  
208 Gulf of Aden. In contrast, the eastern end of the gulf does not show any low velocity anomaly.  
209 Using S-wave tomography, Debayle et al. (2001) found a low velocity anomaly around Afar and  
210 Yemen, along the Red Sea, and along the Gulf of Aden. This low velocity zone was imaged at a  
211 depth of 100 km with a resolution of a few hundred kilometers. Chang and Van der Lee (2011),  
212 using S-wave teleseismic tomography, imaged a low velocity anomaly at depths of 75 and 100 km  
213 with a resolution of 1° in the western Gulf of Aden, southern Red Sea, and Afar region. In the Red  
214 Sea region, the large-scale low velocity anomaly (7.8 km/s) that we imaged within the SLM reaches  
215 the Saudi Arabian coast between latitudes 15°N and 18°N. It is situated under the eastern margin of  
216 the Red Sea. Park et al. (2008) imaged a similar anomaly using S-wave teleseismic tomography. In  
217 contrast, our Pn tomography of the margin along the coast of Oman shows a slightly higher velocity  
218 relative to the 8.1 km/s mean mantle velocity. These results are consistent with heat flow  
219 measurements in Arabia, which show that heat flow is high along the Red Sea coast in Yemen, but  
220 low near the coast of the Gulf of Aden in Oman (Rolandone et al., 2013).

221 When the SLM Pn tomographic map of the Gulf of Aden is superposed on a map of current  
222 magmatic and volcanic activity, low velocity anomalies correlate well with zones of active  
223 volcanism (Fig. 8). Along the southern Yemeni margin, low velocity anomalies (7.9 km/s) appear  
224 beneath active volcanic structures (stars in the map, Fig. 8). Two pronounced low velocity  
225 anomalies (7.7 km/s) are positioned under volcanic structures in the Afar region and around Sana'a

226 in Yemen. A slight low velocity anomaly (8.0 km/s) on the Omani margin is situated under a recent  
227 active volcano (latitude 16°N – longitude 54°E; Fig. 8 top; Leroy et al., 2000). One low velocity  
228 anomaly corresponds to recently volcanic activity on the western Aden Ridge associated with an  
229 episode of magmatic dyke intrusion in November 2010 (Shuler and Nettles, 2012; Ahmed et al.,  
230 2013a).

231 Broad low velocity anomalies (7.7 km/s) are imaged in the region of Socotra Island. In the north of  
232 Socotra, velocity anomalies of at least 4° x 4° scale can be interpreted (Fig. 7c). These anomalies  
233 may be related with the occurrence of broad volcanism near the Sheba Ridge (d'Acremont et al.,  
234 2010; Leroy et al. 2013). On the western margin of Yemen, around the city of Aden, two high  
235 velocity anomalies are visible (8.2 to 8.4 km/s). These anomalies are consistent with the teleseismic  
236 tomography findings of Korostelev et al. (2013) showing high velocity anomalies of about 4 % at  
237 depths of 45 km and 70 km along the western margin of Yemen. Drawing on insights from receiver  
238 functions analysis (Ahmed et al., 2013b), which show spatial coincidence between regions of  
239 overthickened crust with a high Vp/Vs ratio and thick basalt flows (Seaward Dipping Reflectors -  
240 SDRs) suggestive of underplated ultra-mafic bodies under the crust of the Red Sea and Aden  
241 margins, we interpret our low velocity anomalies as underplated magmatic material. We find high  
242 velocity anomalies of about 1.2 to 3.7 % relative to the mean mantle velocity beneath most of the  
243 plateaus and rifted margins, with the exception of locales of Holocene to Recent volcanism. High  
244 velocities are generally explained by a stable, cold and/or thick lithospheric mantle (e.g. Calvert et  
245 al., 2000; Al-Lazki et al., 2004; Hearn et al., 2004; Pei et al., 2007). In this area, the rifting phase  
246 terminated about 16 Ma (Davison et al. 1994; Leroy et al. 2012) and as a result the lithosphere has  
247 cooled and become more stable than the area around. There is also a contrast in the crustal thickness  
248 between these two areas induced by the rifting episode of the Red Sea 34 Ma (Davison et al. 1994;  
249 Leroy et al. 2012). Indeed, the crustal thickness varies from 35 +/- 2 km under the high Plateaus to  
250 20 +/- 3 km under the Tihama plain as found by computation of receivers functions (Ahmed et al.,

251 2013b).

## 252 **Deep anomalies on the Eastern Oman and Gulf of Aden**

253 The tomographic image of the DLM shows a spatial distribution of low velocity anomalies that is  
254 distinctly different from that of the SLM. In the eastern part of the gulf, imaging of the DLM  
255 between the Sheba Ridge and the Oman coast indicates a high velocity anomaly, while velocity of  
256 the mantle between the Sheba Ridge and Socotra Island is low (7.8 km/s). This low velocity in the  
257 DLM south of the ridge is consistent with the findings of Leroy et al. (2010) and d'Acremont et al.  
258 (2010) who measured significant variation of the electric resistivity beneath the oceanic crust on  
259 either side of the Sheba Ridge. Electrical resistivity of mantle to the south of the Sheba Ridge is low,  
260 indicating the presence of hot material related to an off-axis melting anomaly. To the north of the  
261 Sheba Ridge, electrical resistivity is higher and consistent with colder mantle temperatures.

262 A low velocity anomaly within the DLM beneath southern Oman is consistent with Basuyau et al.  
263 (2010) who imaged two low velocity anomalies in the DLM (between 60 and 200 km depth)  
264 beneath the Omani margin aligned with the Alula-Fartak and Socotra-Hadbeen Fracture Zones. The  
265 magnitude of these anomalies is consistent with the presence of partial melting (3–6 per cent). They  
266 interpret these anomalies as melt products migrating from the Sheba Ridge, as a result of upwelling  
267 Afar plume material migrating eastward along the lithosphere-asthenosphere boundary below  
268 thinned lithosphere at the ridge. The presence of a single larger low velocity anomaly (7.8 km/s) at  
269 depth in this area is suggested by our study and may indicate a broader deep zone of melting  
270 accumulation. The 5% reduction in Pn velocity relative to the mean DLM velocity could be  
271 interpreted as the presence of 1.4% melt in the DLM (Stork et al., 2013).

