# Surface wave tomography across Afar, Ethiopia: Crustal structure at a rift triple-junction zone

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[1] The Afar Depression in northeast Africa contains the rift triple-junction between the Nubia, Arabia and Somalia plates. We analyze Rayleigh wave group velocity from 250 regional earthquakes recorded by 40 broadband stations to study the crustal structure across Afar and adjacent plateau regions in northern Ethiopia. The dispersion velocities are inverted to obtain surface wave tomographic maps for periods between 5 and 25 seconds, sensitive to approximately the top 30 km of the lithosphere. The tomographic maps show a significant low dispersion velocity anomaly (>20%) within the upper crust, below the site of recent dyke intrusions (2005–present) in the Dabbahu and Manda-Hararo magmatic segments. Similar low velocity regions are imaged where magma intrusion in the Afar crust has been inferred over the last decade from seismicity or volcanic eruptions. We invert two group velocity curves to compare the S-wave velocity structure of the crust within an active magmatic segment with that of adjacent areas; the active region has a low velocity zone (Vs ∼ 3.2 km/s), between about 6–12 km, which we infer to be due to the presence of partial melt within the lower crust. **Citation:** Guidarelli, M., G. Stuart, J. O. S. Hammond, J. M. Kendall, A. Ayele, and M. Belachew (2011), Surface wave tomography across Afar, Ethiopia: Crustal structure at a rift triple-junction zone, *Geophys. Res. Lett.*, *38*, L24313, doi:doi:10.1029/2011GL046840.

## 1. Introduction

[2] The Afar Depression in Ethiopia is a diffuse extensional province where the Gulf of Aden, the Red Sea and the Main Ethiopian rifts meet to form a triple junction, between the Nubia, Arabia and Somalia plates [*Hoffmann et al.*, 1997]. The region is characterized by the transition between continental rifting of the East African rift and seafloor spreading in the Gulf of Aden and Red Sea [*Makris and Ginzburg*, 1987; *Bastow and Keir*, 2011]. In Afar, extension is largely accommodated by magmatism, at least during discrete rifting events, which is localized along ∼10 km wide and ∼60 km long rift segments [*Hayward and Ebinger*, 1996; *Manighetti et al.*, 1997]. In 2005, a major magmatic intrusion episode along the Dabbahu and Hararo magmatic segments (see Figure 1) was initiated by a 60 km-long 10 m-wide dyke [*Wright et al.*, 2006]. As of June 2010, dyking is still active along these magmatic segments [*Ebinger et al.*, 2010]. The aim of the present paper is to study the properties of highly intruded and extended continental and new igneous crust by the use of surface wave dispersion tomography on a network of 40 stations covering Afar and adjacent plateau regions (Figure 1). Our results represent the first detailed surface wave tomographic study of group velocity distribution in the crust and uppermost mantle of Afar.

[3] Afar is characterized by thinned crust (14–26 km) and low P-wave upper mantle velocities (7.4–7.6 km/s) [*Berckhemer et al.*, 1975]. *Makris and Ginzburg* [1987] interpreted the upper crust (characterized by P-wave velocities in the range 5.9–6.3 km/s) as Pan-African Precambrian crystalline basement. They also concluded that Afar was underlain by highly stretched continental crust of intermediate thickness between normal continental and oceanic crust. More recently, the EAGLE controlled-source experiment showed the crust to have a thickness of 35 km further south in the Main Ethiopian Rift (MER) and up to 43 km thick on its flanking plateau [*Maguire et al.*, 2006; *Keranen et al.*, 2009]. Receiver function analysis found Moho depths between 16–32 km across Afar [*Dugda et al.*, 2005] and suggest that the amount of magmatic input increases northwards along the MER from Vp/Vs ratios [e.g., *Stuart et al.*, 2006]. *Hammond et al.* [2011] found a crustal thickness from ∼44 km beneath the Ethiopian Plateau to ∼14 km beneath northern Afar. In their study Vp/Vs values range from 1.7 to 1.9 in the western plateau, whereas in Afar they increase to greater than 2.0. This is thought to be due to the presence of significant amounts of partial melt in the crust. Previous single path regional inter-station surface wave analysis showed thinned crust and a pronounced S wave low velocity zone in the upper mantle beneath Afar [*Searle*, 1975; *Knox et al.*, 1998]. The purpose of this study is to produce the first 2D tomographic maps of Rayleigh surface wave group velocity in Afar at periods primarily sensitive to crustal and upper mantle velocity structure. While previous body wave studies provided information along 1D single paths [e.g., *Makris and Ginzburg*, 1987] or beneath localized regions around the stations [*Hammond et al.*, 2011], we show in this paper the first 2D images of the uppermost lithosphere in Afar.

