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“Early magmatism in the greater Red Sea rift: timing and significance”

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Abstract

Throughout the greater Red Sea rift system the initial late Cenozoic syn-rift strata and extensional faulting are closely associated with alkali basaltic volcanism. Older stratigraphic units are either pre-rift or deposited during pre-rupture mechanical weakening of the lithosphere. The East African superplume appeared in northeast Africa ~46 Ma but was not accompanied by any significant extensional faulting. Continental rifting began in the eastern and central Gulf of Aden at ~31-30 Ma coeval with the onset of continental flood volcanism in northern Ethiopia, Eritrea, and western Yemen. Volcanism appeared soon after at Derudeb in southern Sudan and at Harrats Hadan and As Sirat in Saudi Arabia. From ~26.5-25 Ma a new phase of volcanism began with the intrusion of a dike field reaching southeast of Afar into the Ogaden. At 24-23 Ma dikes were emplaced nearly simultaneously north of Afar and reached over 2000 km into northern Egypt. The dike event linked Afar to the smaller Cairo mini-plume and corresponds to initiation of lithospheric extension and rupture in the central and northern Red Sea and Gulf of Suez. By ~21 Ma the dike intrusions along the entire length of the Red Sea were completed. Each episodic enlargement of the greater Red Sea rift system was triggered and facilitated by breakthrough of mantle-derived plumes. However the absence of any volumetrically significant rift-related volcanism during the main phase of Miocene central and northern Red Sea/Gulf of Suez rifting supports the interpretation that plate-boundary forces likely drove overall separation of Arabia from Africa.

Key Words: Red Sea, Afar plume, $^{40}\text{Ar}/^{39}\text{Ar}$ dating, continental rifting, volcanism

24 Introduction

25 Kevin Burke and John Dewey (1973) suggested that the most common mode of continental
26 lithospheric break-up involved the formation of rift-rift-rift triple junctions above mantle plumes
27 and the intrusion of axial dikes along each of the three rift arms. The youngest and “most
28 intensely studied” example of such a plume-generated triple junction was Afar (Figure 1). Since
29 the appearance of this landmark paper the geometry and dynamics of continental rupture have
30 received extensive deliberation and seen the appearance of many new geological and geophysical
31 datasets not available in 1973. Building on the work of Milanovsky (1972), Şengör and Burke
32 (1978) proposed that the most fundamental subdivision of continental rifts is the role of active
33 versus passive driving mechanisms – upwelling mantle convection currents versus plate
34 boundary and plate movement forces. Afar and its three associated rifts again took center stage in
35 much of the ensuing debate. Burke (1996) later elaborated on his view of the role of the Afar and
36 other plumes in the formation of Africa’s East African rift system. Burke emphasized the
37 observation that for the past 30 My Africa has been dominated by basin and swell topography
38 and overall higher than world average elevations (Krenkel 1922, 1957; Argand 1924; Holmes
39 1965). He associated this with Africa having been nearly at rest with respect to some part of the
40 underlying mantle, and that the observed topography reflected circulation patterns within the
41 mantle (Burke and Wilson 1972; McKenzie and Weiss 1975). Impingement of multiple plumes
42 at the base of the African lithosphere may have caused or at least contributed to the stationary
43 nature of the plate, and the slow speed of the plate allowed the effects of these plumes to be seen
44 at the Earth’s surface. Burke then noted that the great system of active continental rifts in East
45 Africa – the Western and Eastern branches of East Africa, the Ethiopian rift, Gulf of Aden, Red
46 Sea, and Gulf of Suez (the “Afro-Arabian rift system of Baker 1970; Khan 1975; Kaz’man 1977)

– also formed over the past 30 My. Taking a holistic view of African geology, he reasoned that this was not coincidence and that the appearance of these plumes and associated mantle circulation patterns resulted in the formation of this rift system.

Burke (1996) also discussed plate boundary stresses and the evolution of the East African rift system and suggested that their role became more important after the collision of Arabia with Eurasia along the Bitlis-Zagros suture at about 15-10 Ma (Şengör and Yilmaz 1981; Hempton 1987). Other workers have seen these far-field stresses as more significant, or conversely downplayed the role of hot spots/plumes, during the entire rifting history (Tapponnier and Francheteau 1978; Courtillot 1982; Coleman 1993; Zeyen et al. 1997; Reilinger and McClusky 2011). Collins (2003) interpreted the dispersal of Pangaea, which would include lastly the East African rift system, to have been driven largely by slab retreat at adjacent subduction zones. Thermal blanketing and plumes/hot spots played secondary roles in that they helped determine the breakup pattern. Reilinger and McClusky (2011) were able to link the timing of tectonic events within the Red Sea rift system to changes in subduction zone and back-arc basin evolution in the Mediterranean region. The parallelism between the Arabia-Eurasia collision zone and the Red Sea supports the contention that slab pull beneath the Urumieh-Dokhtar arc likely played an important role during early Red Sea rifting (further discussion in Bosworth et al. 2005).

In order to understand the dynamics of the Red Sea, it is essential to know the timing of when continental rupture and lithospheric extension occurred. While the temporal resolution for older rift systems, such as the extensive Early Cretaceous rifts of northern and central Africa, might be millions of years, for the younger Red Sea rift uncertainties in radiometric and biostratigraphic dates are generally measured in hundreds of thousands of years. It is therefore possible to establish a very detailed overall chronology of volcanism, sedimentation, and faulting

unattainable in older rifts, and from this to generate more tightly constrained models of cause and effect.

Along most of the Red Sea system there are at least local occurrences of late Cenozoic basaltic volcanism now dated by high-precision $^{40}\text{Ar}/^{39}\text{Ar}$ methodologies. These data provide absolute age constraints for the associated stratigraphy. Our own field observations in Egypt and Saudi Arabia, and published accounts for other parts of the rift, suggest that the onset of Red Sea extensional faulting and syn-tectonic deposition occurred synchronously with the phase of basaltic volcanism that occurred at ~23 Ma, the Oligocene-Miocene transition, using the geologic time scale of Gradstein et al. (2012).

In this paper we summarize the magmatic activity that immediately predates opening of the Red Sea and connected rift segments and the distinctly different volcanism associated with rift initiation. We then compile where faulting is interpreted to be coeval with the rift initiation volcanism and document the differences that were present between the southern and northern parts of the rift system. Finally we reconstruct the Eocene to Early Miocene evolution of northeast Africa and discuss the role played by mantle plumes in this model.

Red Sea Rift Volcanism

Igneous activity in the greater Red Sea rift system and environs occurred in distinct phases, each associated with a different part of the lithospheric rupturing process: 1) volcanism at ~46-34 Ma that was associated with appearance of the East African superplume, presently best documented in the southern main Ethiopian rift and with time correlative units in southern Egypt; 2) eruption of the main continental flood basalts in Ethiopia, Eritrea, South Sudan and Yemen at 31-30 Ma, followed by bimodal volcanism from 30-25 Ma (Figure 1); 3) intrusion of

the Red Sea dike system and associated igneous complexes, eruption of the Marda volcanic zone southeast of Afar, and a large extrusive event in northern Egypt and the Harrat ash Shaam region of Jordan at ~26.5-21 Ma (Figure 1); 4) continued volcanism within Afar (mostly after ~20 Ma) and in the younger Harrats of Saudi Arabia from ~17 Ma to Present-day (Figure 1); and 5) oceanic spreading along the southern axis of the Red Sea no later than 5 Ma and continuing to the Present-day. We first briefly discuss the 46-34 Ma volcanism that was not coeval with faulting or other structural aspects of continental rupture and hence do not play a primary role in our model for Red Sea rifting. It formed a backdrop for the opening of the Red Sea and its differences from subsequent phases of volcanism should be appreciated. It is possible that mantle plumes from this Eocene event continued to play a role in subsequent phases of magmatism. The second and third volcanic events form the crux of our model and volcanism with similar relative timing can be recognized in many other continental rift systems.

46-34 Ma (Eocene) Volcanism

Ethiopian Plateau/Afar

The thickest section of volcanic rocks spanning the longest recorded time period in the greater Red Sea rift system is in the Ethiopian Plateau region west and south of Afar (Figure 1). The Mesozoic sedimentary rocks of Ethiopia and Yemen are capped by a major unconformity, upon which were extruded flood basalts that prior to later erosion reached 4 km in thickness (Mohr 1983; Zanettin 1993). Basalts, rhyolites, ignimbrites, tuffs, and local interbeds of fluvial and lacustrine sedimentary rocks immediately overlying the unconformity were interpreted to be about 60 Ma old (mid-Paleocene; Varet 1978) though precise age control was lacking. Megrue et al. (1972) dated three basaltic dikes and one flow from the western Ethiopian Plateau at 66-55

Ma (K-Ar whole-rock). These “Ashangi basalts” (Zanettin and Justin-Visentin 1975; Zanettin et al. 1978) were thought to have continued for some 25 My into the late Eocene. The end Cretaceous to Eocene age range for the Ashangi basalts has not been confirmed by any $^{40}\text{Ar}/^{39}\text{Ar}$ age dating.

Following the Ashangi basalts a significant period of erosion ensued that resulted in another unconformity – the “Ashangi peneplain” (Zanettin and Justin-Visentin 1975). Active faulting during formation of the Ashangi basalt sequence has not been recorded, but large-scale block tilting during the subsequent Ashangi peneplanation has been documented (Zanettin and Justin-Visentin 1975).

