Mantle flow beneath Arabia offset from the opening Red Sea

Sung-Joon Chang,1 Miguel Merino,1 Suzan Van der Lee,1 Seth Stein,1 and Carol A. Stein2

Received 13 October 2010; revised 9 December 2010; accepted 24 December 2010; published 16 February 2011.

1. Introduction

[2] Continental rifting involves a poorly understood sequence of lithospheric stretching, volcanism, and mantle flow that evolves to seafloor spreading. We present new insight from inversion of seismic traveltimes and waveforms beneath Arabia and surroundings. Low velocities occur beneath the southern Red Sea and Gulf of Aden, consistent with active spreading. However, hot material extends not below the northern Red Sea, but is offset eastward beneath Arabia, showing mantle flow from the Afar hotspot. The location of this channel beneath volcanic rocks erupted since rifting began 30 million years ago indicates that flow moves with Arabia. We propose that the absence of seafloor spreading in the northern Red Sea reflects the offset flow. This geometry may evolve to spreading in the Northern Red Sea, rifting of Arabia, or both. This situation has aspects of both active and passive rifting, showing that both can occur before coalescing to seafloor spreading. Citation: Chang, S.-J., M. Merino, S. Van der Lee, S. Stein, and C. A. Stein (2011), Mantle flow beneath Arabia offset from the opening Red Sea, Geophys. Res. Lett., 38, L04301, doi:10.1029/2010GL045852.

2. Tomographic Image

[6] We investigate this transition using a seismic tomographic image of velocity structure beneath Arabia and surroundings derived by joint inversion of a compilation of data. The compilation, described in the auxiliary material, includes global and regional data sets of arrival times, body wave waveforms, regional multimode S and surface wave trains, surface wave group velocities, and constraints on Moho depth from active source seismic studies, gravity surveys, global geological and geophysical interpretations, and receiver functions.1

[7] The results are shown in cross sections across the Red Sea and Gulf of Aden (Figure 2). Low velocities indicating hot mantle are visible below 50 km beneath spreading axes in the Gulf of Aden (profiles G-g, H-h, and I-i) and southern Red Sea (profiles D-d, E-e, and F-f). However, below the northern Red Sea the slowest material is offset to the east, below Arabia (profiles A-a, B-b, and C-c).

1Auxiliary materials are available in the HTML. doi:10.1029/2010GL045852.
channel rather than a broad regional anomaly, and that this channel occurs below Arabia rather than the northern Red Sea.

3. Tectonic Interpretation

[10] The geometry of the low velocity anomaly and the shear wave splitting directions jointly favor their being due to mantle flow, as observed elsewhere [Russo et al., 2010]. However, this geometry differs from cases in which the splitting directions can be interpreted as mantle flow driven by absolute plate motions [Silver, 1996], because Arabia’s NW–SE absolute motion does not match the N–S flow and splitting directions. The narrowness of the velocity anomaly and its depth extent preclude its being due to lithospheric thickness [Rychert and Shearer, 2009].

[11] The new data also suggest how the flow may have evolved. Prior to the availability of tomographic data, the presence of upwelling mantle beneath Arabia was proposed based on the presence of elevated topography and 20–30 Ma volcanism and dike swarms trending parallel to the Red Sea but up to several hundred km eastward [Dixon et al., 1989]. Because little uplift and volcanism occur on the west side of the Red Sea, the asymmetric volcanism and uplift were hypothesized to reflect the initial location of upwelling that caused the Red Sea rifting as Arabia migrated northeastward over the upwelling which was assumed to be fixed in the mantle.

[12] However, the tomographic data show that the hot mantle flow is not beneath the Red Sea. Instead, it occurs beneath the loci of two distinct phases of volcanism in western Arabia. As previously observed [Camp and Roobol, 1992], the older (pre-15 Ma) northwest-trending volcanism and younger north-trending volcanism that continues to the present, overlap with different trends. Thus we hypothesize that the flow from the fixed or slow-moving hotspot forms a channel that has lengthened with time and been deflected by Arabia’s northeastward absolute motion, such that it remains below Arabia but rotated to a more north-south trend consistent with that of the younger volcanics. Figure 4 shows such a scenario, in which present plate motions are used throughout because their detailed history is not well known. The deflection is favored by the fact that Arabia’s absolute motion is almost perpendicular to the Red Sea. Analogous deflection of upwelling mantle by absolute plate motion has been proposed for the Eifel hotspot [Walker et al., 2007].