## 272 **Plume-ridge interaction model: material channeled along the Gulf of Aden ?**

273 Many studies have attempted to understand the influence of the Afar plume on surrounding regions  
274 and its interactions with the East-African, Red Sea and Gulf of Aden rifts (e.g. Hansen et al., 2006;  
275 Park et al., 2008; Lucazeau et al., 2009; Leroy et al., 2010; Albers and Christensen, 2001). As in

276 previous studies, the Pn tomographic image of the SLM shows a low velocity anomaly (7.7 km/s)  
277 beneath the Afar region (Stork et al., 2013). This is low in comparison with the global mean Pn  
278 velocity, and with other rifts and ridges which have similar extension rates (Keir et al., 2013).  
279 The resolution of our study does not permit us to image the DLM beneath the Afar region. Our  
280 image of the shallow upper mantle beneath Afar shows a low velocity anomaly (7.9 km/s) that  
281 extends southwestward, northward and along the Aden Ridge. These zones of low velocity coincide  
282 with active volcanism and are therefore likely to be the result of melt production beneath thinned  
283 lithosphere, or partial melt within the mantle lithosphere beneath the three rift arms of the Afar  
284 triple junction. Partial melt may migrate beneath the Lithosphere-Asthenosphere boundary by  
285 channelized flow. The model proposed by Leroy et al. (2010) that calls for channeling of mantle  
286 material along the Aden Ridge implies that the Afar plume influence may extend toward the eastern  
287 Gulf of Aden. The findings of Chang and Van der Lee (2011) agree with this model for the western  
288 part of the gulf. Our SLM image of low velocity anomalies that extend from Afar toward the Sheba  
289 Ridge is consistent with channeling of plume material beneath the western Gulf of Aden. These low  
290 velocity anomalies may also be explained by small-scale convection in the mantle due to  
291 temperature gradients and/or the difference in thickness of continent and ocean lithospheres in the  
292 deep margins of the gulf (Lucazeau et al., 2008). Small-scale convection would require low velocity  
293 anomalies to be found along the entire length of the ocean-continent transition zone (OCT, Fig. 8)  
294 from east to west. Although low velocity anomalies are imaged along the OCT in the eastern gulf  
295 (southern Oman and northern Socotra Island), they do not seem to be imaged continuously between  
296 the Shukra El Sheik (SSFZ) and the Alula Fartak (AFFZ) Fracture Zones. We therefore suggest that  
297 small-scale convection may not be the only active process.  
298 Our Pn tomography images lend credence to the plume-ridge interaction model, an interpretation  
299 also favored by the physical and rheological characteristics of the region. The Gulf of Aden is a  
300 slow-spreading (20 mm/yr.) narrow oceanic basin segmented by numerous transform faults (Fig. 8)

301 (Leroy et al., 2010; 2012). It has been suggested that transform faults form rheological barriers to  
302 plume dispersion along ridge axis (Georgen et al., 2003). Our results indicate this may occur in  
303 several locations in the Gulf of Aden: in the central Gulf of Aden, the Kanshar Irqah and the Xiis  
304 Mukalla fractures zones (Fig. 8). The low velocity anomaly extends northward between the latter  
305 two fracture zones, and appears to terminate at the southern coast of Yemen beneath a volcanic  
306 structure. The Bosaso Masila Fracture Zone directly aligned with an active volcano located on the  
307 southern coast of Yemen (Fig. 8) may act as a rheological barrier channeling the flow of mantle  
308 material towards the region of active volcanism to the north.

### 309 **CONCLUSION**

310 We conducted a Pn tomography study in order to image the lithospheric mantle of the Gulf of Aden  
311 from the Afar triple junction in the west to the Owen Fracture Zone in the east. We find low velocity  
312 anomalies ( $\sim 7.7$  km/s) in the SLM beneath Sana'a, Aden, and in the Afar region that are  
313 immediately associated with active volcanism. Low velocity anomalies imaged along the Aden and  
314 Sheba Ridges could support plume-ridge interaction model proposed by Leroy et al. (2010) in  
315 which plume material is channeled away from Afar beneath the ridges. In addition we identify low  
316 velocities along the southern coast of Yemen in regions of Holocene to Recent volcanism, and also  
317 along the nearby Kanshar Irqah and Xiis Mukalla Fractures Zones. These observations suggest that  
318 transform fault/fracture zones act as rheological barriers in some cases, diverting flow towards site  
319 of active volcanism away from the ridge. A shallow broad low velocity anomaly (7.7 km/s) is  
320 imaged in the north of Socotra island and could be related to the occurrence of broad volcanism  
321 near the Sheba Ridge. Shallow high velocity anomalies (8.4 km/s) are also imaged to the west of  
322 Sana'a and around the city of Aden. These anomalies could be related to underplating of high  
323 velocity magmatic material under the crust of the Red Sea and Aden margins. A deep low velocity  
324 anomaly is observed to the south of the Sheba Ridge (7.6 km/s, 54°E) which could be related to an  
325 off-axis melting anomaly. Finally, a deep low velocity anomaly ( $\sim 7.6$  km/s) is visible in Oman,

326 suggesting the presence of a large deep zone of partial melting accumulation and a presence of 1.4  
327 per cent of melt.

## 328 **ACKNOWLEDGEMENTS**

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332 global data we use are from IRIS-PASSCAL. We deeply thank Dr Issa-Al Hussein (EMC, Sultan  
333 Qaboos University, Oman) and Dr Ismael Al Ganad (Geological Survey, GSMRB, Yemen) for their  
334 support and Heather Sloan for discussion about the paper.