Volcanic units equivalent to the Ashangi basalts (“Amaro basalts”; Levitte et al. 1974) were erupted in the southern main Ethiopian rift (Figure 2) from about 45 to 35 Ma (K-Ar whole-rock dates; Yemane and Yohunie 1987; WoldeGabriel et al. 1991; Ebinger et al. 1993). 24 sanidine single-crystal laser fusion $^{40}\text{Ar}/^{39}\text{Ar}$ analyses from the associated Amaro tuff gave a weighted mean age of 36.9 ± 0.1 Ma (2σ uncertainty; unless otherwise noted all subsequent $^{40}\text{Ar}/^{39}\text{Ar}$ error bars are 2σ and K-Ar 1σ) (Ebinger et al. 1993). Five $^{40}\text{Ar}/^{39}\text{Ar}$ whole-rock analyses from the Amaro and related Gamo basalts subsequently produced isochron ages of 45.2 ± 1.4 to 34.1 ± 0.5 Ma confirming the ~45 to 35 Ma span of this early south Ethiopian magmatic event (George et al. 1998).

Gilf Kebir Volcanism, Egypt

Isolated circular to elliptical craters have long been recognized in the southwest corner of Egypt, in the vicinity of the vast Gilf Kebir plateau and Gebel Uweinat (Figure 2; Clayton 1933; Sandford 1935; El-Baz 1981, 1982). All these features were later interpreted to be volcanic in

origin (Barakat 1994). Utilizing complete Landsat image coverage, Klitzsch et al. (1987) mapped the presence of a broad area of “Early Tertiary” volcanism consisting of hundreds of monogenetic cones, plugs, dikes and localized basalt flows in southwestern Egypt on, east and south of the Gilf Kebir plateau (Figures 2,3). These basalts are associated with over 1300 circular and elliptical craters and are now exposed over an area of about 37,000 km² (Figures 3a,b). The sedimentary rocks intruded by the Gilf basalts are as young as the Cenomanian (100-94 Ma) (Klitzsch et al. 1987). Franz et al. (1987) have described partially melted sedimentary strata (buchite) in the tilted rims of some of the Gilf craters (Figure 3c).

Paillou et al. (2004) interpreted the Gilf Kebir crater field as the Earth’s largest meteorite impact or strewn field. This was largely based on the presence of shock-related shatter cones and planar fractures in quartz grains of the common rim sandstone breccias. Paillou et al. had only identified a crater field area of ~4000 km² but even so recognized that this could not have resulted from the break-up and impact of a single meteorite. They envisioned the break-up of multiple meteorites. After further study Paillou et al. (2006) recognized that the crater field was an order of magnitude larger than they originally thought which made an impact origin “even less plausible.” Di Martino et al. (2006) re-examined the supposed shatter cones and concluded that the identified features were not of shock origin. Paillou et al. (2006) and Di Martino et al. (2006) offered the alternative interpretation that the craters were formed as hydrothermal vent complexes as fluids seeped through a volcanic-sedimentary basin. The close physical and temporal association of the craters with basalt cones, flows and dikes (Figure 3) leads us to support the interpretation that they are all related to volcanism.

Greenwood (1969, cited in Meneisy 1990) obtained a K-Ar date from an hawaiite sample north of Gebel Uweinat (south of the Gilf) of 37 ± 2 Ma (we do not know the exact location of

this sample). Franz et al. (1987) determined K-Ar ages of 59 ± 1.7 and 37.9 ± 2.0 Ma (mid-Paleocene to late Eocene) for porphyritic olivine-bearing basalts east of the plateau (Figure 3a). Another basalt lava from this area (07 GK 01) sampled by the authors during field mapping yielded a $^{40}\text{Ar}/^{39}\text{Ar}$ whole-rock plateau age of 46.0 ± 0.5 Ma (mid-Eocene; Figures 3a,d,e). This individual flow covers a preserved area of $\sim 1.1 \text{ km}^2$ and is located just west of a NW-SE striking dike that may have been part of its feeder system.

Yemen

Paleocene to Eocene volcanic rocks are not recorded in Yemen. Rather, Early Oligocene basalts directly overly the Mesozoic sedimentary section (Chiesa et al. 1989; Davison et al. 1994; Al-Subbary et al. 1998). The focus for the older Paleogene event appears to have been the southern Ethiopian rift and the Gilf Kebir region, although the full possible extent of these rocks beneath the younger basalts of northern Ethiopia is not known.

Eocene structuration and relative timing

No significant extensional faulting contemporaneous with the extrusion of the Ashangi, Amaro, or Gilf Kebir basalts has yet been identified (Barberi et al. 1972a, 1975; Ebinger et al. 1993; George et al. 1998; unpublished field work in Egypt by the authors). The Paleogene volcanic centers, though geographically widely spaced, could have appeared essentially synchronously over an ~ 10 My time period at 46-34 Ma (mid- to late Eocene) based on the limited $^{40}\text{Ar}/^{39}\text{Ar}$ dating that presently exists.

31-25 Ma (Oligocene) Continental Flood Volcanism

Afar and the Ethiopian Plateau

The Ethiopian Ashangi basalts and their lateral equivalents are capped by a regional peneplain and in northern Ethiopia an associated thick laterite horizon (Zanettin et al. 1978; Coleman 1993; Şengör 2001). Similar laterites are present in Yemen and southern Sudan between the Early Oligocene basalts and the sub-cropping basement or Mesozoic strata (Davison et al. 1994; Al-Subbary et al. 1998; Kenea et al. 2001). Immediately overlying the Ethiopian peneplain and laterites is a thick section of basaltic traps referred to the Aiba series (Zanettin et al. 1978). These basalts are overlain by the bimodal Alaji series in which rhyolites are common (Barberi et al. 1972 b, 1975; Zanettin 1993). The Aiba and Alaji series and their regional lateral equivalents are the Earth's youngest example of continental flood volcanism (CFV; Baker et al. 1996), covering a total area of more than 600,000 km² with estimated volumes of >350,000 km³ (Mohr, 1983) to >10⁶ km³ (Courtillet et al. 1999).

Stratigraphic relationships and K-Ar dates led early workers to consider the age of the Aiba-Alaji volcanics and their lateral equivalents to span from ~34-15 Ma (Zanettin and Justin-Visentin 1974, 1975; Kuntz et al. 1975; Juch 1975; Mohr 1975; Zanettin et al. 1978; Mohr and Zanettin 1988; Zanettin 1993). More recent ⁴⁰Ar/³⁹Ar data have significantly revised this picture. Hofmann et al. (1997) studied three sections in the northern Ethiopian plateau west of Afar and the basalt outliers to the north at Adigrat (Figure 1). The stratigraphically lowest sampled basalt gave a whole-rock plateau age of 30.8 ± 0.4 Ma (Hofmann et al. reported confidence levels at 1σ). A slightly higher basalt in another section provided a plagioclase isochron age of 31.3 ± 0.7 Ma. The basalt immediately overlying Jurassic strata at Adigrat yielded a consistent plateau age of 30.4 ± 0.4 Ma. Basalts from the middle parts of the studied sections gave plateau and/or isochron ages (7 samples, plagioclase and whole-rock) from 30.5 ± 1.0 to 28.5 ± 0.5 Ma. The

208 plateau capping section of ignimbrites and rhyolites gave three sanidine isochron ages from 30.2
209 ± 0.1 to 28.2 ± 0.1 Ma and a whole-rock isochron age of 26.7 ± 0.3 Ma. Rochette et al. (1998)
210 later reported additional sanidine plateau ages of 30.1 ± 0.1 and 30.2 ± 0.1 from the same area.
211 Hence, volumetrically most of the basalts were erupted from ~ 31 -30 Ma, comprising about 10^6
212 km^3 of material. Lesser basaltic volcanism continued for another 1-2 My, and felsic volcanic
213 rocks first appeared at ~ 30 Ma and quickly became dominant by 28 Ma. In another study of the
214 same and similar northern Ethiopia plateau sections Coulié et al. (2003) found that the oldest
215 basalts were 30.6 ± 0.4 Ma (K-Ar whole-rock) and confirmed the sequence of events and timing
216 identified by Hofmann et al. (1997) and Rochette et al. (1998).

217 A similar sequence of events was found in sections of the southern Ethiopian escarpment. A
218 trachyte near the base of the section produced a weighted phlogopite isochron age of $30.92 \pm$
219 0.11 Ma (Ukstins et al. 2002). Overlying ignimbrites gave sanidine isochron ages of $30.16 \pm$
220 0.13 , 29.61 ± 0.12 and 29.68 ± 0.15 Ma, while overlying basalts yielded 29.34 ± 0.15 , 25.1 ± 0.2 ,
221 and 25.0 ± 0.2 Ma plagioclase isochron ages. A second profile produced an ignimbrite sanidine
222 isochron age of 25.30 ± 0.13 Ma. Ukstins et al. (2002) also studied younger volcanic sections
223 and identified a significant gap in the stratigraphy of the escarpment with no units present from
224 ~ 25 to 20 Ma. More recent detailed mapping and age dating of the central Afar region confirms
225 that the main phase of CFV was complete by ~ 25 Ma and was followed by major changes in
226 eruptive style and tectonic activity discussed below (Stab et al. 2016).

