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Evidence of hotspot paths below Arabia and the Horn of Africa and consequences on the Red Sea opening

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ABSTRACT

Rifts are often associated with ancient traces of hotspots, which are supposed to participate to the weakening of the lithosphere. We investigated the expected past trajectories followed by three hotspots (Afar, East-Africa and Lake-Victoria) located around the Red Sea. We used a hotspot reference frame to compute their location with respect to time, which is then compared to mantle tomography interpretations and geological features. Their tracks are frequently situated under continental crust, which is known to strongly filter plume activity. We looked for surface markers of their putative ancient existence, such as volcanism typology, doming, and heat-flow data from petroleum wells. Surface activity of the East-Africa hotspot is supported at 110 Ma, 90 Ma and 30 Ma by uplift, volcanic activity and rare gas isotopic signatures, reminiscent of a deep plume origin. The analysis of heat-flow data from petroleum wells under the Arabian plate shows a thermal anomaly that may correspond to the past impact of the Afar hotspot. According to derived hotspot trajectories, the Afar hotspot, situated (at 32 Ma) 1000 km north-east of the Ethiopian–Yemen traps, was probably too far away to be accountable for them. The trigger of the flood basalts would likely be linked to the East-Africa hotspot. The Lake-Victoria hotspot activity appears to have been more recent, attested only by Cenozoic volcanism in an uplifted area. Structural and thermal weakening of the lithosphere may have played a major role in the location of the rift systems. The Gulf of Aden is located on inherited Mesozoic extensional basins between two weak zones, the extremity of the Carlsberg Ridge and the present Afar triangle, previously impacted by the East-Africa hotspot. The Red Sea may have opened in the context of extension linked to Neo-Tethys slab-pull, along the track followed by the East Africa hotspot, suggesting an inherited thermal weakening.

1. Introduction

Hotspots are the surface expression of mantle thermal instabilities, which arise from high temperature and low viscosity zones. Their activity is revealed by surface and subsurface phenomena, such as volcanic traps, or chains of volcanoes on oceanic floor. A thin conduit with a spherical head (Olson et al., 1988) characterises hotspots in laboratory experiments and numerical simulations. Traps, which are the most common continental volcanism linked to hotspots (Courtillot et al., 2003), would result from an impingement under the lithosphere of a plume head (about 1000 km wide), while hotspot tracks on the ocean floor, result from impingement of a plume conduit (about 100 km wide). The present resolution of seismic tomography is insufficient to precisely image objects of this size, although some interpretations may display conduits as large as 300 to 500 km wide (French and Romanowicz, 2015).

Hotspot activity is episodic and irregular, as shown by the discontinuously spaced volcanic edifices on oceanic hotspot tracks, while the track itself has a finite duration of tens to hundreds of millions of years. Based on laboratory experiments and observations, Davaille et al. (2005) showed that hotspot activity is episodic, and computed a recurrence time range between 100 and 180 Myr.

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Table 1
Afar, East-Africa and Lake-Victoria hotspot coordinates, according to several studies.

Hotspot name – Coordinates			Reference
Afar (10°; 42°)	East-Africa (6°; 34°)	Lake-Victoria (−3°; 34°)	Burke and Wilson, 1976[a]
Afar (10°; 42°)	East-Africa (6°; 34°)	Lake-Victoria (−3°; 34°)	Thiessen et al., 1979[a]
Ethiopia (10°; 43°)	–	East-Africa (−3°; 38°)	Crough, 1983[a]
Afar/Ethiopia (12°; 42°)	–	Lake-Victoria/East-Africa (−3°; 36°)	Richards et al., 1988[b]
–	East-Africa (6°; 34°)	–	Steinberger, 2000[b]
Afar (10°; 43°)	–	–	Courtillot et al., 2003[b]
Afar (7°; 39°)	–	Lake-Victoria (−3°; 38°)	Montelli et al., 2006[b]
Afar (7°; 39°)	East-Africa (6°; 34°)	Lake-Victoria (−3°; 38°)	Ritsema et al., 2011[c]
Afar (12°; 42°)	East-Africa (6°; 34°)	Lake-Victoria (−3°; 38°)	This study

[a] Hotspots coordinates determined from a map georeferencing.
[b] Hotspot coordinates from datasets.
[c] Hotspot location derived from tomographic model images.