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480 **Web Site**

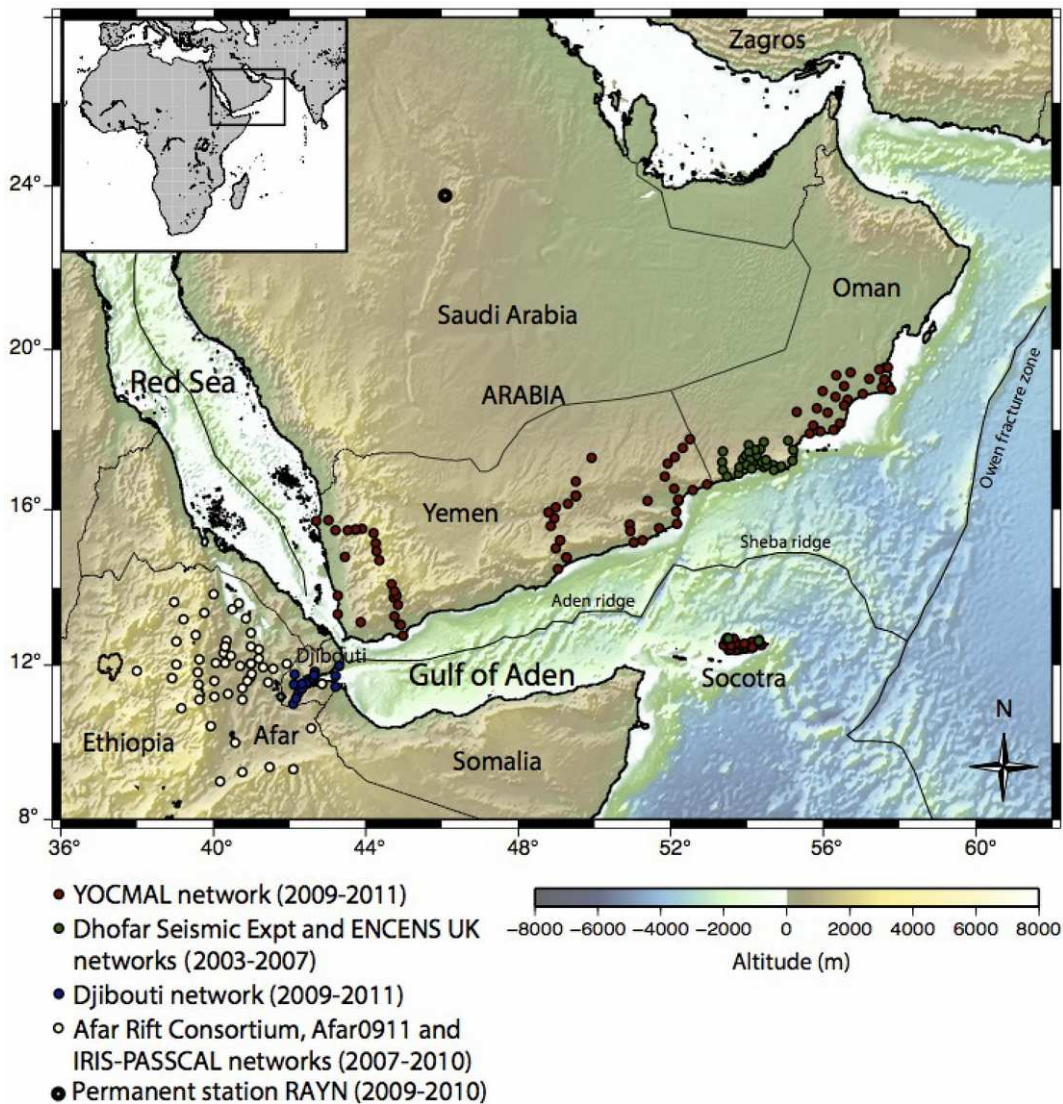
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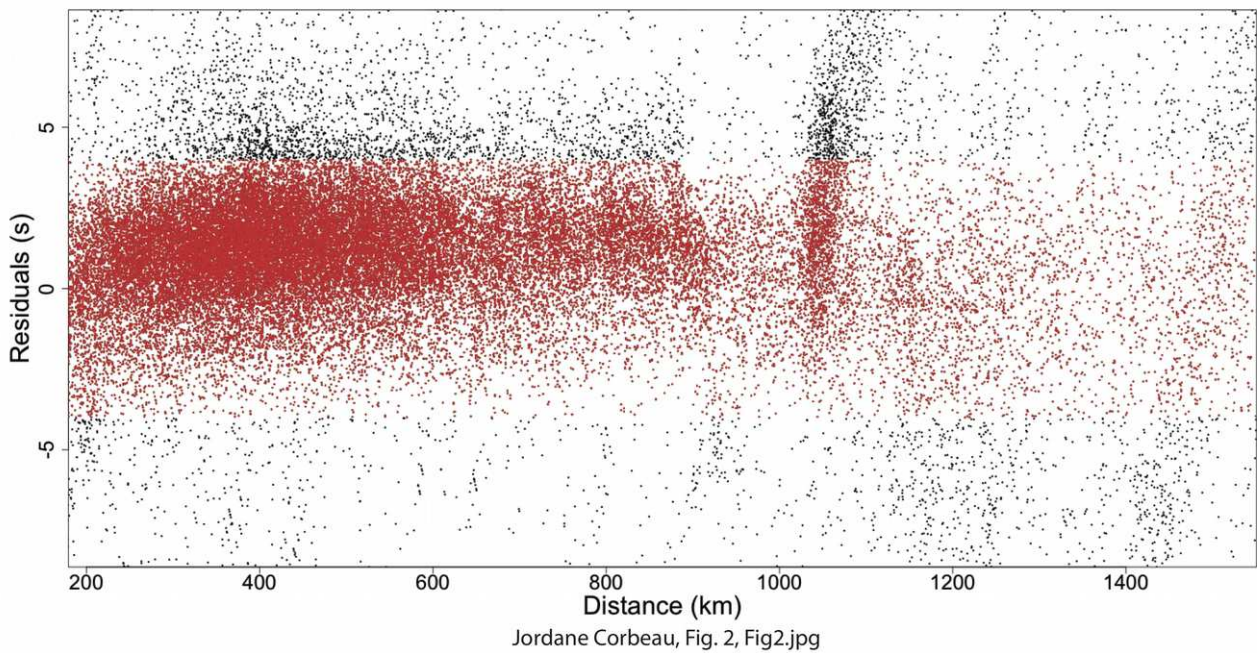
484 **FIGURES**

485

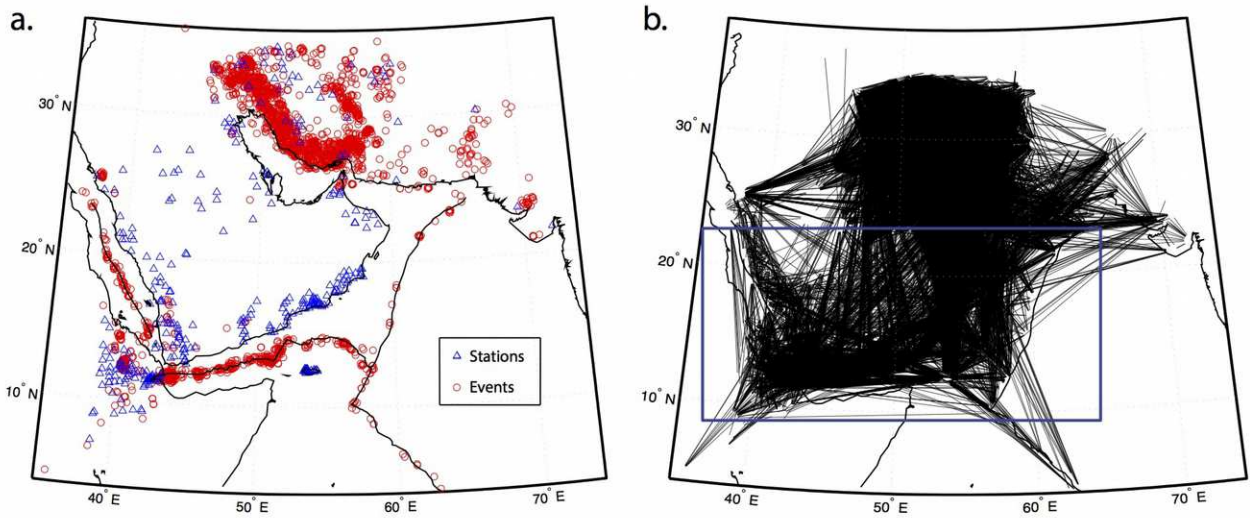


Jordane Corbeau, Fig. 1, Fig1.jpg

486 Figure 1. Topographic and bathymetric map of the study area. The locations of the seismic stations  
487 from different temporary networks used in this study are indicated by circles.

