Journal of African Earth Sciences 109 (2015) 107–119

Contents lists available at ScienceDirect

Journal of African Earth Sciences

journal homepage: www.elsevier.com/locate/jafrearsci

Integrated outcrop, 3D seismic, and geochronologic interpretation of Red Sea dike-related deformation in the Western Desert, Egypt – The role of the 23 Ma Cairo "mini-plume"

William Bosworth [a,*], Daniel F. Stockli [b], Daniel E. Helgeson [a]

[a] Apache Egypt Companies, 11, Street 281, New Maadi, Cairo, Egypt
[b] The University of Texas at Austin, Jackson School of Geosciences, Dept. of Geological Sciences, 1 University Station C9000, Austin, TX 78712-0254, USA

ARTICLE INFO

Article history:
Received 13 January 2015
Received in revised form 11 May 2015
Accepted 12 May 2015
Available online 21 May 2015

Keywords:
Red Sea rifting
$^{40}Ar/^{39}Ar$ dating
Mantle plumes
Western Desert
Gulf of Suez
Egypt

ABSTRACT

Most of the northern Red Sea and Gulf of Suez formed as a non-volcanic rift. This is in stark contrast to the Afar province far to the south where flood basalts several kilometers thick cover an area of >600,000 km^2. The Afar volcanism erupted coevally with the onset of Gulf of Aden rifting and the two events are generally thought to be genetically linked. The lack of northern Red Sea exposed volcanic rocks suggests that this segment of the rift system initiated through a mechanism very different from Afar-Aden. However, a large late Cenozoic basalt field covering >15,000 km^2 does exist in northern Egypt centered on the city of Cairo. Large-scale basaltic dikes, monogenetic volcanoes, and coeval extensional faults and grabens are associated with these alkali basalts and physiographically and structurally link this province to the Gulf of Suez. Compositionally the northern Egypt basalts are very similar to the initial 31–30 Ma flood basalts of Afar. New $^{40}Ar/^{39}Ar$ dating indicates that this widespread and voluminous Egyptian volcanism occurred over a short time interval of less than 2 Ma at the Oligocene–Miocene boundary (23 Ma). In the subsurface west of Cairo, high-quality 3D reflection seismic data indicate that narrow, linear grabens formed above the intruding dikes and show that the structural effects of Red Sea rifting extended far into the Western Desert. Circular depressions within the grabens probably formed first as conduits to overlying cinder cones and then underwent collapse when magma was evacuated from below. Some outliers of basalt flows were erupted at the cores of Late Cretaceous Syrian arc anticlines as at Bahariya oasis.

The northern Egypt $^{40}Ar/^{39}Ar$ ages are indistinguishable from those of early syn-rift Red Sea-parallel dikes in western Arabia, Sinai and the Eastern Desert of Egypt. This suggests that the Red Sea propagated through Arabia/Sudan and into Egypt as a single, very rapid pulse and only stopped at the interface with stronger Neotethyan oceanic crust near the coast of the modern Mediterranean Sea. Extension almost immediately thereafter became focused in the Gulf of Suez where it evolved into well-developed rift basins, and deformation in the Western Desert and vicinity of Cairo ceased. Prior to extrusion of the northern Egypt basalts there was no identifiable surface extension and the lithosphere was not yet thinned. The relatively constant thickness of the basalts suggests that there was little pre-rift topography or uplift in northern Egypt. The volcanism of northern Egypt was volumetrically smaller than that of Afar some 7–8 My earlier, but we suggest that it played a similar role as a trigger for a large-scale rift event. We propose that this volcanic center be referred to as the Cairo mini-plume. Similar modest, focused magmatic events may have played equivalent roles in other older "non-volcanic" rift systems.

