The Red Sea: Birth of an Ocean

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Abstract

Nowhere on the present-day Earth can the transition from a continental to an oceanic rift be observed and studied better than in the Red Sea region, where three rifts in different stages of evolution meet in a triple point located in the Afar region. A thermal and/or compositional mantle plume may have risen from the upper mantle below Afar already at ∼30 Ma, and may have triggered, at least in part, the rifting process. The axial area of the rifts is marked by intense seismicity. While the East African is a fully continental rift, the Gulf of Aden rift experienced oceanic crust accretion between Arabia and Somalia starting already at 17 Ma with a progressive westward propagation that impacted against Africa in the Afar Triangle starting at <1 Ma. The axial zone of oceanic crustal accretion in the Gulf of Aden is segmented by several small (<30 km) offsets, including two major transform-fracture zones, the Socotra (offset ∼50 km) and the Alula-Fartak (offset 180 km). Spreading is asymmetric, faster in the northern (Arabia) side (11–13 mm/a) than in the southern (Somalia) side (8 mm/a). The Afar Triangle is a topographically depressed region, located between the continental blocks of Nubia, Somalia, and the Danakil Alps, that separate it from the southern Red Sea. It is an area of thin crust, seismicity related to extension, and intense intrusive and extrusive, mostly basaltic, magmatism. Intrusive basaltic magmatism appears to be important in triggering the rifting process in Afar. Northern Afar displays basaltic ranges oriented parallel to the axis of the Red Sea, such as the Erta Ale, with a crestal permanent lava lake. These ranges represent an incipient oceanic accretionary plate boundary separating Africa from Arabia. At the northern tip of Afar, the plate boundary is displaced to the axial zone of the southern Red Sea, an elongated basin oriented ∼N30°W. Its southern part is characterized by an axial rift valley floored by oceanic basalt and accompanied by parallel Vine-Matthews magnetic anomalies,

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suggesting initial oceanic crust accretion at ~5 Ma, although alternative interpretations suggest that the entire width of the southern Red Sea is underlain by oceanic crust. Moving still farther north, the axial valley becomes discontinuous and the initial accretion of oceanic crust appears to take place in discrete cells that become younger northward. Propagation from these initial nuclei will result in a continuous axial zone of oceanic accretion. Some of these axial "deeps" are the locus of intense hydrothermal activity and metallogenesis. Moving north, the oceanic rift impacts against the Zabargad fracture zone, a major topographic-structural feature that crosses the Red Sea in a NNE direction, offsetting its axis by nearly 100 km. Zabargad island, located at the SSW end of the fracture zone, exposes a sliver of sub-Red Sea lithosphere, including mantle peridotite bodies, Pan-African granitic gneisses criss-crossed by basaltic dykes, gabbro intrusions, and a sedimentary sequence starting with pre-rift Cretaceous deposits. North of the Zabargad Fracture zone, the Red Sea lacks an axial rift valley; it probably consists of extended thinned and faulted continental crust injected by gabbros and basaltic dykes. The activation of the NNE-trending Aqaba-Dead Sea fault at about 14 Ma has deactivated rifting in the Gulf of Suez. Basalt chemistry suggests that the degree of melting of the Red Sea subaxial mantle decreases from south to north, in parallel with a decreasing spreading rate and a lesser influence of the Afar plume.

Introduction

For over two billion years, the Earth's internal engine has fueled a cyclical process, whereby continents assemble in a single "Supercontinent", and then gradually fragment and disperse again. An even cursory look at a globe shows that at present we are in a phase when a number of continental blocks are scattered seemingly at random on the surface of our Planet. Reconstructions of the geological past suggest that continental masses were last assembled in a single Supercontinent, called Pangea, roughly from 250 to 150 Ma. An entire cycle of continental breakup, dispersal, and reassembly lasts roughly 500 million years. A fundamental step in this "Wilson Cycle" (named after the great Canadian earth scientist Tuzo Wilson, a key figure in the Plate Tectonics scientific revolution) is the splitting of a continent and the birth and growth of a new ocean.