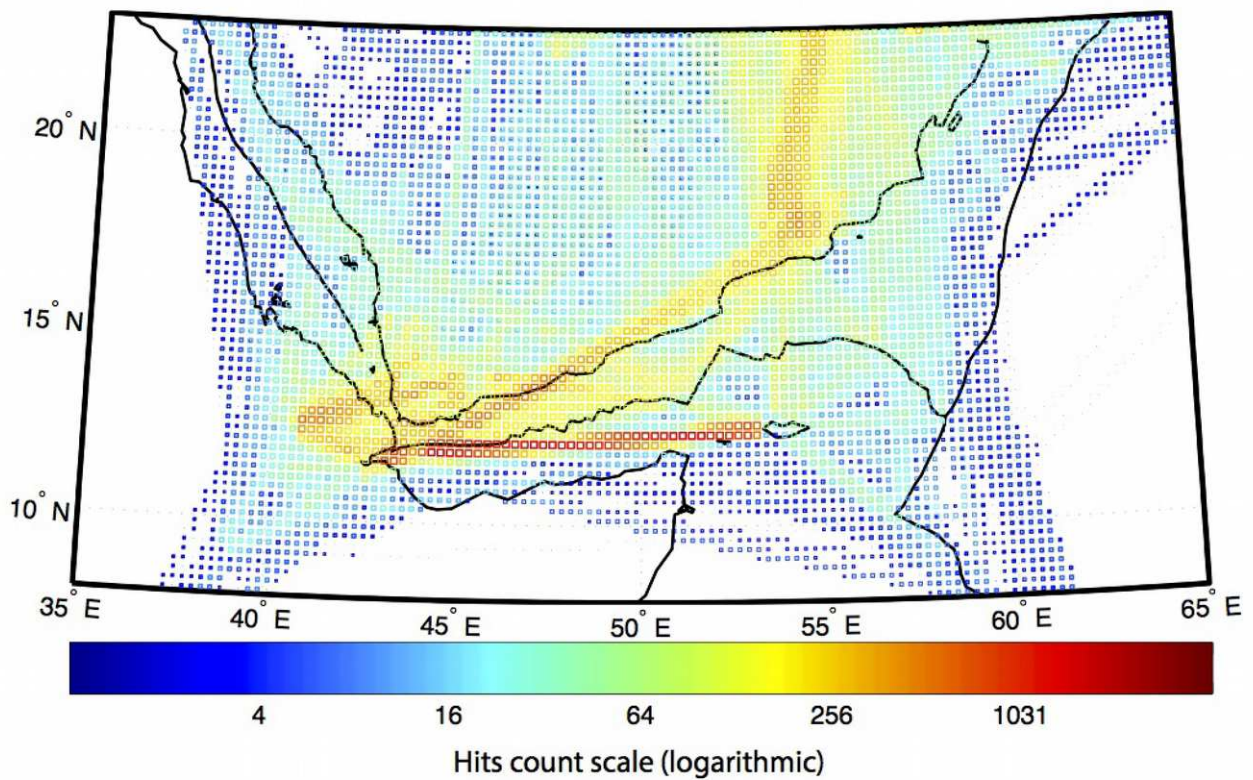


489 Figure 2. Plot of the travel times from the total data set relative to an initial uppermost mantle  
490 velocity of 8.16 km/s. The vertical trend of the residuals around 1000 km could be due to  
491 mislocated events. We use strict criteria (see text) to select the data and furthermore we only use the  
492 travel times with residuals less or equal to 4 s in the Pn tomography inversion as shown in red in the  
493 figure.



Jordane Corbeau, Fig. 3, Fig3.jpg

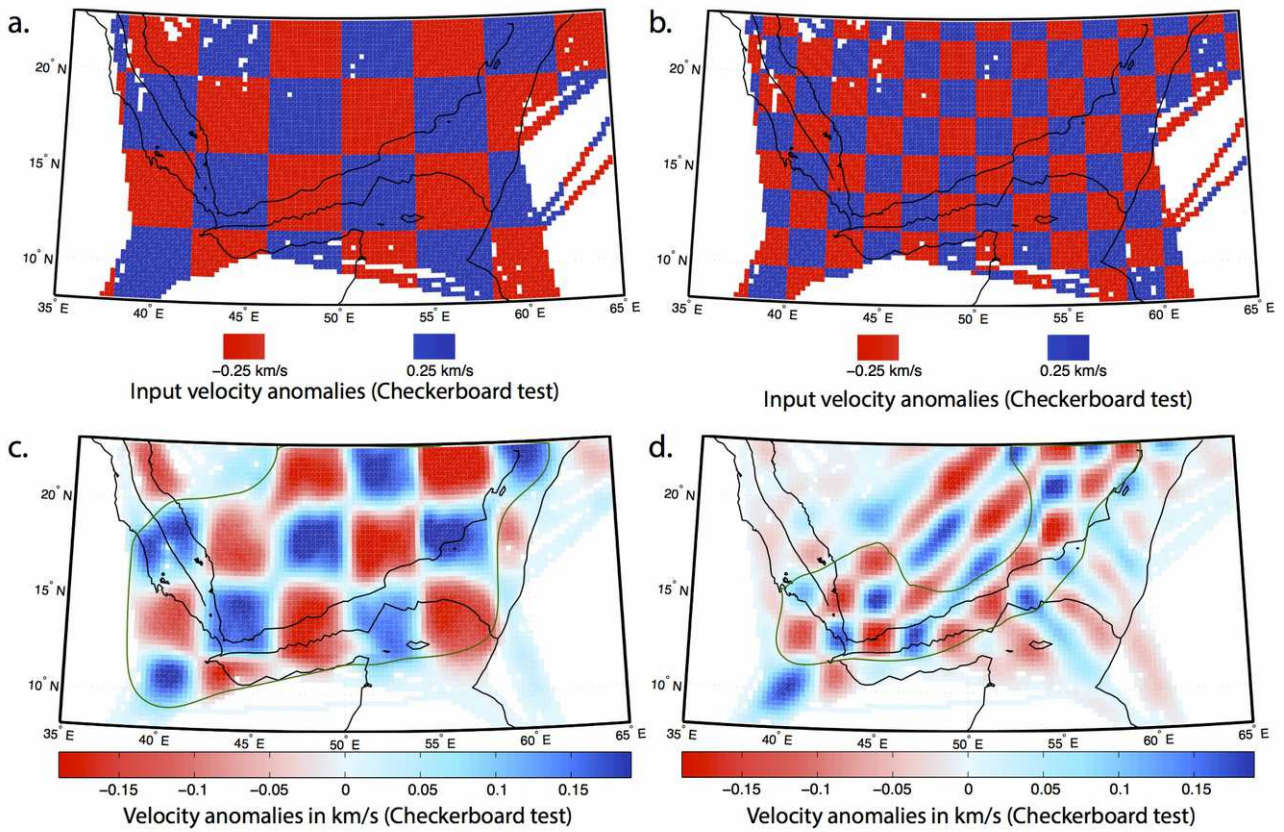
495 Figure 3. A: Map of stations (blue triangles, temporary networks and catalogues) and seismic events  
 496 (red circles) used for the inversion. A total of 3,778 events and 352 stations are used. B: Pn rays  
 497 used for the inversion. A total of 52,947 rays were selected. Only the results of the blue rectangle  
 498 area are discussed in this study.