1. Introduction

Afar lies at the junction of three large rifts: the Gulf of Aden, Red Sea, and Ethiopian/East African (Fig. 1). The magmatism of Afar has long been viewed as either a driving force in the development of these basins or at least an important component of their overall geometry and kinematics of opening (Laughton, 1966; McKenzie and Morgan, 1969; Mohr, 1970, 1972; Barberi et al., 1972; Baker et al., 1972; Le Pichon and Francheteau, 1978; Coleman, 1993; Burke, 1996; Courtillot et al., 1999; Buck, 2006). Complete agreement on the role of the Afar plume in this rift setting has not been reached (e.g. White and McKenzie, 1989; Ebinger and Sleep, 1998; Rychert et al., 2012), but key aspects of the timing of the volcanic

* Corresponding author. Tel.: +1 20 122 398 9872.
E-mail address: bill.bosworth@apachecorp.com (W. Bosworth).

http://dx.doi.org/10.1016/j.jafrearsci.2015.05.005
1464-343X/

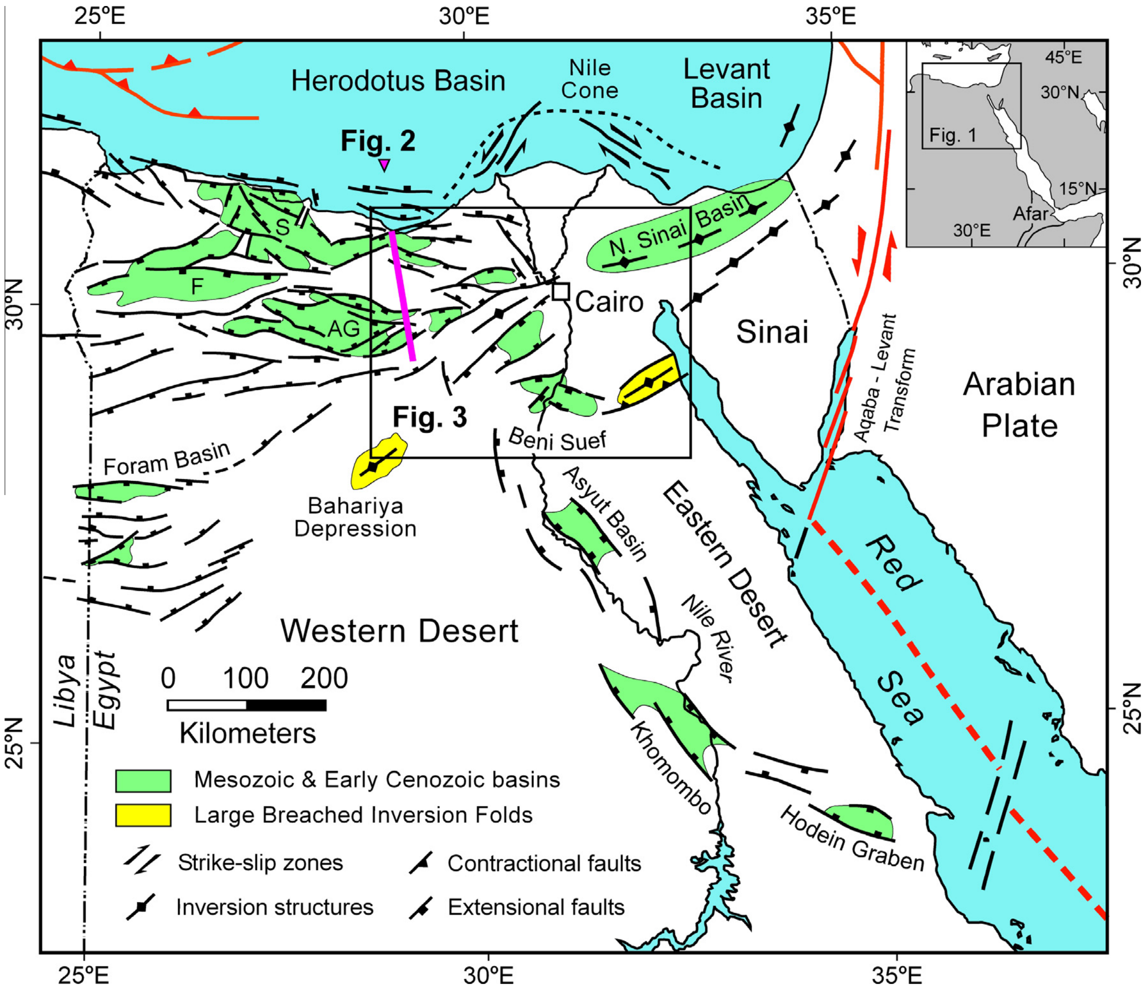

Fig. 1. Location of the Red Sea Neogene basin relative to the Mesozoic and Early Cenozoic basins (green) of northern and central Egypt. Location of Fig. 2 cross-section is shown by bold line; Fig. 3 is indicated by box. Major structures associated with present-day plate boundaries are shown in red. Structural interpretation after Bosworth et al. (2008). AG = Abu Gharadig basin; F = Faghur basin; S = Shushan basin. Universal Transverse Mercator Zone 35 projection. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

history are now well understood. Stratigraphic relationships and K–Ar age dates suggested that the early, voluminous outpourings of Afar flood basalts lasted from about 32 to 15 Ma (the Aiba basalt and equivalents; Mohr, 1975; Zanettin et al., 1978; Zanettin, 1993). Detailed $^{40}Ar/^{39}Ar$ dating, however, has shown that the basaltic trap eruptions in Afar, southern Sudan and Yemen all began within a few 100 Ka of 31 Ma, were joined by rhyolitic volcanism about 1 My later, and that trap eruptions finished by about 25 Ma (Féraud et al., 1991; Baker et al., 1994, 1996; Zumbo et al., 1995; Hofmann et al., 1997; Rochette et al., 1997; Chernet et al., 1998; George et al., 1998; Kenea et al., 2001; Ukstins et al., 2002; Coulié et al., 2003). Most of the basaltic section was erupted from 31 to 29 Ma. This also corresponds with the age