## 2. Data and Method

[4] From March 2007 until October 2009 a combined NERC Seis-UK and IRIS-PASSCAL network of 40 broadband stations were deployed in Afar (Figure 1). These recordings,

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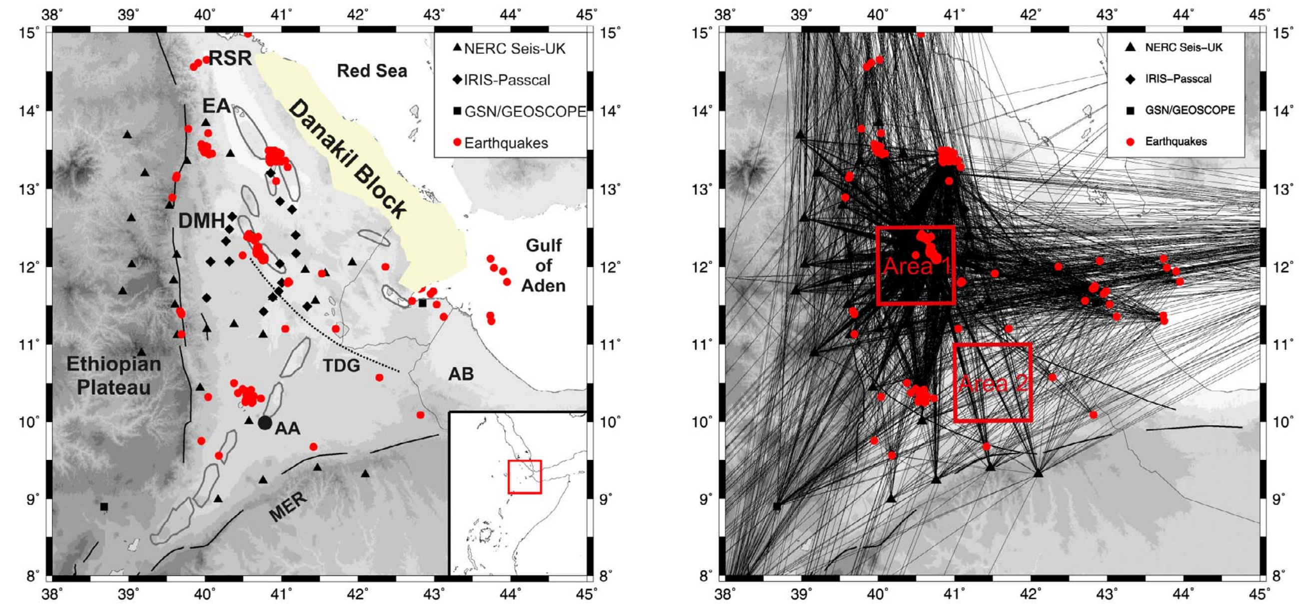


**Figure 1.** (left) Map of the Afar Depression: solid black lines show Oligo-Miocene border faults. Grey bounded regions show the locus of Quaternary faulting and magmatism: Erta'Ale (EA), Dabbahu-Manda Hararo (DMH), Ayelu-Amoissa (AA). Seismic stations are shown in black and the earthquakes used in red. Inset shows the location of the study area with respect to northeast Africa. Dashed line shows the Tendaho-Goba'ad Discontinuity (TGD); at the end of the TGD is located the Aisha Block (AB). The Main Ethiopian Rift (MER), Red Sea Rift (RSR) and Gulf of Aden rift from the three arms of the Afar Triple Junction. (right) Epicenter to station path coverage used for group velocity tomography; Area 1 and Area 2 are the selected square areas for which the average group velocity curves are determined.

together with those from the permanent stations ATD and FURI (GEOSCOPE/GSN), were searched for well-distributed local earthquakes with Ml > 3 and regional earthquakes with epicentral distances <2000 km and Ml > 4. The hypocentral locations of local earthquakes were computed by *Belachew et al.* [2011]. In total, we measured fundamental mode Rayleigh wave group velocity curves for 250 earthquakes in period range 5 to 25 s, using the Frequency Time Analysis (FTAN) technique [*Levshin et al.*, 1992], to obtain >4500 dispersion curves. Figure 1 shows the distribution of source-receiver paths for the earthquakes analyzed.