227

228 *South Sudan Red Sea Hills*

229 Exposures of Oligocene basalts are very limited in the Sudan. The best documented examples
230 outcrop in the Derudeb region south of Port Sudan near the border with Eritrea (Figure 1).

Basalts, felsic tuffs and rhyolites are present in two small basins, the Odi and Adar Ribad, both of which are presently at least partially fault-bounded (Delany 1956; Hassan 1990; Kenea 1997). A 2-40 m thick section of undated sedimentary rocks underlies the basalts and tuffs in the Odi Basin, and the sedimentary/volcanic contact is observed to be conformable (Kenea et al. 2001). No pre-volcanic sedimentary strata are reported from Adar Ribad.

Possibly four major basaltic flows are present in the northern Odi basin, with individual thickness of 35-55 m (Hassan 1990). Kenea et al. (2001) analyzed an aphyric, largely unaltered basalt from the lowermost flow and obtained a K-Ar age of 30.8 ± 1.0 Ma. Other Odi basin basalt flows, a basaltic dike, rhyolites and a tuff yielded K-Ar ages of 29.5 to 22.8 Ma. Feldspar separates from one of the basal basalt flow samples (K-Ar 28.3 ± 1.0 Ma) was also step-wise degassed to give a $^{40}\text{Ar}/^{39}\text{Ar}$ total fusion age of $29.9 \text{ Ma} \pm 0.3 \text{ Ma}$.

Basalts and rhyolites at Adar Ribad are compositionally similar to those in the Odi basin (Hassan 1990; Kenea et al. 2001). Basalt and rhyolite flows from this area gave K-Ar ages of $27.9 \pm 1 \text{ Ma}$ and $24.5 \pm 1 \text{ Ma}$ (Kenea et al. 2001). Again, feldspar separates from the rhyolite yielded a somewhat older $^{40}\text{Ar}/^{39}\text{Ar}$ total fusion age of $29.6 \text{ Ma} \pm 0.3 \text{ Ma}$.

The $^{40}\text{Ar}/^{39}\text{Ar}$ age data from Derudeb demonstrate that the basaltic volcanism initiated at ~ 30 Ma, perhaps slightly after initiation in northern Ethiopia. There was soon thereafter a shift to rhyolitic/bimodal volcanism similar to that observed in Ethiopia.

Yemen Volcanic Group

The CFV of southwest Yemen share many similarities with those of northern Ethiopia (Figure 1). The maximum thickness is greater than 2 km and composition is bimodal, consisting of predominantly lower basalts overlain by mixed rhyolitic tuffs, ignimbrites, basalts and

occasional rhyolite flows higher in the stratigraphy (Moseley 1969; Civetta et al. 1978; Chiesa et al. 1989; Baker et al. 1994; 1996). The basal basalts are underlain by lithic tuffs and volcanic ashes referred to the Jihama Member (Al-Subbary et al. 1998). The Jihama Member disconformably overlies siliciclastic units of the Cretaceous to Eocene Tawilah Group (Menzies et al. 1990; Davison et al. 1994; Al-Subbary et al. 1998). Extensive K-Ar dating suggested that the Yemen Volcanic Group was formed over a period of greater than 50 Ma (summarized in Baker et al. 1996). However some K-Ar studies indicated that the main phase of CFV eruptions was of much shorter duration, probably 30-26 Ma (Chiesa et al. 1989).

Baker et al. (1994) obtained a $^{40}\text{Ar}/^{39}\text{Ar}$ amphibole plateau age of 30.44 ± 0.18 Ma from a basalt at the base of section, and anorthoclase plateau ages of 29.32 ± 0.1 Ma and 28.26 ± 0.1 Ma from ignimbrites at the top. More extensive $^{40}\text{Ar}/^{39}\text{Ar}$ analyses by Baker et al. (1996) across much of the volcanic terrane (18 age dates) showed that basalt eruptions started at ~ 30.9 Ma in the northwest and ~ 29.2 Ma in the southwest. Rhyolitic volcanism appeared throughout Yemen slightly later at 29.3 to 29.0 Ma. Baker et al. (1996) also estimated that flows were erupted in the lower basalt section every 10-100 ky, whereas timing for the upper bimodal eruptions was about 100-500 ky. They interpreted this as indicative of longer residence time within the lithosphere for the magmas that generated the rhyolites. The youngest plateau ages obtained for the CFV were an ignimbrite sanidine of 26.94 ± 0.20 Ma and a rhyolite lava anorthoclase of 26.51 ± 0.12 Ma (Baker et al. 1996).

The $^{40}\text{Ar}/^{39}\text{Ar}$ dating of the Yemen CFV is very similar to that obtained in Ethiopia and approximately in line with the earlier work of Chiesa et al. (1989). Basaltic volcanism first appeared at ~ 31 Ma and had reached all of western Yemen by ~ 29 Ma. Bimodal volcanism started at 29 Ma and dominated until the end of the CFV at ~ 26.5 Ma.

Saudi Arabia Older Harrats

Large volcanic constructional features in Saudi Arabia are referred to as Harrats (Figure 1), and this extensive province of volcanism has intrigued and puzzled geoscientists since they were first recognized. Why long-lived and voluminous magmatic activity has occurred east of the Red Sea rift has evoked numerous interpretations but not consensus (e.g. Gass 1970; Almond 1986a, 1986b; Camp and Roobol 1989, 1992).

Those centers that initiated shortly after the Early Oligocene Afar CFV are termed the “Older Harrats” (Coleman et al. 1983; Brown et al. 1989; Camp and Roobol 1992). Best known from this sequence are Harrats Uwaynd, Hadan and As Sirat (Figure 1; Coleman 1993). Compilation of radiometric age dates (mostly K-Ar) suggested that the Older Harrats formed from about 30-20 Ma with a significant peak at 24-21 Ma (Camp and Roobol 1992). This was followed by only minor activity until about 12-10 Ma at which time the Younger Harrat volcanism appeared, accelerating significantly in volume after 5 Ma. Based on the temporal progression, Cenozoic Harrat basalt has been arranged into three major groups: >26 Ma, 24-15 Ma, and 12 Ma-present. These magmatic phases are sometimes referred to as “pre-, syn-, and post-rift” (e.g. Chazot et al. 1998), but the validity and timing of this classification is contingent upon location within the rift margin and there is considerable temporal overlap of magmatic phases at individual Harrats given their longevity (e.g. Harrat Hadan 28-15 Ma; Stern and Johnson 2010).

Harrat Hadan is about 150 m thick and covers an area of roughly 5,000 km² (Figure 1). A basalt flow from the base of the section gave a ⁴⁰Ar/³⁹Ar plagioclase plateau age of 28.0 ± 0.2 Ma (Sebai et al. 1991). Alkali basalt and hawaiite dikes produced whole-rock plateau ages of

27.2 $\pm$ 0.2 and 26.9 $\pm$ 0.9 Ma. Three other basalt dikes displayed more disturbed spectra but integrated ages were still within the range of 28.1-26.4 Ma (Sebai et al. 1991).

The Harrat Hadan olivine alkali basalts were erupted from central vents that generally trend north-south. They are very similar to the 31-30 Ma alkali basalts of Afar, and perhaps represent material derived from an offshoot of the same plume-system. These oldest Harrats were erupted onto a moderate- to low-relief topographic surface within the Afro-Nubian Shield (e.g. Coleman et al. 1983; Coleman 1993). Laterite deposits are preserved beneath the basal flows of several of the volcanic fields.

Early Oligocene Structuration

Although there is a significant, regionally diachronous time-gap between the Yemen Volcanic Group and the underlying Tawilah Group, the two units are conformable in outcrop and there is no evidence for uplift at the onset of CFV (Davison et al. 1994; Baker et al. 1996). There is likewise no evidence for significant faulting during their eruption (Menzies et al. 1990, 1997; Davison et al. 1994; Al-Subbary et al. 1998). Similar relationships are described in the Ethiopian CFV where syn-extrusive faulting is absent (Barberi et al. 1972a, 1975). Early Oligocene faulting has not been described in association with any of the older Harrats of Saudi Arabia, nor are Early Oligocene syn-rift strata present in any Red Sea exploratory wells (Hughes et al. 1991). Kenea et al. (2001) speculated that Early Oligocene volcanics in the Odi basin (Derudeb) may have been deposited in an already active rift. However, as shown in their structural cross-sections the authors recognized that no thickening of the sedimentary or volcanic section into the mapped basin-bounding faults could be demonstrated, and that therefore most of the local extension probably occurred after eruption of the volcanics.