Jordane Corbeau, Fig. 4, Fig4.jpg

500 Figure 4. Number of rays traveling in each cell of the 2D grid model. Ray coverage is dense near  
 501 the Afar triple junction, the north coast of the Gulf of Aden, and between Afar and the Socotra  
 502 Island.



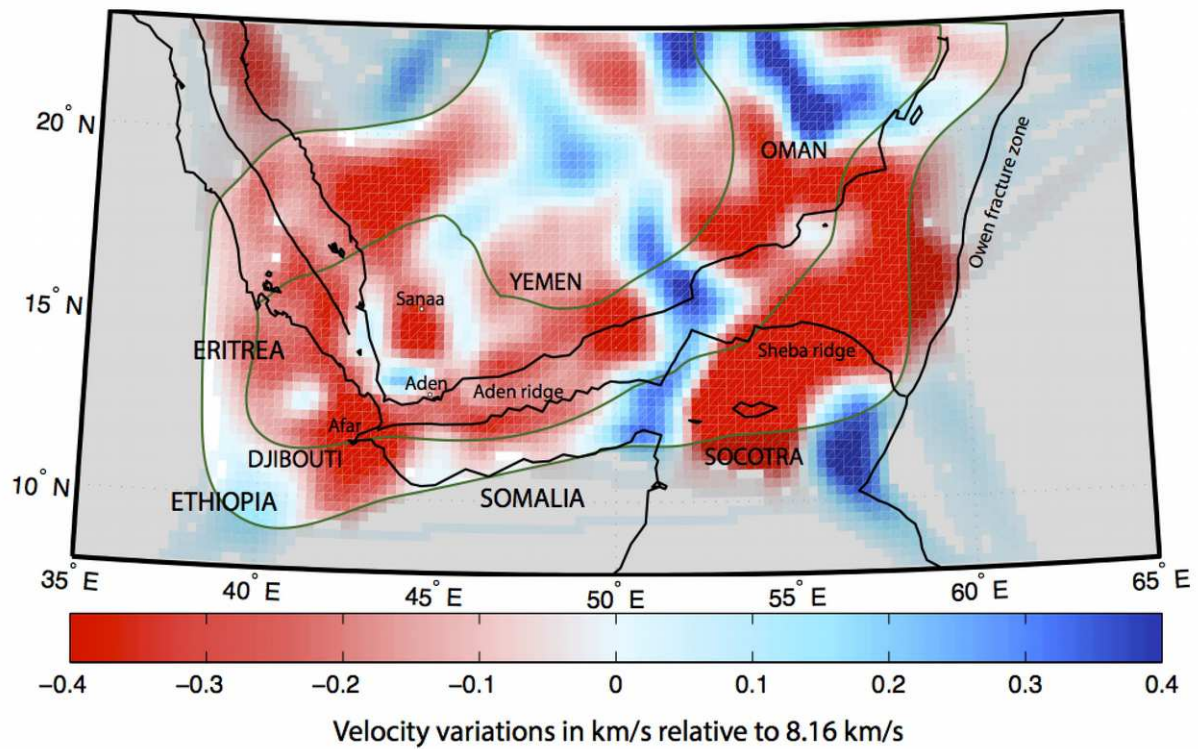


Jordane Corbeau, Fig. 5, Fig5.jpg

504 Figure 5. Pn velocity checkerboard tests. A: Input checkerboard test ( $4^\circ$  by  $4^\circ$ ). B: Input  
 505 checkerboard test ( $2^\circ$  by  $2^\circ$ ). C:  $4^\circ$  by  $4^\circ$  checkerboard test resolved, the green line delimits the  
 506 resolution area. D:  $2^\circ$  by  $2^\circ$  checkerboard test resolved, the green line delimits the resolution area.  
 507 Synthetic data are generated with 0.25 km/s isotropic velocity perturbations and a 1s random  
 508 Gaussian noise to simulate Pn picking errors. In the Afar region and along the north coast of the  
 509 Gulf of Aden, features as small as  $2^\circ$  can be resolved, while in the rest of the study area, the  
 510 resolution limit is  $4^\circ$  or larger.