[5] The tomography method of *Yanovskaya and Ditmar* [1990] was used to estimate 2D group velocity maps from the observed source-receiver dispersion measurements on a 0.5 by 0.5 degree grid. This method is a generalization to 2D of the 1D inversion approach of *Backus and Gilbert* [1968] and has been applied in several papers [e.g., *Ritzwoller and Levshin*, 1998; *González et al.*, 2007]. The density of paths, the azimuthal coverage, and the average path length control the resolution of the data set. Using the formalism of *Yanovskaya* [1997], in the central part of the Afar depression the spatial resolution is 50 km. The elongation parameter, $\varepsilon$, of the averaging area (the ratio of the difference between the maximum and the minimum sizes of the area to its mean size) is used to describe the quality of source receiver path coverage. In Figure 2 we have only shown anomalies in the area where the spatial resolution is <100 km and the parameter $\varepsilon$ reveals a uniform orientation of source-receiver paths.

## 3. Results

[6] Figure 2 shows group velocity tomographic maps at periods of 5, 8, 12, 16, 20, and 25 s relative to the average across each map. Analysis of group velocity derivatives with respect to elastic parameters versus depth show that these periods are primarily sensitive to S-wave velocity structure in the depth range approximately 5–30 km, as shown by computed sensitivity kernels for group velocity (auxiliary material).[1] The spectral bandwidth of the regional earthquakes studied meant that we could not obtain reliable maps outside the period range 5–25 s.

[7] The resulting tomographic maps reveal several crustal group velocity anomalies. Low group velocity regions relative to mean can either be blocks of continental crust surrounded by heavily intruded crust, or zones of active intrusion where partial melt is present in the mid- to lower crust. We can try to differentiate between these two models taking into account the differences of the study area in terms of active and inactive magmatic segments and variations in crustal stretching.

[8] The group velocity maps (Figure 2) at shorter periods (5 and 8 s), typically sampling the upper crust, show low velocity anomalies that correlate well with the areas that have been magmatically active in the past decade: the Afdera - Erta'Ale segment in the north, the Dabbahu-Manda Hararo segment, which produces the largest anomaly, and the Ayelu-Amoissa volcanoes in the south (Figures 1 and 2). Magmatic intrusions in the form of dykes have been inferred from upper crustal magma chambers for the Dabbahu-Manda Hararo (DMH) segment [*Wright et al.*, 2006; *Ebinger et al.*, 2010] and the Ayelu-Amoissa volcanoes [*Keir et al.*, 2011]; there was an eruption in the Afdera - Erta'Ale segment in 2008 (C. Pagli et al., personal

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GL046840.