26.5-21 Ma (Late Oligocene-Early Miocene) Volcanism

Ethiopian Plateau and Afar

The Ethiopian Plateau saw only sporadic and localized volcanic activity in the latest Oligocene to earliest Miocene (~25-20 Ma) (Ukstins et al. 2002; Stab et al. 2016). Most of the volcanic rocks of this period are found along the border fault complex of the northern plateau and in what are referred to as the ‘marginal grabens’ (Figure 1; Morton and Black 1975). Coulié et al. (2003) obtained $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages of 23.43 ± 0.24 and 20.51 ± 0.30 Ma from felsic volcanoclastic rocks and a K-Ar date of 20.7 ± 0.3 Ma from a 10 m thick basalt flow at Alem Ketema north of Addis Ababa (Figure 1). Wolfenden et al. (2005) produced integrated ages of 24.71 ± 0.20 Ma (plagioclase) and 25.97 ± 0.11 Ma (ground mass) from a basalt flow and alkali feldspar plateau ages of 26.47 ± 0.15 Ma (rhyolite flow), 25.90 ± 0.16 Ma (intermediate lava), and 24.80 ± 0.13 Ma from sites in the marginal grabens and near the northern plateau border faults. South of the Gulf of Tadjoura in the area of the Ali Sabieh block (Republic of Djibouti; Figure 4) Zumbo et al. (1995a) reported a $^{40}\text{Ar}/^{39}\text{Ar}$ whole-rock plateau age 23.6 ± 0.5 Ma from an altered basalt flow. Ali Sabieh is also cut by numerous rhyolitic and basaltic dikes but these all yield younger ages in the range of ~19-17 Ma (Zumbo et al. 1995a).

The volumetrically minor Oligocene-Miocene boundary volcanic rocks of the Ethiopian plateau and Afar were erupted during active extensional faulting, the oldest well-documented Cenozoic deformation in this region (Barberi et al. 1972b, 1975; Zanettin et al. 1978; Wolfenden et al. 2005; Stab et al. 2016).

Ogaden Region, Ethiopia

Afar and the Main Ethiopian Rift are bordered on the southeast by a region commonly referred to as the Ogaden (Figures 1,2,4). Much of this terrane is underlain by a complex, broadly SW-NE trending Mesozoic basin that extends from northernmost Kenya to Somaliland and roughly parallels the northern Ethiopian rift (Assefa 1988; Hunegnaw et al. 1998). Regionally the Ogaden basin is tilted to the southeast exposing basement, late Triassic and Jurassic rocks near Afar and Cretaceous rocks in southeast Ethiopia and Somalia (Hunegnaw et al. 1998). A major NW-SE striking fault zone cuts through the Ogaden in the Marda Range (Figure 4). These hills consist of Jurassic limestone overlain by a body of basalt roughly 150 km long, 2 km wide and locally about 200 m thick (Mège et al. 2015). Smaller bodies of basalt are exposed on trend to the southeast nearly as far as the Somalia border, defining a volcanic zone about 500 km in length. Where the Marda fault zone cuts through exposed basement near Afar it is marked by mylonites. Gouin and Mohr (1964) and Purcell (1975, 1976) suggested that this fault zone initiated in the Precambrian and remained an active tectonic boundary through much of the Phanerozoic.

Basalts from the northern and central section of the Marda fault zone dated by K-Ar gave ages of 25.5 ± 1.3 Ma and 24.2 ± 1.3 Ma (Maxus Ethiopia 1993 cited in Mège et al. 2015). More recent $^{40}\text{Ar}/^{39}\text{Ar}$ ground mass plateau dates from the northern Marda basalt flows and dikes are 22.55 ± 0.89 Ma, 23.68 ± 0.54 Ma, and 25.04 ± 0.65 Ma (Mège et al. 2015). These Marda basalts are geographically and morphologically distinct from the earlier 31-25 Ma CFV of the nearby Afar region. Basalts from the southern extension of the Marda zone near the border with Somalia yielded a broader range of $^{40}\text{Ar}/^{39}\text{Ar}$ ground-mass dates: 24.40 ± 0.73 Ma, 24.85 ± 0.46 Ma, 25.44 ± 0.73 Ma, 26.56 ± 0.45 Ma, 28.09 ± 0.81 Ma, and a plagioclase age of 30.0 ± 1.9 Ma (Mège et al. 2015). These data indicate that in the south volcanism probably initiated at the time

of the Early Oligocene Afar CFV, similar to the local eruptions at Derudeb in the Sudan.

However the most significant volcanism in the Ogaden was a basaltic dike event that lasted from ~26.5-22.5 Ma.

Southeast of the Marda fault zone on the west side of the Shebelle Valley near Bulobarde, Somalia basalt flows and sills are exposed over an area of ~1200 km² (Figure 4; Ali Kassim et al. 1992). Similar volcanics are reported in the Mudug region further north, including wellbore penetrations (Bosellini 1992; Faillace 1993). Unfortunately no reliable radiometric age dates have been obtained from any of these Somali basalts due to the presence of excess argon (Ali Kassim et al. 1992).

Yemeni Red Sea Margin Dikes and Plutons

The Oligocene Yemen Volcanic Group, pre-Red Sea rift sedimentary rocks, and Precambrian basement of the Yemeni continental margin are cut by numerous individual mafic and felsic dikes and dike swarms (Moseley 1969; Forgacs 1988 (cited by Zumbo et al. 1995b); Mohr 1991; Davison et al. 1994). Individual dikes vary from 1 to 15 m thick and the most common orientation is parallel to the Red Sea at ~N120-150°E (Zumbo et al. 1995b). N-S, N60°E and N95°E orientations are also present. Compositions include basalt, trachyte, rhyolite, comendite and pantellerite (Chazot et al. 1991; Zumbo et al. 1995b).

Two dikes from the southern Radfan region produced whole-rock ⁴⁰Ar/³⁹Ar ages of 25.4 ± 0.1 Ma (integrated ages 25.40 ± 0.04 Ma and 24.8 ± 0.2 Ma; Zumbo et al 1995b). A broader range of plateau/accepted ages were reported for the nearby Al'Anad area: 20.6 ± 0.5 Ma, 18.5 ± 0.6 Ma, 18.2 ± 0.5 Ma, and 16.1 ± 0.9 Ma (a total of 11 whole-rock and single crystal feldspar integrated ages 26.6 ± 0.4 to 18.00 ± 0.07; Zumbo et al 1995b). Related gabbro and syenite

plutons at Dhala gave plateau ages of 22.3 ± 0.1 Ma (biotite) and 21.4 ± 0.1 Ma (K-feldspar) respectively (integrated ages 22.1 ± 0.2 Ma and 21.6 ± 0.3 Ma; Zumbo et al. 1995b).

Along the Great Escarpment in western Yemen there are also extensive exposures of granite intrusions and associated silicic porphyritic lava (Davison et al. 1994). K-Ar dates of the granites are 26-20 Ma (Civetta et al. 1978; Capaldi et al. 1987). Blakely et al. (1994) confirmed an age range of ~ 22 -21 Ma with Rb-Sr dating. Similar to the plutons at Dhala these granites were intruded coevally with the major latest Oligocene to Early Miocene dike event of the Yemen Red Sea margin.

Saudi Arabian Red Sea Margin Dikes and Mafic Igneous Complexes

The Late Oligocene-Early Miocene dike system along the Saudi Red Sea margin is an impressive regional feature, occupying a nearly continuous belt generally 50-150 km wide and reaching 1700 km from northern Yemen to the Gulf of Aqaba (Figure 1). Many individual dikes are over 50 km in length, and the largest – the great Ja'adah dike – is at least 450 km long based on the interpretation of aeromagnetic data (Zahran et al. 2003).

Sebai et al. (1991) obtained $^{40}\text{Ar}/^{39}\text{Ar}$ dates for mineral separates from six of the Saudi margin dikes. Two hornblendes and a plagioclase gave plateau ages of 22.0 ± 0.3 Ma, 21.1 ± 0.5 Ma, and 22.50 ± 0.06 Ma respectively. A biotite produced a plateau age of 22.3 ± 0.5 Ma and a whole-rock analysis from the same sample yielded 23.9 ± 0.3 Ma. Two other plagioclases, though with only partial plateaus, gave nearly concordant integrated ages of 21.5 ± 0.1 Ma and 21.1 ± 0.2 Ma. A basalt flow associated with the margin dikes and found interstratified with the Oligocene-Miocene Baid Formation near Al Lith (Al Qunfudah) yielded a plagioclase plateau age of 21.7 ± 0.3 Ma.

The southern Saudi margin was also the site of more extensive Red Sea related magmatism, with development of what has been referred to as a Miocene ophiolite (Coleman et al. 1975, 1978; Coleman 1984). The Tihama Asir igneous complex is located 40 km east of Jizan (Figure 1) and includes sheeted dikes, layered gabbro bodies, and granophyre stocks intruded into the Neoproterozoic basement and Paleozoic to Cenozoic sedimentary strata (Coleman et al. 1979; Blank and Gettings 1984). Isolated basalt dikes similar to those present along the rest of the margin are also common. Recent interpretation of high resolution aeromagnetic data indicate that in the greater Jizan and Tihama (Tihamat) Asir region many large dikes are present that are either covered by the alluvium of the coastal plain or do not reach the surface within the Neoproterozoic basement rocks (Roobol and Kadi 2013).

Coleman et al. (1979) observed that hydrothermal alteration of the Tihama Asir sheeted dikes made them unsuitable for K-Ar dating. However they obtained five whole-rock dates from gabbros, granophyres and a hornfels that range in age from 24.3 ± 1.0 Ma to 20.0 ± 2.0 Ma. Voggenreiter et al. (1988) and Voggenreiter and Hötzel (1989) reported that ten K-Ar dates had been obtained from dikes of the Jizan area with ages of 26-18 Ma but to our knowledge the details of these analyses were not published. It is not clear if any of these dates were from the actual sheeted dike complex.