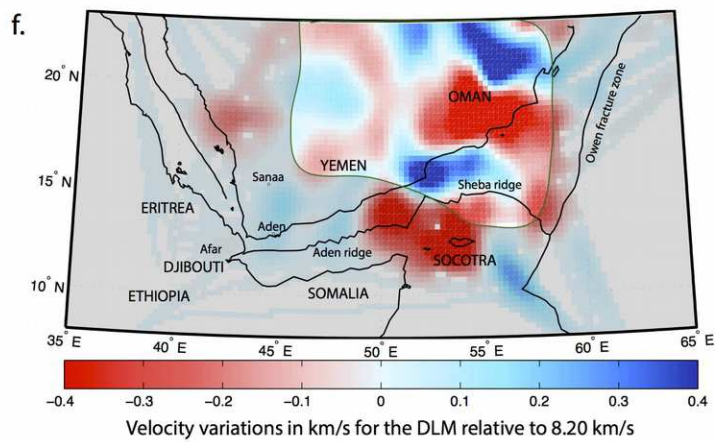
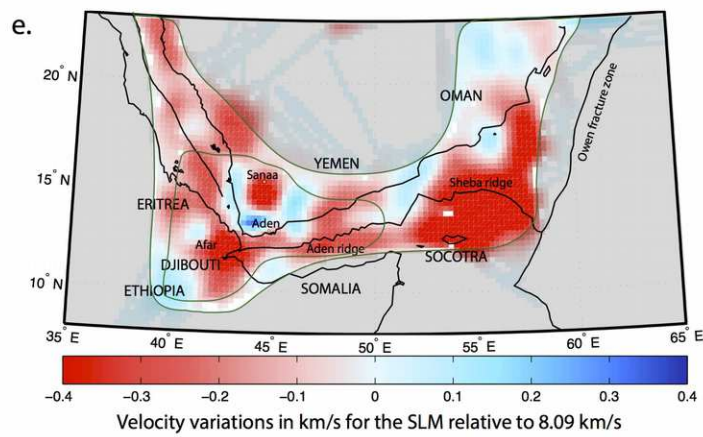
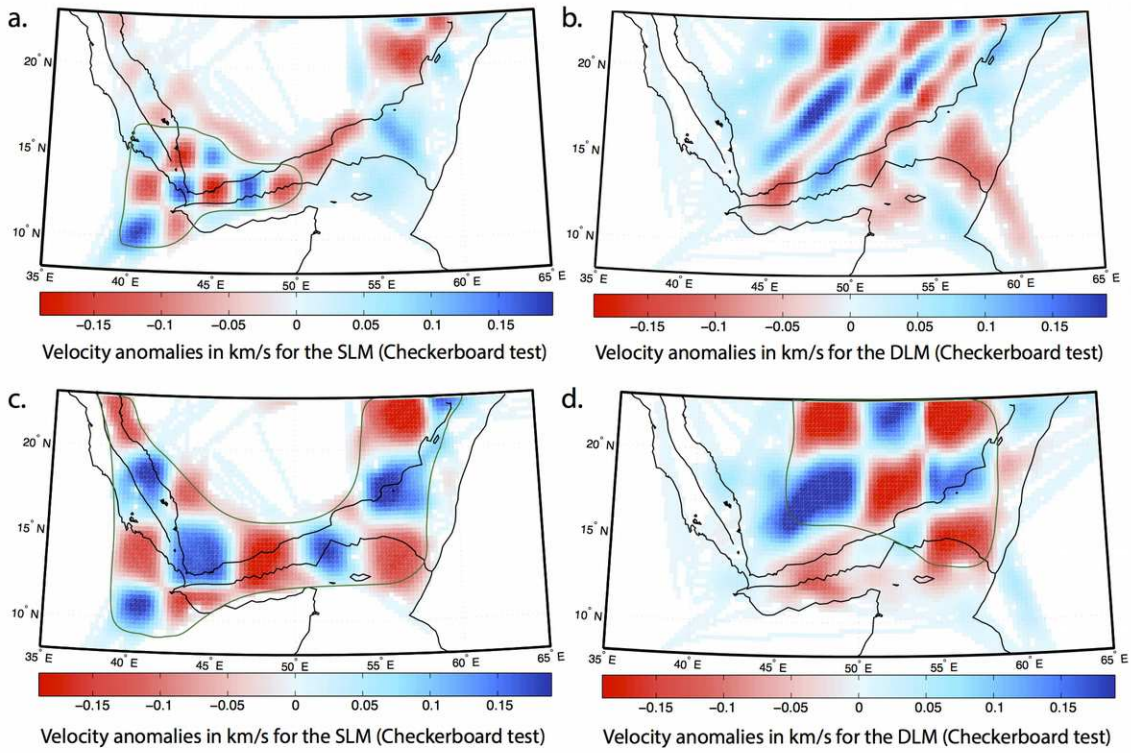






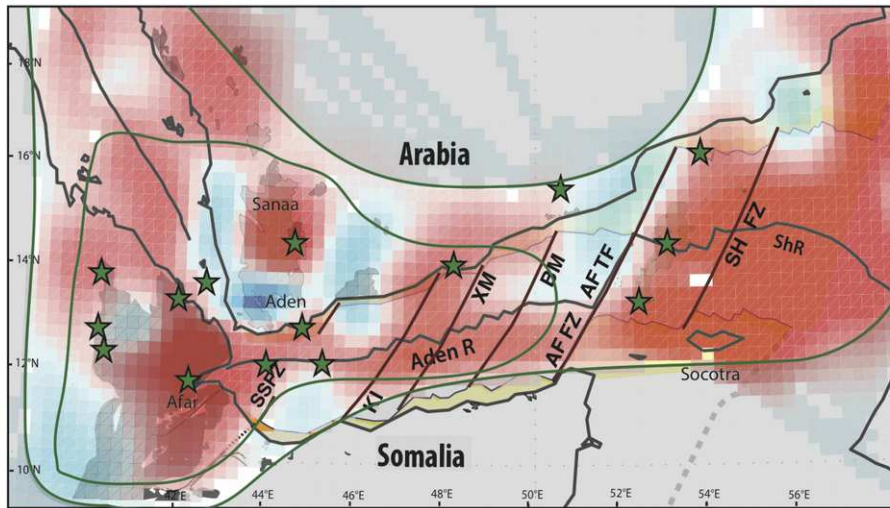
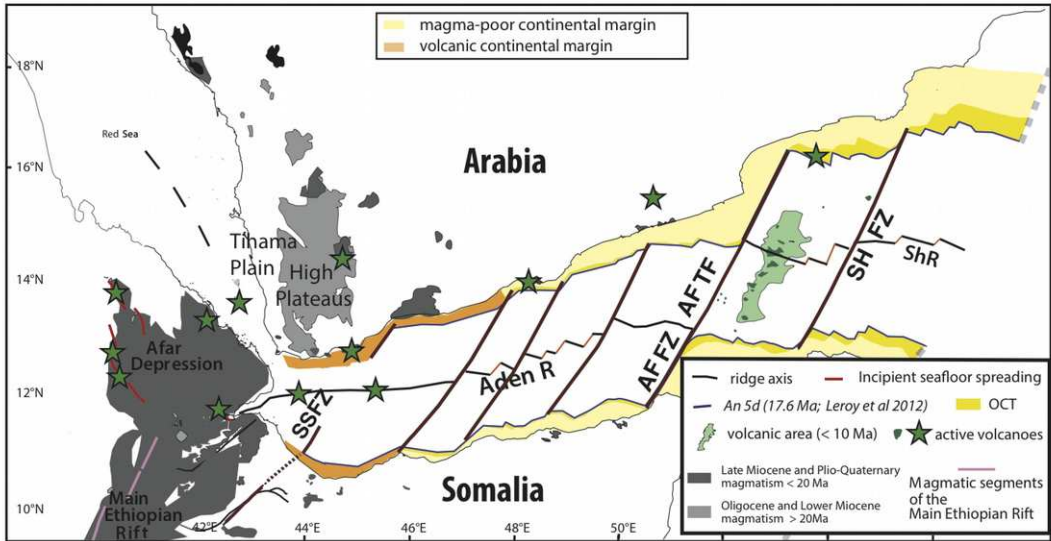
Jordane Corbeau, Fig. 6, Fig6.jpg