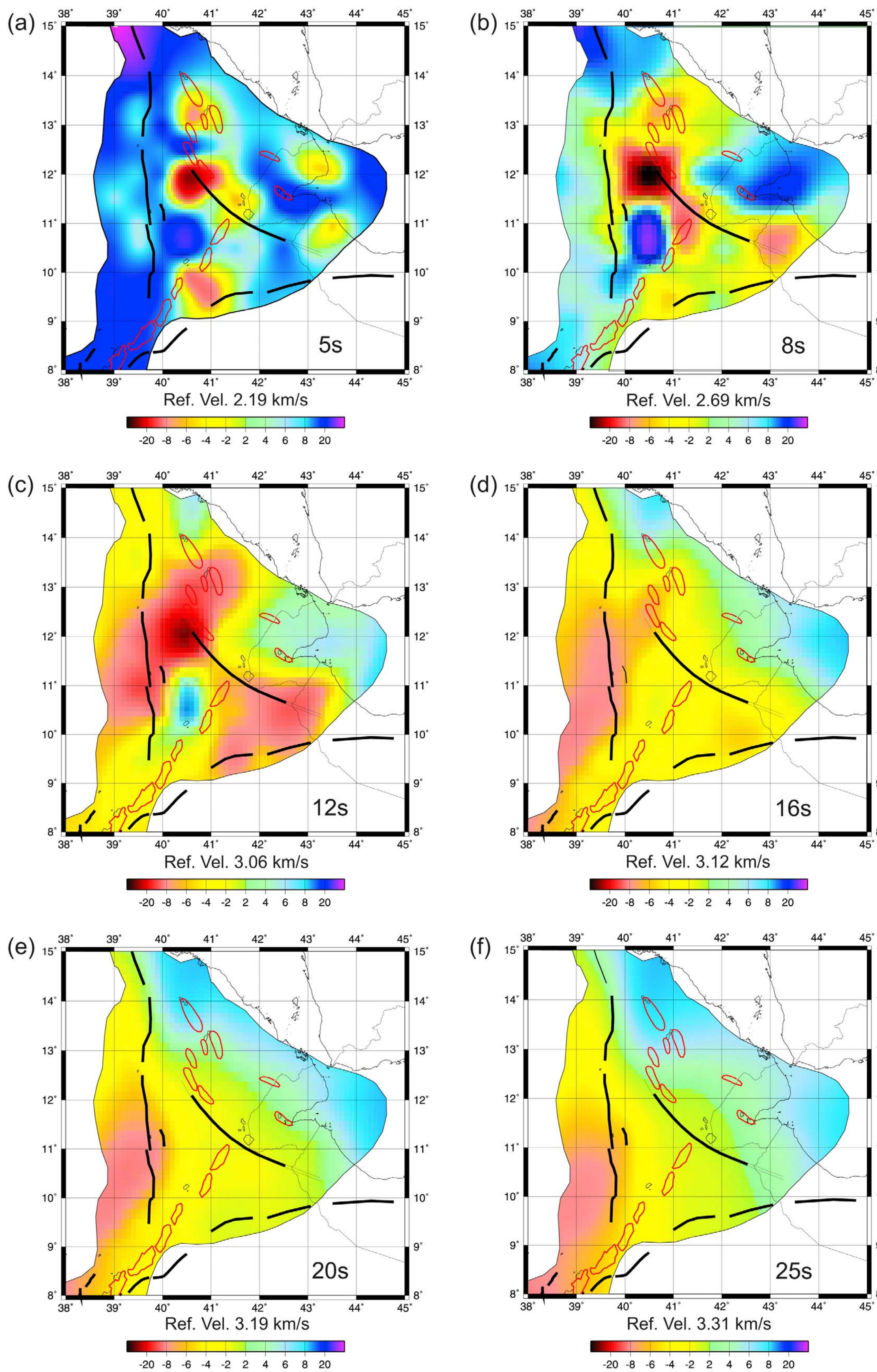


**Figure 2.** (a–f) Group velocity maps at the indicated periods in percentile deviation from the average velocity; areas for which the resolution length is larger than 100 km are in white. Major faults are marked as black lines.