Sebai et al. (1991) presented $^{40}\text{Ar}/^{39}\text{Ar}$ data for six basaltic dikes, one rhyolitic dike, and three cumulate gabbros from the Jabal al Tirf pluton area of the Tihama Asir complex. The gabbros gave plagioclase plateau ages of 22.2 ± 1.1 Ma and 22.0 ± 0.5 Ma and an integrated age of 20.9 ± 0.3 Ma. Three plagioclase and one whole-rock plateau age for the basalts were 21.25 ± 0.05 Ma, 22.6 ± 0.9 Ma, 24.5 ± 1.3 Ma, and 21.8 ± 0.3 Ma. The rhyolitic dike yielded a whole-rock partial plateau age of 21.7 ± 0.2 Ma and similarly for another basaltic dike of 23.3 ± 0.4 Ma.

A second intrusive complex is located 70 km northwest of Al Lith (Figure 1; Pallister 1987). As at Tihama Asir sheeted dikes intrude into Neoproterozoic basement rocks. Lava flows coeval with the sheeted dikes are also present. K-Ar ages reported for the Al Lith dikes and flows are wide ranging from 158 ± 0.8 Ma to 21.2 ± 2.2 Ma (Brown 1972; Pallister 1987). Some of these dates are clearly unreliable. Other igneous units include gabbroic, dioritic and anorthositic plutons. These plutons produced six K-Ar dates ranging from 27.9 ± 5.6 Ma to 26.7 ± 4.6 Ma (Pallister 1987). These plutons and dikes are interpreted to be generally coeval due to mutual crosscutting relationships similar to Tihama Asir.

Sebai et al. (1991) analyzed samples from basaltic and acidic dikes, two plutons and a basalt flow from the Al Lith complex. Two whole-rock $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages (one discordant step from each rejected) from the dikes were 23.5 ± 0.9 Ma and 26.0 ± 1.3 Ma. A plagioclase from a dike yielded a partial plateau age (concordant minimum ages) of 23.1 ± 0.4 Ma and an isochron age of 22.8 ± 2.4 Ma. From the plutons an amphibole gave a plateau age of 24.0 ± 0.2 Ma and a plagioclase 22.3 ± 0.6 Ma. The basalt flow plagioclase plateau age was of 23.3 ± 0.5 Ma.

A detailed comparison was made by Sebai et al. (1991) of the distribution of their 23 $^{40}\text{Ar}/^{39}\text{Ar}$ ages versus 21 published conventional K-Ar ages for all the Late Oligocene-Early Miocene magmatism along the Saudi Arabian Red Sea margin. The K-Ar data show a broad distribution from about 29 to less than 15 Ma. In contrast, all $^{40}\text{Ar}/^{39}\text{Ar}$ ages, with the exception of a single dike at Al Lith, tightly cluster between 24.5 and 21 Ma. Similar results were obtained for essentially the same datasets by Féraud et al. (1991) using a somewhat different statistical approach.

Egyptian Dikes and Flows

Late Cenozoic volcanic rocks in Egypt occur in several forms in widely dispersed areas: 1) basaltic dikes and a single flow on Sinai; 2) basaltic dikes in the subsurface of the Gulf of Suez rift basin and along its western margin (the Eastern Desert); 3) a cluster of small basaltic flows on the Red Sea margin south of Quseir; 4) extensive basaltic flows west, north, and east of Cairo; 5) aligned monogenetic basaltic cinder cones and isolated flows west of the Nile near Asyut; 6) basaltic flows within the Bahariya Oasis and on the plateau to its northwest; and 7) basaltic dikes of several ages on the Brothers and Zabargad Islands in the central waters of the Egyptian Red Sea. All of these volcanic units are generally sub-alkaline tholeiites (Baldrige et al. 1991; Abdel Aal 1998; Endress et al. 2011; Shallaly et al. 2013) and no rhyolites of this age have been reported (Meneisy 1990). The basalts are temporally and spatially related to NW-SE faults that are present from the Libyan Plateau in the west to Sinai in the east.

- Sinai and Gulf of Suez

A basaltic lava flow is exposed on the eastern margin of the central Gulf of Suez in Wadi Tayiba (Figure 5). The thickness of the flow varies from ~30 to ~5 m and prior to erosion it must have covered ~0.5 km² or more. Steen (1984) gave K-Ar ages for the Wadi Tayiba flow, a feeder dike in nearby Wadi Nukhul, several dikes further south on Sinai, and a dike in a nearby offshore well of from 32 to 18 Ma with a stated average age of 24 ± 1.3 Ma. Further details were not reported. Ott d'Estevou et al. (1986b) produced two K-Ar dates for the Tayiba flow of ~22 Ma (21.95 ± 0.5 Ma and 22.15 ± 0.5 Ma). Bosworth et al. (2015) obtained a ⁴⁰Ar/³⁹Ar whole-rock total fusion age of 23.1 ± 0.9 Ma for the flow. They also produced a whole-rock plateau age of 24.4 ± 0.3 Ma and a total fusion age of 23.0 ± 3.0 Ma for a basaltic dike in Wadi Nukhul.

A few other isolated basaltic dikes are exposed along both margins of the Gulf of Suez. K-Ar dates of 25.7 ± 1.7 Ma and 24.7 ± 0.6 Ma were reported for a dike on the south side of Gebel

Ataqa (Bosworth and McClay 2001) and a dike at Gebel Monsill (Gharamul) (Ott d'Estevou et al. 1986a) (Figure 5). A $^{40}\text{Ar}/^{39}\text{Ar}$ whole-rock plateau age of 22.3 ± 0.2 Ma was obtained for a very large dike exposed on the south side of Wadi Araba (Figure 5; Bosworth et al. 2015).

- Egyptian Red Sea Margin

As with the Saudi Red Sea margin, NW-SE striking late Cenozoic basaltic dikes are found along the Egyptian Red Sea margin but they are rare and often poorly exposed. A small dike is present on the north side of Wadi Naqara near Safaga but it is too altered to be dated (Figure 5; Bosworth et al. 1998). South of Quseir at Sharm el Qibli and Sharm el Bahari small, thin basalt flows are interbedded with red sandstone and siltstone of the Nakheil Formation. Roussel et al. (1986) obtained a K-Ar date of 24.9 ± 0.6 Ma from the flow at Sharm el Bahari.

- Cairo Basalts

The basaltic rocks of the Cairo area have now been studied for over a century (Beadnell 1902, 1905; Andrew 1937; Rittmann 1954). Surface exposures are not extensive, but petroleum exploration wells demonstrate that a continuous sheet of basalt generally 20-80 m thick extends across a subsurface area of at least 15,000 km² (Figure 5; Williams and Small 1984; Bosworth et al. 2015). The original extent of this small "CFV" province prior to uplift and erosion is estimated to be ~25,000 km² (Bosworth et al. 2015).

Kappelman et al. (1992) published the first incremental-heating $^{40}\text{Ar}/^{39}\text{Ar}$ date in Egypt from the base of the basalt flows at Gebel Qatrani (Figure 5). This exposure had previously yielded K-Ar ages of ~25.3 Ma, 27.7 ± 3.0 Ma and 31.0 ± 1.0 Ma (Simons 1967; Simons and Wood 1968; Fleagle et al. 1986). Kappelman et al. (1992) ran three splits from the same whole-rock sample and determined very consistent $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages of 23.67 ± 0.15 Ma, 23.68 ± 0.14 Ma and 23.62 ± 0.16 Ma.

Lotfy et al. (1995) next obtained whole-rock plateau ages of 22.4 Ma and 22.6 Ma for basalt flows of the Cairo area (locations and other details of the dated samples were not given). Bosworth et al. (2015) resampled the ~22 m thick basalt from the Gebel Qatrani section and from base to top determined whole-rock isochron ages of 22.0 ± 0.5 Ma, 21.9 ± 0.6 Ma, and 22.6 ± 0.8 Ma. A small flow east of Cairo in the highly faulted Gebel Qatamiya district (Figures 6,7) produced a whole-rock isochron age of 21.4 ± 0.2 Ma. Integration of all dates from these three studies suggests that the Cairo basalts were erupted over a very brief time period from ~23.5-21.5 Ma.

- West of Nile Cinder Cones, Flows and Dikes

Several linear arrays of monogenetic cinder cones are present in the eastern part of the Western Desert southwest of Gebel Qatrani (Figure 5) and ending west of the Nile River near Asyut (Figure 8). The Eocene and Oligocene strata that cover most of this area are extensively dissected by NW-SE striking extensional faults, similar to the region of Gebel Qatamiya. Outcrop and industry 3D seismic data show that the monogenetic cones were formed above large NW-SE striking feeder dikes, and that during emplacement the dikes caused the formation of overlying linear graben structures (Bosworth et al. 2015).

The small flow at Qaret Dab'a (Figure 8) gave a $^{40}\text{Ar}/^{39}\text{Ar}$ whole-rock plateau age of 23.4 ± 0.4 Ma (Bosworth et al. 2015). Flows associated with monogenetic cones along strike to the northwest produced whole-rock isochron ages of 23.9 ± 1.4 Ma and 21.8 ± 0.5 Ma (Bosworth et al. 2015).