512 Figure 6. Variation of mantle Pn velocity in km/s relative to the mean velocity of 8.1 km/s. This  
 513 inversion used ray paths from 1.8° to 16°. The cell size is 0.25° by 0.25°. The surrounding green  
 514 line delimits the area of 4° resolution and the inside green line the 2° resolution area.



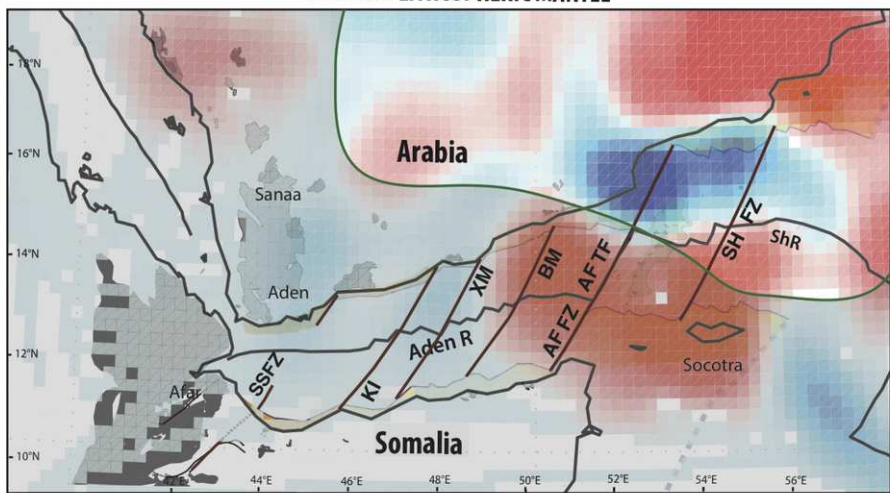
Jordane Corbeau, Fig. 7, Fig7.jpg

516 Figure 7. Checkerboard tests for short ray path inversion ( $1.8^\circ$  to  $9.5^\circ$ ) and long ray path inversion  
517 ( $9.5^\circ$  to  $16^\circ$ ), and variation of Pn velocity for the Shallow Lithospheric Mantle (SLM) and the  
518 Deeper Lithospheric Mantle (DLM). A:  $2^\circ$  by  $2^\circ$  checkerboard test for the SLM. B:  $2^\circ$  by  $2^\circ$   
519 checkerboard test for the DLM. C:  $4^\circ$  by  $4^\circ$  checkerboard test for the SLM. D:  $4^\circ$  by  $4^\circ$   
520 checkerboard test for the DLM. The green lines delimit the different resolution areas. E: Variation of  
521 SLM Pn velocity in km/s relative to the mean velocity of 8.09 km/s. The surrounding green line  
522 delimits the area of  $4^\circ$  resolution and the inside green line the  $2^\circ$  resolution area. F: Variation of  
523 DLM Pn velocity in km/s relative to the mean velocity of 8.20 km/s. Note that the scale is different  
524 between Figure 7e and 7f due to a different mean velocity calculated by the model. The green line  
525 delimits the  $4^\circ$  resolution area.