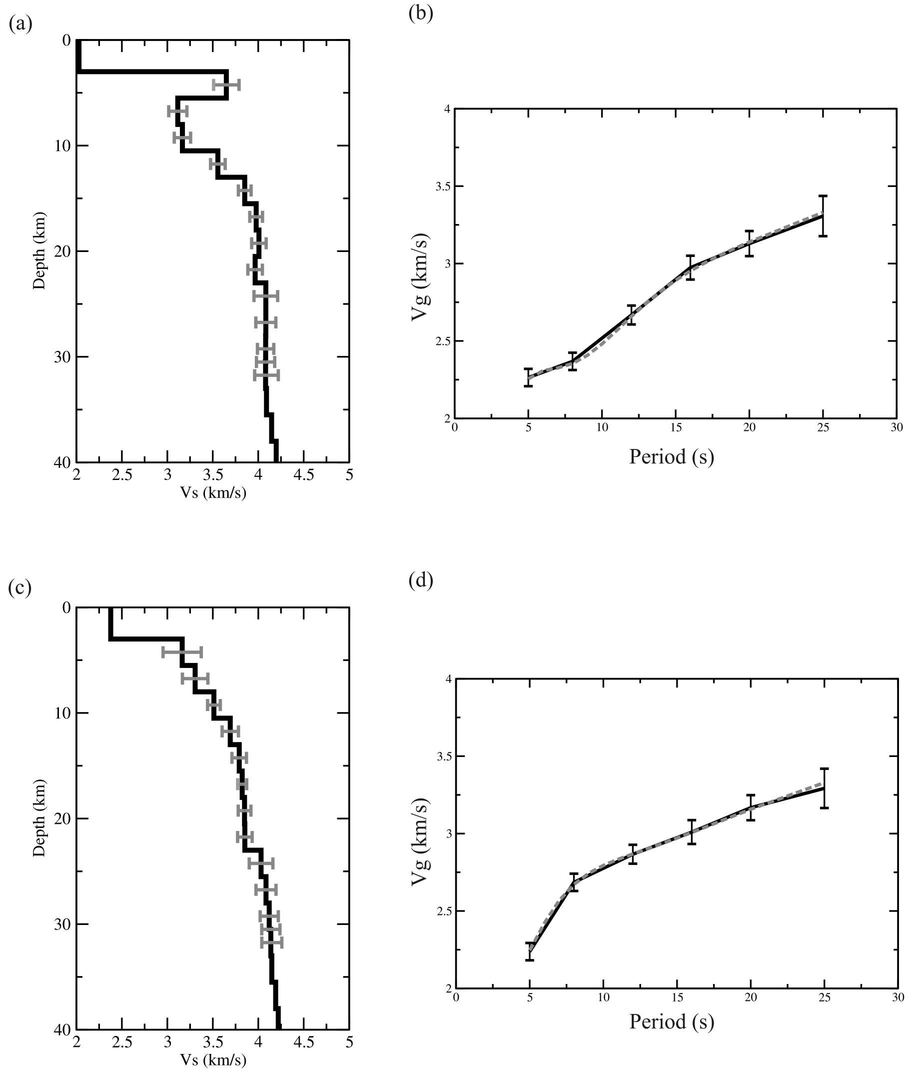


**Figure 3.** (a) Inverted velocity 1D profile for Area 1 on an active magmatic segment; the properties of the first layer are fixed in the inversion. (b) Average group velocity dispersion curve for Area 1 (black line) and dispersion curve corresponding to the solution model (grey). (c) Inverted velocity 1D profile for Area 2; the properties of the first layer are fixed in the inversion. (d) Average group velocity dispersion curve for Area 2 (black line) and dispersion curve corresponding to the solution model (grey).

communication, 2011), and the persistent lava lake at Erta'Ale overflowed in 2010. The low group velocities at 5 s in the central Afar (~11.5 N, 41.5 E) are approximately at the location of the present-day triple junction; we are interpreting these as the lacustrine deposits associated with the lakes in this region. At 8 s there is an anomaly to the SW of these lakes, which marks the termination of the Main Ethiopian Rift against the Tendaho-Gob'ad discontinuity, the seismically active fault zone separating the Main Ethiopian, Red Sea, and Gulf of Aden rifts. The low velocities (5 s and 8 s maps) in northern Somaliland overlie sediments of the Gubon / Berbera basin on the edge of the Gulf of Aden. We interpret the low velocities at 5 s in northern Djibouti as due to sedimentary cover rocks also.

[9] The largest velocity anomaly is located close to the Dabbahu-Manda Hararo segment, the site of recent dyke intrusions. Melt in the form of upper crustal dykes solidifies within day to week-long timescales after emplacement. The seismicity accompanying this dike propagation extends down to 10 km [*Belachew et al.*, 2011] suggesting that the active magma plumbing system, maybe represented by the presence of significant and diffuse pockets of melt in the crust at these depths, is the cause of the low group velocities at 8 s associated with the magmatic segments. We cannot rule out the possibility that they may also be the result of temperature/compositional variations.

[10] In contrast the crustal regions thought to have strong oceanic affinities in northernmost Afar and eastern Djibouti / Gulf of Aden show up as higher velocity anomalies at 8 s period. We surmise that this is representative of frozen oceanic crust with respect to the intruded stretched continental crust in southern Afar, which shows up as 'normal' group velocities.

[11] A noticeable feature at 8 s and 12 s is the high velocity region south of the Dabbahu-Manda Hararo segment (Figure 2). We interpret this anomaly as an area with thicker crust; the most reliable interpretation being the presence of relatively un-extended, but intruded continental

crust marking the southern termination of the Red Sea rift in Miocene time [*Wolfenden et al.*, 2004].