Understanding the processes that occur during the transition from a continental to an oceanic rift, the earliest stages of seafloor spreading, and the formation of passive margins, has been for years a major challenge in the Earth sciences. Nowhere in today's Earth are these events better displayed that in the Red Sea region where Arabia is in the process of splitting form Africa (Figs. 1, 2 and 3). Here, within one and the same region, we find a network of rift zones in different stages of evolution, from fully continental (East African), to "pre-oceanic" (Afar and northern Red Sea), to oceanic (southern Red Sea and Gulf of Aden). The three rifts meet in the Afar region in a classical "triple point". A thermal and/or compositional mantle plume may have risen below this region as early as at ~30 Ma, causing massive volcanism. Plate tectonic reconstructions suggest that, while emplacement of oceanic crust initiated as early as at 17 Ma in the eastern Gulf of Aden, it started more recently (at ~5 Ma) in the Southern Red Sea, but has not yet started in the northern Red Sea. Although different parts of this system have been the object of many studies, a number of key aspects remain poorly known. Adjacent to the southern part of the Red Sea on the African side lies the northern Afar Triangle, a piece of dry land partly below sea level, located between the Eritrean-Ethiopian plateaus and a coastal range (Danakil Alps) that reaches up to over 2,000 m above sea level.

The Red Sea has been the object of some very early geological reasoning. For instance, Herodotus, discussing the Red Sea in his "Histories" (~400 BC), provides us with some of the earliest speculations concerning the importance of "geological time" (Rawlinson 1858):

> …Suppose now that the Nile should change its course and flow into this gulf, the Red Sea: what is to prevent it from being silted up by the river within, say, twenty thousand years? Personally I think even ten thousand would be enough. That being so, surely in the vast stretch of time which has passed before I was born, a much bigger gulf than this could have been turned into dry land by the silt brought down by the Nile, for the Nile is a great river and does, in fact, work great changes…

Jumping over 2,000 years, we reach Alfred Wegener, who early in the last century pioneered the concept of Continental Drift. Wegener realized that the Red Sea is a young oceanic rift formed by the separation of Arabia from Africa. He also understood that the Afar Triangle obstructs any attempt to fit the African and Arabian coastlines; he therefore suggested that the Afar region must have developed by volcanism that took place during and after the separation of the two continental blocks: A remarkable intuition, particularly since at that time information on the geology of Afar was very scant. It is worth citing a few

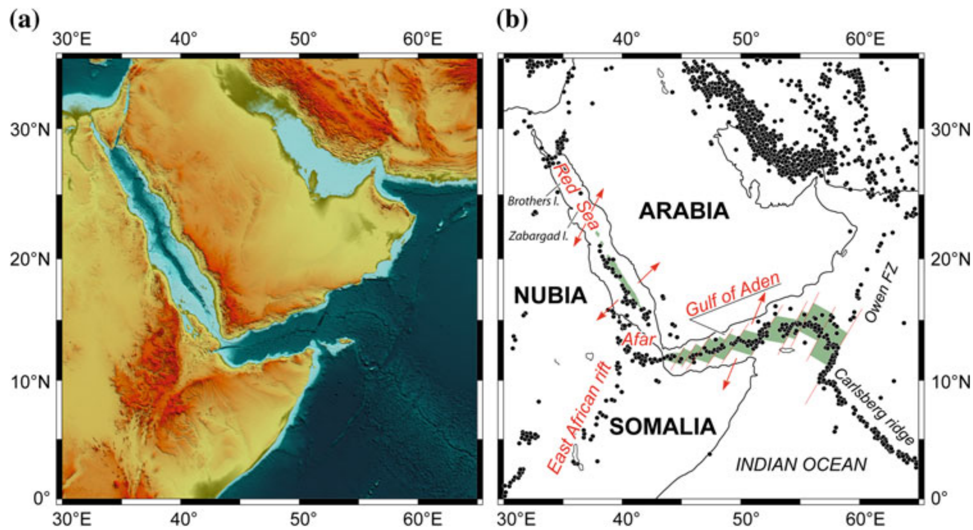

Fig. 1 **a** Red Sea–Afar–Gulf of Aden–East African Rift region. **b** Distribution of earthquakes. Areas underlain by oceanic crust are *dark shaded*. Spatial analysis and mapping were performed using the GMT (Wessel and Smith 1995) and PLOTMAP (Ligi and Bortoluzzi 1989) packages