Velocity variations in km/s relative to 8.09 km/s

**SHALLOW LITHOSPHERIC MANTLE**

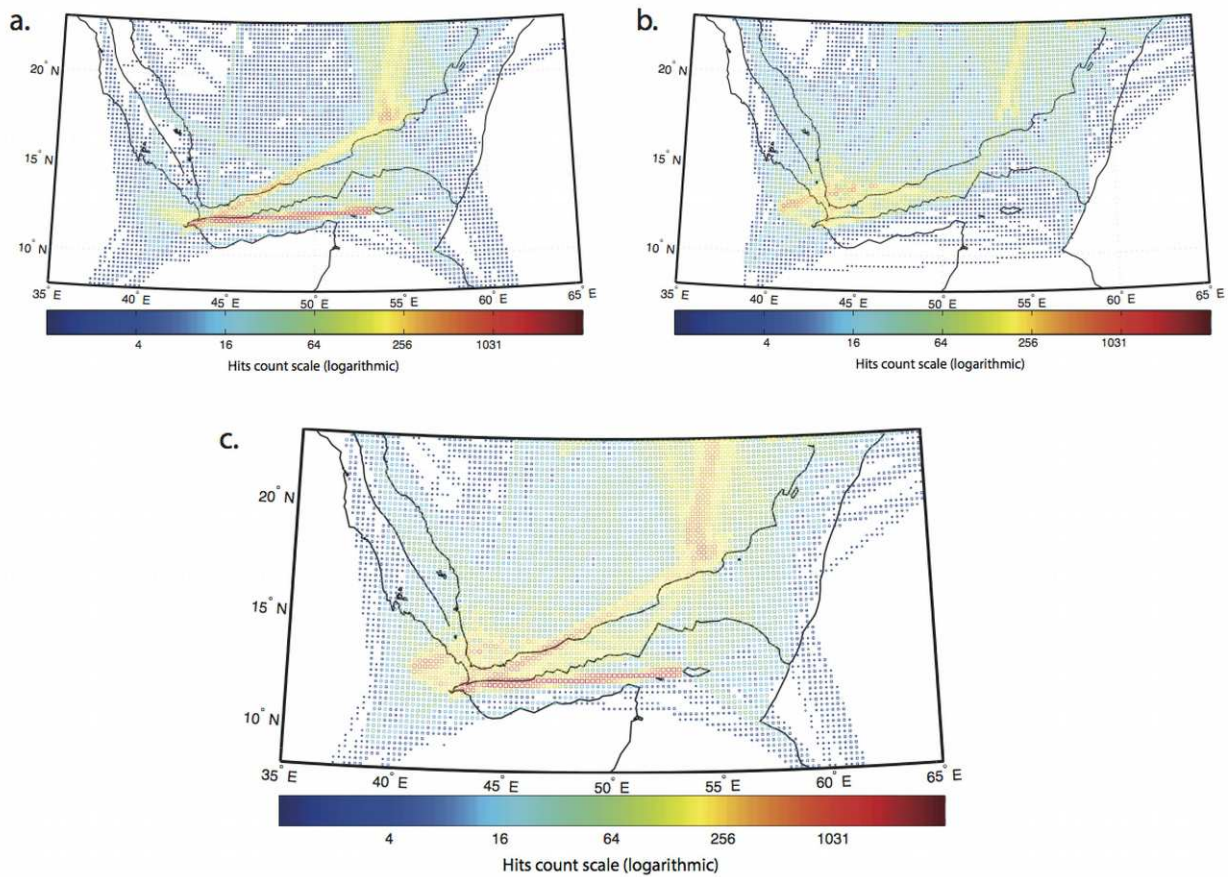


Velocity variations in km/s relative to 8.20 km/s

**DEEPER LITHOSPHERIC MANTLE**

Jordane Corbeau, Fig. 8, Fig8.jpg

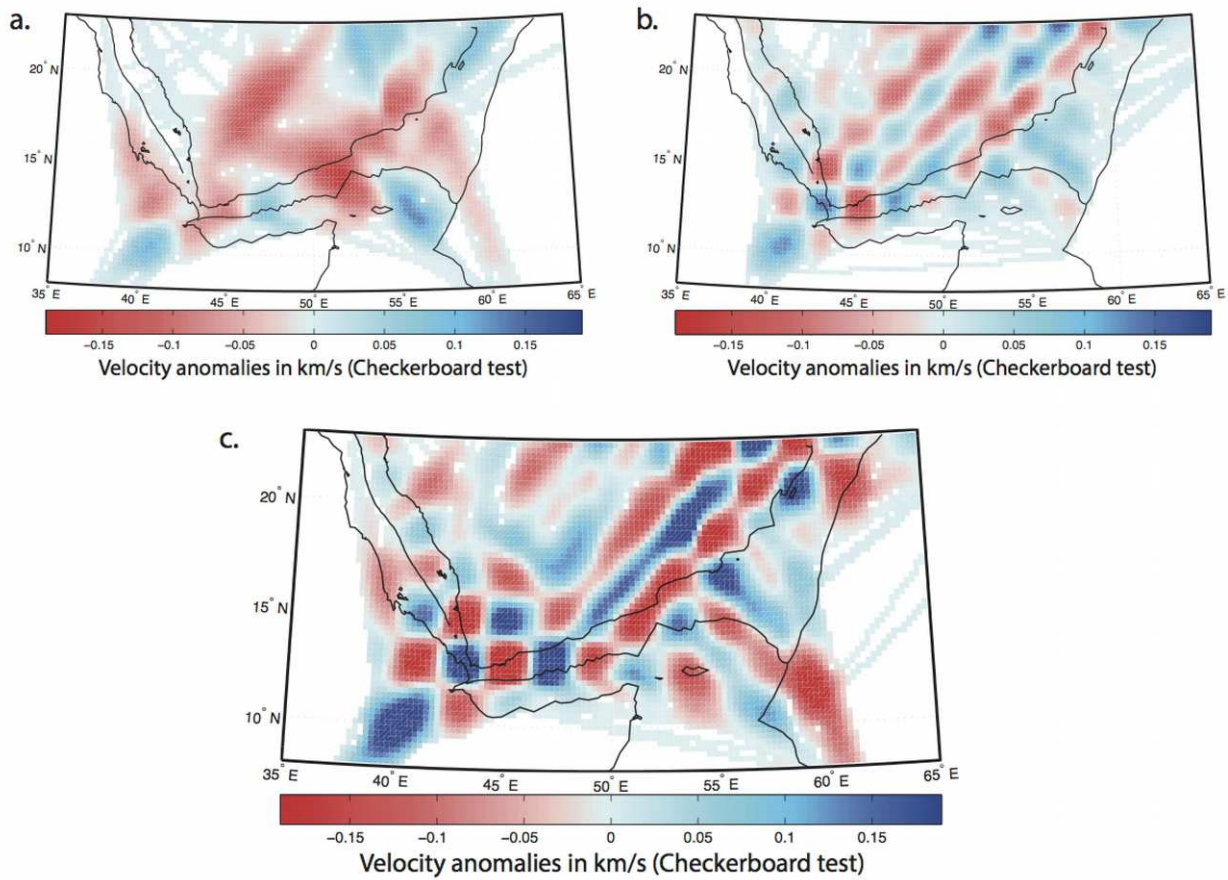
527 Figure 8. Superposition of the velocity images of the SLM (middle) and DLM (bottom) on a map of  
 528 the magmatic and volcanic activity (top, modified from Ebinger et al., 2008 and Leroy et al., 2010;  
 529 2012). Aden R = Aden ridge, ShR = Sheba ridge, SSFZ = Shukra el Sheik Fracture Zone, KI =  
 530 Kanshar-Irqah, XM = Xiis-Mukalla, BM = Bosaso-Masila, AFFZ = Alula-Fartak Fault Zone, AFTZ  
 531 = Alula-Fartak Transform Zone, SHFZ = Socotra Hadbeen Fault Zone, OCT = Ocean-Continent  
 532 Transition. The surrounding green line delimit the area of 4° resolution and the inside green line the  
 533 2° resolution area.



Jordane Corbeau, Fig. DR1, FigDR1.jpg

535 Figure DR1. Number of rays traveling in each cell of the 2D grid model. A: Ray density for the  
 536 temporary seismic network data set. B: Ray density for the ISC catalogue data set. C: Ray density  
 537 for the total data set used in this study, combining the ISC catalogue and the temporary seismic  
 538 network data sets. The combined data set has a higher density of rays in the Gulf of Aden and Afar





Jordane Corbeau, Fig. DR2, FigDR2.jpg

541 Figure DR2.  $2^\circ$  by  $2^\circ$  checkerboard test resolved. Synthetic data are generated with 0.25 km/s  
 542 isotropic velocity perturbations and a 1s random Gaussian noise to simulate Pn identification errors.  
 543 A: Checkerboard test for the temporary seismic network data set. B: Checkerboard test for the ISC  
 544 catalogue data set. C: Checkerboard test for the total data set used in this study, combining the ISC  
 545 catalogue and the temporary seismic network data sets. The checkerboard test for the combined data  
 546 set shows better  $2^\circ$  by  $2^\circ$  resolution in the southwest of Yemen, in Afar and along the Gulf of Aden  
 547 north coast.