- Bahariya Basalts

The Bahariya depression (Figure 1) is a large, breached anticline that formed during Late Cretaceous ("Syrian arc") shortening and regional inversion (Moustafa et al. 2003).

Subsequently and unrelated to the folding event, basalts were erupted within the depression and on the surrounding Eocene plateau to the west. K-Ar ages of 20 to 15 Ma have been reported for the Bahariya basalts (Meneisy and El Kalioubi 1975; Meneisy and Abdel Aal 1983), and they were therefore interpreted to represent a separate Miocene volcanic phase unrelated to initial opening of the Red Sea (Meneisy 1990; Moustafa et al. 2003).

Bosworth et al. (2015) attempted to date flows from northern and central outcrops of Bahariya. The northern basalts produced two $^{40}\text{Ar}/^{39}\text{Ar}$ whole-rock plateau ages of 23.1 ± 0.2 Ma and 23.6 ± 0.2 Ma. The central flows were somewhat altered and yielded only total fusion dates of 25.0 ± 0.3 Ma, 24.2 ± 0.2 Ma, and 20.8 ± 0.2 Ma. The more reliable plateau ages indicate that the Bahariya basalts do not represent a separate volcanic event, but rather were erupted at the same time as the Cairo and Gulf of Suez basalts within the uncertainties of all the dating.

- Western Desert Graben without Basalt

The Bahariya depression basalt flows are the westernmost Late Cenozoic basalts presently identified in Egypt, either in outcrop or the subsurface. However, NW-SE striking faulting, cutting up to the levels of Oligocene or Miocene strata, is observed in Western Desert seismic datasets. These faults are often similar in style to those described above for west of the Nile, forming very linear graben that continue uninterrupted for many tens of kilometers., as illustrated for the eastern Abu Gharadig basin by Bosworth et al. (2015). They interpreted these structures as having been formed above intruding dikes. The westernmost members of this family of NW-SE graben that we have observed are located on the Libyan Plateau, near the border between Egypt and Libya (Figure 9). Most of this region exposes Miocene strata at the surface. The faults are extremely straight and in several cases over 100 km in length. One cluster of faults starts at the Qattara Depression and continues northwest to a significant step in the coastline. We suggest

that there are very likely large dikes at depth beneath these grabens, probably of the same age as the basalts seen in outcrop further east.

- The Brothers and Zabargad Island Basalts

The Brothers Islands are located 60 km offshore from Quseir, Egypt (Figure 5). The two small islets are comprised of gabbro cut by basaltic dikes and capped by a Pleistocene coral terrace (Taviani et al. 1986). K-Ar dating of the basalts gave an unreasonably broad range of ages: 92.3 ± 7.2 Ma, 44.4 ± 1.8 Ma, and 31.6 ± 3.1 Ma (Bosworth unpubl. data 1993) and were deemed inaccurate and the consequence of alteration.

Zabargad Island and a small satellite Rocky Island are located 50 km southeast of the Ras Banas peninsula (Figure 5). The geology of Zabargad is much more complex than that of the Brothers, with exposures of high-grade gneiss, unserpentinized peridotite, Mesozoic and Cenozoic sedimentary strata, Pleistocene coral terraces, and mafic dikes and sills (El Shazly and Saleeb Roufaiel 1977; Bonatti et al. 1983). Bonatti et al. (1983) first suggested that the Zabargad peridotites represented an important component of Red Sea rifting and proposed that they were emplaced at a depth of ~30 km within the proto-Red Sea rift mantle. Subsequent incipient fracture zone tectonics brought them to their position near sea level. Wernicke (1985) interpreted the island as uplifted constituents of a Red Sea rifting-related metamorphic core complex. Other workers have suggested that the peridotite formed within diapiric asthenospheric upwelling during Red Sea rifting (Nicolas et al. 1987; Boudier et al. 1988). Nicolas et al. (1985) had determined a K-Ar age of 23 ± 7 Ma for amphiboles from an amphibolite adjacent to the peridotites. This would place crystallization well within the general Oligocene-Miocene age of early Red Sea rifting. Isotopic studies by Brueckner et al. (1995) brought into question these models and indicated that at least some of the peridotite is of Neoproterozoic age.

The basalts intruding Zabargad are generally as unhelpful as those at the Brothers. Bosworth et al. (1996) obtained eight K-Ar whole-rock and plagioclase ages for the Zabargad dikes and sills that ranged from 70 to 7 Ma. Villa (1990) dated hornblendes from a basalt dike, a peridotite, a gneiss and a pyroxenite by $^{40}\text{Ar}/^{39}\text{Ar}$ and all produced saddle-shaped age spectra reflective of the presence of excess ^{40}Ar . Total gas ages were 45.0 Ma, 64.4 Ma, 107.2 Ma, and 238.0 Ma, respectively. The basalt age is within the range of K-Ar results obtained at the Brothers and Zabargad but taken together they are clearly not indicative of the timing of basalt emplacement unless a very prolonged intrusion history is envisioned. This is not supported by field relationships.

Bosch and Bruguier (1998) separated five zircon crystals from a felsic gneiss adjacent to the central peridotite and obtained a concordia lower intersection age of 23.2 ± 5.9 Ma. The youngest concordant grain ^{238}U - ^{206}Pb age of 22.4 ± 1.3 Ma was interpreted to be the age of a high-temperature metamorphic event. This metamorphism would be coeval with the extensive dike event described above for the Saudi Red Sea margin.

Harrat ash Shaam, Jordan

The Harrat ash Shaam volcanic field covers over 50,000 km² in northern Saudi Arabia, Jordan and southern Syria (Figures 1,2; Ibrahim 1993, 1996). It is closely associated with the Azraq-Sirhan graben and other related NW-SE striking faults. Ilani et al. (2001) obtained 132 whole-rock K-Ar dates from olivine basalts distributed across the field. Six ages were grouped from 27-22 Ma and were considered to represent the initiation of the volcanism in association with opening of the Red Sea. There is then a gap until ~13 Ma (one age ~40 and one ~14 Ma were discarded) and the majority of the dates fall into this younger period. The renewed volcanic

activity at ~13 Ma (Middle Miocene) was thought to be associated with movement on the Aqaba-Dead Sea transform fault system.

Late Oligocene-Early Miocene Structuration and Syn-rift Deposition

Despite the resolution that is possible when looking at a geologic system that is only about 30 Ma, there remains a fundamental problem with pegging the timing of Red Sea rift initiation itself. Throughout much of northeast Africa, Oligocene strata were deposited in continental, or stressed marginal marine environments. Bosworth et al. (2005; see references therein) compiled data along the length of the Red Sea basin. The immediate pre- or in some cases “proto”-rift strata are all generally of Oligocene age and referred to the Tayiba, Matiyah, Hamamit, and Dogali Formations for the Gulf of Suez, central Saudi margin, Sudan margin and central Eritrea margin respectively. The corresponding earliest syn-rift deposits are the Abu Zenima/Nukhul Formations, Al Wajh Formation, lower Magharsum Group, and lower Habab Formation. All these units are dominated by coarse siliciclastics and often red bed sequences. Microfossil assemblages are commonly poorly preserved and of low diversity due to the stressed environments of deposition. There have been long running debates about the ages of these units and where precisely to place the base-rift unconformity. Micropaleontological studies of exploratory wells and some outcrops have suggested that the oldest syn-rift formations, exclusive of the very southern Red Sea, are ~23 Ma, near the Oligocene-Miocene boundary (Bunter and Abdel Magid 1989; Hughes and Beydoun 1992; McClay et al. 1998; Bosworth et al. 1998; Hughes et al. 1999). Other interpretations have placed the base syn-rift unconformity within the Late Oligocene (Dullo et al. 1983; Bayer et al. 1988; Purser and Hötzel 1988; El-Barkooky and

620 El-Araby 1999; Bosworth and McClay 2001; Jackson et al. 2006; Jackson 2008), or even Early
621 Oligocene (Hughes and Filatoff 1995; Koeshidayatullah et al. 2016).

622 In many locations along the margins of the central and northern Red Sea, Gulf of Suez, and
623 Eastern and Western Deserts of Egypt, the 26.5-22 Ma basalts we have described in this section
624 are found with coeval sedimentary rocks and extensional faults. Precise age dating of the basalts
625 often provides a more definitive means for dating the first appearance of syn-rift strata.

626 In the greater Cairo basalt province, most of the smaller, isolated basalt flows are confined to
627 grabens like those illustrated in Figures 7 and 8. The earliest syn-rift strata are similarly confined
628 to the same grabens. Where the bases of flows are exposed, as at Wadi Tayiba in the northern
629 Gulf of Suez, this either marks or is within a few meters of the base-rift unconformity (Sellwood
630 and Netherwood 1984; Plaziat et al. 1998; Jackson et al. 2006; Jackson 2008). Where flows are
631 not present, cobbles of basalt are often found immediately above the unconformity. The close
632 association of 24-21 Ma basalts, coeval faults and earliest syn-tectonic strata is a recurring
633 attribute of the rift system from southern Saudi Arabia to northern Egypt. Identifying any along-
634 strike time progression or evidence for rift propagation in the existing $^{40}\text{Ar}/^{39}\text{Ar}$ data is difficult
635 and very minor if it did exist. The weighted mean average of 12 plateau ages compiled for Egypt
636 was 23.0 ± 0.1 Ma and for 17 ages from Saudi Arabia it was 21.8 ± 0.03 Ma (Bosworth 2015).
637 The oldest ages in each subset were 24.4 ± 0.3 Ma and 24.5 ± 1.3 Ma, respectively.