of the oldest syn-rift strata in the Gulf of Aden (Roger et al., 1989; Hughes et al., 1991; Watchorn et al., 1998; Fantozzi and Sgavetti, 1998; stratigraphic uncertainties are discussed in Bosworth et al., 2005). Pre-31 Ma basalts and tuffs were erupted in southwest Ethiopia from ~45 to 37 Ma (K–Ar and $^{40}Ar/^{39}Ar$ methods), demonstrating that the complete evolution of the greater Ethiopian volcanic province was more complex than summarized here (e.g. Ebinger et al., 1993). However, following Burke (1996) and many other workers we focus on the 31 Ma and younger history because this marks the onset of extension in the Gulf of Aden – Red Sea rift system.

Opposite to Afar at the north end of the Red Sea lie the vast Western and Eastern Deserts of Egypt (Fig. 1). The Western Desert is an important hydrocarbon producing region and has been intensely explored since the middle of the last century (El Ayouty, 1990; Egyptian General Petroleum Corporation, 1992). Most production is from siliciclastic reservoirs that were deposited in Jurassic and Cretaceous rift basins, some of which have been inverted (Fig. 2). Exploration has focused on structural traps at depths of ~1000 to 5000 m. With a few exceptions, field size tends to be small, typically covering a few square kilometers. Consequently, most of the Western Desert has been covered by 3D reflection seismic surveys, and in many cases now multiple generations of surveys. In the eastern Abu Gharadig basin (Figs. 1 and 2) the quality of these datasets is excellent.

While interpreting the extensive Abu Gharadig seismic database it was noted that extremely straight faults with very minor offsets cut the shallow stratigraphy in a NNW–SSE orientation, generally forming grabens 1–2 km wide (Fig. 3). In Egypt this orientation is commonly referred to as the Red Sea trend, and it has long been recognized within the petroleum industry that minor Red Sea-related deformation affected the Western Desert during the Early Miocene. The straight graben faults however typically have length to throw ratios in excess of 1000, and hence their aspect ratios are distinct from faults that define rift basin geometries. The Hamra-10 development well[1] (Fig. 3) drilled within the

[1] Details of wells used in this study are included in Supplementary Data files.