Thanks to oceanic tracers, it is possible to directly assess the duration of hotspot activity. For instance, Clouard and Bonneville (2001) highlighted that the Louisville hotspot could have formed the Ontong Java Plateau at about 121–124 Ma, and the oceanic seamounts between 66 and 12.5 Ma. Therefore, the Louisville hotspot activity could have had a lifetime of 100 Myr.

With the exception of continental flood basalts, the knowledge of hotspot effects on the continental lithosphere remains poor, and their tracks are particularly difficult to evidence, as the lithospheric thickness filters their surface effects. However, Chu et al. (2013) observed a hotspot track under the North American continental lithosphere, using seismological data. Also, Davies et al. (2015) cross-correlated the episodic volcanism in eastern Australia with the Cosgrove hotspot track, in regions where the lithosphere is thin.

In this study, we investigated the history of three hotspots of the East African area, widely described in the literature, namely Afar, East-Africa and Lake-Victoria, with the aim of retrieving traces of their ancient activity. In addition, we highlight new considerations and questions about the Red Sea rift system, which is superimposed on the East-Africa hotspot trajectory.

2. Hotspot tracks in the Arabian plate and the Horn of Africa

We aimed to retrieve the path followed by three hotspots. All are currently situated in Eastern Africa – Afar, East-Africa and Lake-Victoria. To do that, we first described the geological setting of the studied area, then defined the present day hotspot coordinates, using various lines of evidence, and finally, following a comparative hotspot reference frame study, we used the more accurate reference frame to derive the expected hotspot paths for the last 110 Myr.

2.1. Geological context

During the Neoproterozoic, the Pan-African orogeny led to the formation of the Arabian–Nubian Shield through the amalgamation of microcontinents and arcs (Fritz et al., 2013). Then, Arabia and Africa moved together, before splitting at the end of the Miocene. The rifting started during the Oligocene, occurring along two rift systems – the Red Sea and the Gulf of Aden (e.g., Bellahsen et al., 2003). It is generally considered that the trigger of the rifting were the tectonic forces related to the Neo-Tethys slab-pull and the subsequent subcontinental mantle delamination, combined with a hotspot impact that thermally weakened the lithosphere in the Afar region (Zeyen et al., 1997; Bellahsen et al., 2003; Faccenna et al., 2013; Autin et al., 2013). Different scenarios have been proposed for the Red Sea rifting and drifting since the Ethiopian–Yemen traps emplacement (Bosworth et al., 2005; Almalki et al., 2014); however, all of them converge to consider a drifting onset at 5 Ma. The Red Sea rift developed from the Afar region northeastward. By contrast, the Gulf of Aden opening started east of the Gulf of Aden from the Carlsberg Ridge, propagating westward, through the Sheba Ridge, at 17.6 Ma, and the Aden Ridge from ∼10 Ma onward (Bosworth et al., 2005; Fournier et al., 2010; Leroy et al., 2012).

2.2. Hotspot present day locations

In the literature, the names of the three hotspots may refer to different volcanic activities, or suspected plumes, in space and time. For example, the 'Afar hotspot' is considered to correspond to the plume that generated the Ethiopian–Yemen traps (see Courtillot et al., 2003), while its present location is associated with the Stratoid Series volcanism (see Stab et al., 2016) and with tomographic studies (Montelli et al., 2006). On the contrary, the 'Afar hotspot' in French and Romanowicz (2015), located at 6°N, 34°E, clearly refers to the 'East-Africa hotspot'. A review of the present day coordinates and hotspot names of several authors is, thus, given in Table 1. We considered the following three hotspots, using related traps and tomographic images (Table 1):

(1) The Afar hotspot (see review in Stab et al., 2016) is defined by the Stratoid Series at 4 Ma, and by tomographic interpretation of a large low-velocity anomaly below the Afar triple junction (12°N, 42°E).

(2) The East-Africa hotspot's present position is indirectly established from the mean position of the Ethiopian–Yemen traps, as suggested by Steinberger (2000). We determined the mean position of these traps at 30 Ma, assuming that the relative hotspot was located in the mantle vertically from the mean traps position. Then, using O'Neill et al.'s (2005) hotspot reference frame (see Section 2.3), we computed the current position of the mean traps