[12] At longer periods (16 s, 20 s, 25 s), sampling mainly the lower crust and upper-most mantle, the low group velocity signatures of the volcanic areas disappear and a SW-trending elongated low velocity anomaly (~10%) parallels the western border faults of Afar. We interpret this feature as due to thicker crust beneath the Ethiopian Plateau as suggested by *Mackenzie et al.* [2005] and by density contrasts in gravity maps of *Tiberi et al.* [2005]: higher velocity upper-most mantle material in Afar contrasts with lower velocity lower crust on the Ethiopian plateau. Group velocity increases north of 11.5°–12°, probably because of different crustal composition (possibly due to the Precambrian basement exposure to the north along the escarpment as the flood basalts thin). Maps at 20 s and 25 s show uniform group velocities in northern MER and southern Afar; this is consistent with a flat Moho as suggested by *Makris and Ginzburg* [1987] for this part of Afar. Group velocities change near the intersection of the MER and the Tendaho-Gob'ad discontinuity, which marks the separation of different tectonic domains. Group velocities start to increase northwards of about 12°N, due to a progressively shallower Moho. The crust thins sharply north of latitude ~13°N, reaching depths in the range 13–15 km [*Makris and Ginzburg*, 1987]. Our tomographic map at 16 s reveals for the first time the nature of upper mantle for the whole of northern Afar; the group velocities are uniform between 9.5°–12°N, increasing (corresponding to decreasing crustal thickness) north of ~12°N. Similar group velocities north of 14°N and in the Gulf of Aden, indicate the presence of oceanic crust in this poorly studied area of the Red Sea.

[13] To quantify our results in terms of S-wave velocity structure we compute an average group velocity dispersion curve for two areas (Figure 1), one showing low short period group velocities around the Dabbahu-Manda Hararo segment, the other region lacking this signal (Figure 3). The linear dimensions of the regions are comparable with the spatial resolution of the tomographic results. Using a linearized least-squares inversion scheme [*Herrmann and Ammon*, 2002], we invert these dispersion curves to obtain the 1D best-fitting S-wave velocity models shown in Figure 3. The linearized inversion methodology shows some dependence on the initial model. To account for this dependence and non-uniqueness, we repeated the inversion of group velocities using 220 different initial models, with a strategy similar to that adopted by *Rapine et al.* [2003]. We constructed a master model, parameterized with layer thicknesses of 2.5 km, from the controlled-source P-wave models for Afar [*Makris and Ginzburg*, 1987]; then we perturbed each layer velocity of the master model (except for the uppermost one) by increments of ±0.2 km/s, in order to span the shear velocities observed in previous studies in Afar and in the MER [*Makris and Ginzburg*, 1987; *Maguire et al.*, 2006]. Vp/Vs values were taken from *Hammond et al.* [2011] while crustal densities were computed from P-wave velocities through the Nafe-Drake relationship. After the inversion each starting model resulted in a slightly different optimum shear wave velocity model; the final S-wave velocity structure was the average of all the inversion solutions. The standard deviation of the family of the final models is 0.05–0.2 km/s depending on depth.

[14] Area 1, characterized by recent magma intrusion, has Vs velocities of about 3.8 km/s at around 5 km. From 5 km Vs decreases and a 6 km thick low velocity layer is imaged. The lowest S-wave velocity reached (3.2 km/s) suggests 5–10% partial melt [*Christensen and Mooney*, 1995]. We note that this estimate is an upper-bound, as the shape of the melt inclusions strongly influences the velocity reduction [e.g., *Blackman and Kendall*, 1997]. Vs then increases to a value of 4.01 km/s at around 19 km. For the area that corresponds to the northernmost tip of the MER, we found no low velocity zone in the upper crust; Vs increases gradually with depth, with a thin upper crust (about 12 km) and has characteristics more similar to stretched continental crust. The boundary of the lower crust and the Vs value of 4.15 km/s are probably beyond the limit of resolution of our model.

[15] Our Vs velocity models show a likely transition from a continental type crust area to a zone of active intrusions where partial melt is present in the crust. The progressive increase of the longer period group velocities from about 12°N towards the NE is interpreted as a progressively shallower Moho. This crustal thinning seems to be approximately coincident with the Tendaho-Gob'ad discontinuity. Our results seem to support the mechanism of extension through plate thinning in an area of continent-ocean transition.

## 4. Conclusions

[16] Our surface wave tomography maps and group velocity inversions reveal low group velocity anomalies corresponding to areas that have been magmatically active during a recent dyke intrusion episode or in the past decade. The period of the dispersion velocities affected, and our inversion of a localized dispersion curve over the Dabbahu-Manda Hararo segment, suggest that the lower crust contains significant amounts of partial melt (~6 to 12 km depth) for extended periods after individual dyking events. The tomographic maps at longer periods reveal for the first time the nature of crust and uppermost mantle for the whole Afar. The velocity contrasts mark the separation between different crustal domains (crust with oceanic characteristics and intruded continental crust) and a progressively thinner crust starting from the Tendaho-Gob'ad discontinuity. Our study shows the crust thickening across the western border faults of Afar on the Ethiopian plateau.

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