638

639 Discussion

640 Burke and Dewey's 1973 proposal that plumes result in the formation of rift-rift-rift triple
641 junctions which in turn can drive continental break-up remains a powerful tectonic model today.
642 From the perspective of deep time the Afar plume and the Gulf of Aden-Red Sea-Ethiopian rift

triple junction would perhaps be a convincing example of this model's usefulness. Living within a phase of this triple junction's evolution enables us to place some qualifiers and details in this interpretation at a time scale not often resolvable in the rock record.

Donato and Coleman (1978) suggested that the ~22 Ma dike swarms and igneous complexes of Tihama Asir represented the initial stage of continental rupture and rifting in the Red Sea. The subsequent efforts of many geochronologists utilizing increasingly reliable dating techniques have enabled later researchers to refine and extend this hypothesis to the entire length of the Red Sea rift (Figure 10). As discussed above this same ~22 Ma igneous event is not recognized in the main Ethiopian rift, and volcanic rocks are not even present along most of the margins of the Gulf of Aden. The temporal evolution of volcanism therefore suggests that the three arms of the rift system probably evolved differently and only post-circa 15 Ma coalesced into a textbook rift triple junction.

Stratigraphic and paleontologic data are in agreement with this basic volcanologically-derived observation. Based on data from offshore wells, Hughes et al. (1991) were the first to demonstrate that syn-rift deposition was ongoing in the central Gulf of Aden sector by ~30-29 Ma. The oldest syn-rift strata exposed in the central Yemen and Oman Gulf of Aden margin are no younger than Early Oligocene (~34-28 Ma) (Watchorn et al. 1998; Robertson and Bamakhalif 1998), though some authors place the base syn-rift unconformity even lower in the stratigraphy (reviewed in Bosworth et al. 2005). The basal syn-rift strata in northern Somalia are only constrained to be Oligocene, but the long-ranging faunas are compatible with an Early Oligocene age (Fantozzi and Sgavetti 1998). Though volcanic rocks are not present, these data demonstrate that continental rifting in the central and eastern Gulf of Aden initiated roughly at the same time as the CFV of Ethiopia, Eritrea and Yemen. This arm of the triple junction matches the Burke

and Dewey model most closely in regard to timing, and the corresponding lithospheric-scale dikes may be hidden in the offshore.

Hughes et al. (1991) also examined a well in the southernmost Red Sea offshore from Eritrea and found that the basal syn-rift section was Late Oligocene, within the range of ~28-23 Ma. Their analysis at that time, and confirmed by many recent studies discussed above, indicated that north of Eritrea the rest of the Red Sea and Gulf of Suez did not experience syn-rift sedimentation until the Early Miocene (23 Ma). The Gulf of Aden – Red Sea continental rift system appears to have opened in a series of pulses, locking briefly at Afar (~30-28 Ma), then northern Eritrea with a coeval incursion into the Ogaden (~28-23 Ma; Mége et al. 2015), and finally quickly reaching Egypt during the 24-21 Ma dike event (Figure 11). Courtillot (1982) proposed similar periods of propagation interrupted by stalled modes during the progression from stretched continental lithosphere to focused oceanic spreading in the Gulf of Aden and southern Red Sea. However the three pulses of continental rifting we describe all predate the oldest oceanic crust of the Gulf of Aden that formed at ~19 Ma (Sahota 1990; Leroy et al. 2004). Van Wijk and Blackman (2005) have numerically modeled the propagating versus stalled modes of rift formation and specifically addressed evolution of the Gulf of Aden spreading centers.

Continental rifting and associated volcanism in the well-exposed southern part of the main Ethiopian rift didn't appear until 18-14 Ma (Ebinger et al. 1993). Both the Ethiopian and Red Sea arms of the triple junction support the role of lithospheric dikes and magmatism envisioned by Burke and Dewey and other workers (e.g. Buck 2006) in the plume-driven continental break-up process, but here the timing is more complex. The Afar region didn't become a true plate-scale triple junction until ~15 My after the appearance of the main continental flood volcanism. The timing of rupture of the Red Sea arm is interpreted to be the result of the emergence of a second,

but much smaller, plume-like feature in northern Egypt at ~24-23 Ma (Bosworth et al. 2015). Rifting in southern Ethiopia may have been triggered by other discrete plume activity in East Africa or perhaps the delayed consequence of one complex superplume (Ebinger and Sleep 1998).

Synthesis

- Intra-plate basaltic volcanism appeared in southern Ethiopia in what would later become the Main Ethiopian rift at ~46 Ma and lasted for about 10 Ma (Figure 11a). Similar age basalts were erupted in southwest Egypt at about the same time. The Ethiopian volcanism is commonly linked to the East African superplume and the Egyptian volcanism may be a more distant, less voluminous manifestation of this same phenomenon.
- After a short hiatus new basaltic eruptions – the main continental flood volcanism – began at ~31Ma over a large part of northern Ethiopia/Eritrea and northwestern Yemen (Figure 11b). This spread to parts of southeast Ethiopia, southern Sudan, Saudi Arabia and most of western Yemen by 30-29 Ma. This period of volcanism was coeval with initial faulting and deposition of syn-rift strata in the Gulf of Aden and hence from a regional perspective is “syn-tectonic” although no or little faulting occurred in the area of the eruptions.
- Rhyolitic volcanism appeared in the Ethiopian traps at ~30 Ma and in Yemen at ~29 Ma (Figure 11c). By about 28 Ma bimodal eruptions were dominant throughout the volcanic province.

- At ~26.5 Ma a local system of basaltic dikes appeared southeast of Afar in the Ogaden region of eastern Ethiopia (Figure 11c). An incipient continental rift was propagating from Afar towards the Indian Ocean but activity ceased by ~22.5 Ma.
- The last eruptions of the CFV occurred at ~26.5 Ma in Yemen and ~25 Ma in Ethiopia. Continental rifting was active at this point along the length of the Gulf of Aden and reaching into present-day offshore Eritrea (Figure 11c). Faulting was still not recorded till this time in the plateau regions of Ethiopia and Yemen. After ~25 Ma extensional faulting commenced in Afar.
- At ~24 Ma basaltic dikes and igneous complexes formed northwest of Afar along the present-day Red Sea margin of Yemen and Saudi Arabia (Figure 11d). Coincidentally a large basaltic volcanic province developed in northern Egypt – the Cairo mini-plume – and in the Harrat ash Shaam region of Jordan. This phase of volcanism culminated from ~24-22 Ma and was accompanied by extensive faulting and deposition of syn-rift strata. This marks the birth of the Red Sea rift. The presence of the sheeted dike and associated plutonic complexes at Al Lith and Asir Tihama suggests that oceanic-like rifting occurred very early and very briefly in the Red Sea rift history in the region close to the Afar plume.
- Large volumes of continental margin magmatic material were never intruded or erupted during the rifting of the central or northern Red Sea nor in the Gulf of Suez. These margins have remained essentially avolcanic throughout their evolution.
- As the amount of magmatism decreased along the length of the Red Sea with distance from the Afar plume, the width of the structurally affected zone increased. At the intersection with Neotethys (the present Mediterranean margin) the extending zone was

briefly 1200 km wide. After 1-2 My deformation in the north collapsed to a narrow rift valley that would become the Gulf of Suez basin.

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Figure Captions

Figure 1. Distribution of Northeast Africa and Arabia Cenozoic volcanism. Sources of >20 Ma ages are discussed in the text. Younger ages are from Camp and Roobol (1992), Coleman (1993), Chazot et al. (1998), Ilani et al. (2001), and Szymanski (2013). Map is modified from Chazot et al. (1998) and Stern and Johnson (2010). Ogaden and Marda region basalts in eastern Ethiopia are from Mège et al. (2015).

Figure 2. Location of detailed figures of greater Red Sea rift system basaltic volcanism and associated faulting. Shaded relief image of the SRTM derived digital elevation model (DEM) from CIAT (version 4) (Jarvis et al. 2008). All subsequent shaded relief images in this paper are from the same source and their projections are geographic (latitude/longitude) on WGS84 datum.

Figure 3. Gilf Kebir Paleogene volcanic province. a) Extent of scattered surface flows, monogenetic cones, explosive craters, plugs, and associated dikes. Location of new $^{40}\text{Ar}/^{39}\text{Ar}$ age date sample 07 GK 01 is shown with purple dot ($23^{\circ} 24' 21.2''\text{N}$; $27^{\circ} 02' 36.8''\text{E}$); K-Ar dates from Franz et al. (1987) are shown with triangles. “El-Baz” is an early discovered large crater (El-Baz 1981). Landsat image from Google Earth. b) Example of small basalt flows and elliptical explosive craters. DigitalGlobe image from Google Earth. c) Elliptical explosive crater with exposed central basalt plug. The crater is 400 m across in this view. Position from which photographs were taken is shown in ‘b’. d) field view of sample 07 GK 01 location looking NW; small knob is 500 m distant and 140 m wide at its base. e) whole-rock $^{40}\text{Ar}/^{39}\text{Ar}$ step-heating

spectrum and isochron for sample 07 GK 01 (analytical details are the same as those described in Bosworth et al. 2015).