[13] This model is schematic in several ways. The channel geometry is reasonably but not perfectly resolved. A similar direction of anisotropy is observed east of the channel, where lithosphere is thicker [Stern and Johnson, 2010], consistent with the view that anisotropy can arise from both mantle flow and lithospheric structure [Hansen et al., 2006]. Not all volcanism is directly above the channel, presumably because the locations of volcanism also reflect structures in the lithosphere or due to ongoing opening of the Red Sea. Most intriguingly, the volcanism occurred in pulses rather than continuously. However, the model offers a general explanation for the persistence of volcanism with changing trend above the channel’s current location. It is consistent with geochemical data [Camp and Roobol, 1992; Krienitz et al., 2009] interpreted as showing that the Arabian volcanics
reflect melting that progressed northward and involved a
plume source.

[14] This geometry may have evolved as flow from the
hotspot was channeled by the pre-rifting structure of the
base of the lithosphere [Ebinger and Sleep, 1998] and may
still be affected by lithospheric structure. In particular,
Cenozoic volcanic activity is absent in the Afif Terrane that
contains some of the oldest crust in the Arabian Shield, of
Paleoproterozoic age, but present to the west [Stoeser and
Frost, 2006]. Similarly, the locus of rifting may have been
controlled by preexisting weakness in the continental lith-
osphere [Dixon et al., 1989; Cloetingh et al., 1995].

[15] This situation shows aspects of both active and pas-
sive rifting models, and could remain as is or evolve in
either direction (Figure 4). There is no reason to believe that
active sea floor spreading will begin soon in the northern
Red Sea, because the hot mantle flow remains to the east.
The present regime of extension in the north seems stable, as
also suggested by the basement fault geometry [Cochran
and Karner, 2007]. It could eventually evolve into sea
floor spreading, in which case the mantle flow should be
deflected to the northern Red Sea, as observed below the
Gulf of Aden. At present this seems not to be occurring,
given the shear-wave splitting data. Alternatively, active
rifting could evolve in Arabia above the channel, given that
some extension occurs along the active volcanic trend
[Camp and Roobol, 1992; Pallister et al., 2010]. Ultimately,
the northern Red Sea rift could be abandoned. This “rerift-
ing” situation would be similar those observed in the North
Atlantic, where volcanism associated with hotspots pro-
duced renewed continental rifting that eventually developed
into new sea floor spreading axes [Skogseid et al., 2000;
Müller et al., 2001].

[16] Arabia and its surroundings thus illustrate how many
complexities of the rifting process observed in the geologi-
cal record [Corti et al., 2003; Huismans and Beaumont,

---

Figure 2. Shear wave velocity cross-sections across the Red Sea and Gulf of Aden. Seafloor and surface topography are
shown by black solid lines with tenfold vertical exaggeration. Moho depth is also shown. Black arrow indicates location of
the ridge on each cross section. White circles on the map correspond to ticks in the cross sections.

Figure 3. Shear wave velocity map at 150 km depth, showing
perturbations relative to reference velocity. Shear wave
splitting data are from Gashawbeza et al. [2004] and Hansen
et al. [2006].
2003] can arise. The order, timing, magnitude, and locations of volcanism and extension have varied during rifting, as shown by the fact that the East Africa rift has considerable volcanism and little extension, whereas the Gulf of Aden has less volcanism but more extension. The fact that in the Red Sea and Arabia a situation with aspects of both active and passive rifting occurs and seems stable for some time illustrates that lithospheric extension and mantle flow can act somewhat independently in different places for a long time before coalescing to seafloor spreading.

**Acknowledgments.** We thank S. McClusky for providing GPS results and H. Bedle, M. Benoit, E. Engdahl, M. Flanagan, F. Marone, E. Matzel, W. Mooney, A. Nyblade, Y. Park, M. Pasyanos, and C. Schmid for providing seismological data and results. We thank S. Cloetingh and Z. Garfunkel for helpful comments.

**References**


**Figure 4.** (top) Schematic model for the evolution of the low velocity channel, assuming flow from a fixed hotspot has been deflected by Arabia’s northeastward absolute motion. (bottom) Possible future geometries in which (left) extension in the northern Red Sea develops into seafloor spreading or ceases as rifting develops within Arabia along the low velocity channel and (right) progresses to seafloor spreading.


Hadiouche, O., and W. Zurn (1992), Structure of the crust and upper mantle beneath the Afro-Arabian region from surface wave dispersion, Tectonophysics, 209, 179–196, doi:10.1016/0040-1951(92)90022-X.