Figure 4. Marda fault zone and volcanic rocks in the Ogaden region of Ethiopia on shaded relief DEM image. Location of Late Oligocene and Late Miocene basalt flows are from Mège et al. (2015). Age of the Bulobarde volcanics is uncertain (Ali Kassim et al. 1992). White dashed lines outline the reactivated Marda fault zone and associated late Cenozoic dikes.

Figure 5. Location map for exposures of basalts in the Gulf of Suez and Egyptian Red Sea margin referred to in the text. None of these occurrences are large enough to plot their actual extent. Shaded relief DEM image.

Figure 6. NW-SE early Red Sea faulting in the region between Cairo and Suez, Egypt. East-west trending structures are inherited from Neotethyan rifting and subsequent compressional events related to convergence of Africa and Eurasia. Shaded relief DEM image.

Figure 7. Detail of Cairo-Suez faulting and basaltic volcanism at Gebel Qatamiya. SW-NE cross-section passes near to small basalt outcrop dated by $^{40}\text{Ar}/^{39}\text{Ar}$ (21.5 ± 0.2 Ma plateau age; Bosworth et al. 2015). Location of map is shown in Figure 6. DigitalGlobe image from Google Earth.

Figure 8. NW-SE early Red Sea faulting and basaltic volcanism in the Eastern Desert and Nile Valley near Asyut. Except for recent alluvium in the Nile River Valley most of the surface in this

1282 area is underlain by resistant Middle and Early Eocene limestone (a small area of underlying
1283 Late Cretaceous strata appears in the NE below the South Galala Plateau). Small basalt
1284 exposures occur at Gebel Gibeil and Qaret Dab'a ($^{40}\text{Ar}/^{39}\text{Ar}$ age date is from Bosworth et al.
1285 2015). Shaded relief DEM image.

1286
1287 Figure 9. NW-SE early Red Sea related faulting in the far Western Desert of Egypt and on the
1288 Libyan Plateau. Similar structures exist in the eastern part of the Western Desert and are
1289 associated with the extensive Cairo basalt flows and dikes. Most of the surface in the Libyan
1290 Plateau and far Western Desert exposes Early to Middle Miocene limestone. Yellow arrows
1291 point to the subtle surface expression of several of the faults that align with a step in the coastline
1292 and the young coastal fault system. Shaded relief DEM image.

1293
1294 Figure 10. Compilation of $^{40}\text{Ar}/^{39}\text{Ar}$ radiometric age dates for the greater Red Sea rift versus
1295 latitude. ^{238}U - ^{206}Pb data are included for Zabargad Island (Bosch and Bruguier 1998). Heights of
1296 individual boxes capture published uncertainties (usually 2σ) except for the continental flood
1297 volcanism (CFV) and younger magmatic rocks of Ethiopia and the basalts from Cairo and
1298 Bahariya which are composites of numerous samples. Expanded and updated from Bosworth et
1299 al. (2005). Sources of data are listed in the text.

1300
1301 Figure 11. Paleogeographic maps for the early phases of the northern Afro-Arabian rift system.
1302 a) 46-34 Ma; b) 31-30 Ma; c) 30-25 Ma; d) 24-21 Ma. Continental rifting began in the Gulf of
1303 Aden at ~31-30 Ma whereas most of the Red Sea and areas to the north didn't undergo extension
1304 until ~24-23 Ma. A brief volcanic/rift event appeared in the Ogaden in the mid-Oligocene but

1305 was aborted by ~22.5 Ma (Mège et al. 2015). Similarly the widespread volcanism and faulting
1306 near the Neotethyan margin ceased by ~22 Ma and collapsed to just the confines of the Gulf of
1307 Suez. Maps b, c, and d are modified from Bosworth (2015).

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Figure 1. Distribution of Northeast Africa and Arabia Cenozoic volcanism. Sources of >20 Ma ages are discussed in the text. Younger ages are from Camp and Roobol (1992), Coleman (1993), Chazot et al. (1998), Ilani et al. (2001), and Szymanski (2013). Map is modified from Chazot et al. (1998) and Stern and Johnson (2010). Ogaden and Marda region basalts in eastern Ethiopia are from Mège et al. (2015).
146x243mm (300 x 300 DPI)

Figure 2. Location of detailed figures of greater Red Sea rift system basaltic volcanism and associated faulting. Shaded relief image of the SRTM derived digital elevation model (DEM) from CIAT (version 4) (Jarvis et al., 2008). All subsequent shaded relief images in this paper are from the same source and their projections are geographic (latitude/longitude) on WGS84 datum.
264x351mm (300 x 300 DPI)

Figure 3. Gilf Kebir Paleogene volcanic province. a) Extent of scattered surface flows, monogenetic cones, explosive craters, plugs, and associated dikes. Location of new 40Ar/39Ar age date sample 07 GK 01 is shown with purple dot (23° 24' 21.2"N; 27° 02' 36.8"E); K-Ar dates from Franz et al. (1987) are shown with triangles. "El-Baz" is an early discovered large crater (El-Baz 1981). Landsat image from Google Earth. b) Example of small basalt flows and elliptical explosive craters. DigitalGlobe image from Google Earth. c) Elliptical explosive crater with exposed central basalt plug. The crater is 400 m across in this view. Position from which photographs were taken is shown in 'b'. d) field view of sample 07 GK 01 location looking NW; small knob is 500 m distant and 140 m wide at its base.
409x268mm (300 x 300 DPI)

e) whole-rock $^{40}\text{Ar}/^{39}\text{Ar}$ step-heating spectrum and isochron for sample 07 GK 01 (analytical details are the same as those described in Bosworth et al., 2015).
 361x626mm (72 x 72 DPI)

Figure 4. Marda fault zone and volcanic rocks in the Ogaden region of Ethiopia on shaded relief DEM image. Location of Late Oligocene and Late Miocene basalt flows are from Mège et al. (2015). Age of the Bulobarde volcanics is uncertain (Ali Kassim et al., 1992). White dashed lines outline the reactivated Marda fault zone and associated late Cenozoic dikes.
295x261mm (300 x 300 DPI)

Figure 5. Location map for exposures of basalts in the Gulf of Suez and Egyptian Red Sea margin referred to in the text. None of these occurrences are large enough to plot their actual extent. Shaded relief DEM image.

261x351mm (300 x 300 DPI)

Figure 6. NW-SE early Red Sea faulting in the region between Cairo and Suez, Egypt. East-west trending structures are inherited from Neotethyan rifting and subsequent compressional events related to convergence of Africa and Eurasia. Shaded relief DEM image.
1436x992mm (72 x 72 DPI)

Figure 7. Detail of Cairo-Suez faulting and basaltic volcanism at Gebel Qatamiya. SW-NE cross-section passes near to small basalt outcrop dated by $^{40}\text{Ar}/^{39}\text{Ar}$ (21.5 ± 0.2 Ma plateau age; Bosworth et al., 2015). Location of map is shown in Figure 6. DigitalGlobe image from Google Earth.
491x450mm (300 x 300 DPI)

Figure 8. NW-SE early Red Sea faulting and basaltic volcanism in the Eastern Desert and Nile Valley near Asyut. Except for recent alluvium in the Nile River Valley most of the surface in this area is underlain by resistant Middle and Early Eocene limestone (a small area of underlying Late Cretaceous strata appears in the NE below the South Galala Plateau). A small basalt exposure occurs at Gebel Gibeil. Shaded relief DEM image.
1022x957mm (72 x 72 DPI)

Figure 9. NW-SE early Red Sea related faulting in the far Western Desert of Egypt and on the Libyan Plateau. Similar structures exist in the eastern part of the Western Desert and are associated with the extensive Cairo basalt flows and dikes. Most of the surface in the Libyan Plateau and far Western Desert exposes Early to Middle Miocene limestone. Yellow arrows point to the subtle surface expression of several of the faults that align with a step in the coastline and the young coastal fault system. Shaded relief DEM image.

1343x1044mm (72 x 72 DPI)

Figure 10. Compilation of $^{40}\text{Ar}/^{39}\text{Ar}$ radiometric age dates for the greater Red Sea rift versus latitude. ^{238}U - ^{206}Pb data are included for Zabargad Island (Bosch and Bruguier, 1998). Heights of individual boxes capture published uncertainties (usually 2σ) except for the continental flood volcanism (CFV) and younger magmatic rocks of Ethiopia and the basalts from Cairo and Bahariya which are composites of numerous samples. Expanded and updated from Bosworth et al. (2005). Sources of data are listed in the text.

Figure 11. Paleogeographic maps for the early phases of the northern Afro-Arabian rift system. a) 46-34 Ma; b) 31-30 Ma; c) 30-25 Ma; d) 24-21 Ma. Continental rifting began in the Gulf of Aden at ~31-30 Ma whereas most of the Red Sea and areas to the north didn't undergo extension until ~24-23 Ma. A brief volcanic/rift event appeared in the Ogaden in the mid-Oligocene but was aborted by ~22.5 Ma (Mège et al., 2015).

Similarly the widespread volcanism and faulting near the Neotethyan margin ceased by ~22 Ma and collapsed to just the confines of the Gulf of Suez. Maps b, c, and d are modified from Bosworth (2015).

426x397mm (300 x 300 DPI)