paragraphs and reproducing an illustration (our Fig. 2) from the 4th edition of Wegener's classic "The Origin of Continents and Oceans" (Wegener 1929).

> "The finest examples of such faults are provided by the East African grabens [rift valleys]. They belong to a large fault system which can be traced northwards through the Red Sea, the Gulf of Aqaba and the Jordan Valley to the edge of the Taurus fold range (Fig. 50). According to recent investigations, these faults are continuing south-wards also, as far as the Cape Province, but the finest examples of them are to be found in eastern Africa. Neumayr-Uhlig (183) describes them approximately as follows:
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> From the mouth of the Zambesi, a 50–80 km wide graben of this type, runs north, including the Shiré River and Lake Nyasa, then turns northwest and disappears. In its place, close by and parallel to it, begins the graben of Lake Tanganyka, whose grandeur is indicated by the fact the depth of the lake is 1700–2700 m, but the height of the wall-like precipice 2000–2400, even 3000 m. In its northerly continuation, this rift valley includes the Russisi River, Lake Kivu, Lake Edward and Lake Albert." He goes on "The margins of the valley appear ridged as if the earth had burst here with a certain upward movement of the fault margins as they were suddenly released. This peculiar protrusive shape of the edges of the plateau may well be connected with the fact that immediately east of Lake Tanganyka the sources of the Blue Nile are located, while the lake itself drains into the Congo River. A third prominent rift valley begins east of Lake Victoria, including Lake Rudolf farther north and turning near Abyssinia towards the northeast, where it continues on to the Red Sea on one side and the Gulf of Aden on the other. In the coastal region and in the interior of what was formerly German east Africa, these faults mostly take the form of step faults whose eastern side is downthrown.
>
> Of special interest is the large triangle, marked in Fig. 50 by dots in the same way as the valley floors, which lies in the angle formed by Abyssinia and the Somali peninsula (between Ankober, Berbera and Massawa). This relatively flat, low-lying area is composed entirely of recent volcanic lavas. Most authors regard it as a vast broadening of the rift floor. This idea is suggested particularly by the shape of the coastlines on either side of the Red Sea, whose otherwise accurate parallelism is spoilt by this salient; if one cuts this triangle out, the opposite corner of Arabia fits perfectly into the gap."

The intuitions of Wegener have been confirmed by field work carried out in the Gulf of Aden, Afar, and the Red Sea particularly in the second half of last century, in parallel with the establishment of the theory of Plate Tectonics. Some of this early work includes Cochran (1981) and Girdler and Styles (1978) for the Gulf of Aden, the C.N.R.-C.N.R.S. Afar Team (1971) for the Afar Rift, and Girdler and Styles (1974), Coleman (1974) and Cochran (1983) for the Red Sea.

In this chapter, we will provide a brief introduction to our knowledge of the Gulf of Aden, Afar, and the Red Sea Rifts.

Gulf of Aden Rift

Of the three rifts that converge toward the Afar region, the Gulf of Aden rift involved the gradual development of a new accretionary plate boundary between Arabia and Somalia. The axial zone of the Gulf of Aden displays oceanic spreading segments (Fig. 3) offset frequently by transform faults (Cochran 1981) and floored by MORB-type basalts, with a mild Afar Plume signature (Cann 1970; Schilling et al. 1992). Vine-Matthews magnetic stripes accompany the axial oceanic zone, indicating a spreading direction (N37°E) oblique to the general trend of the spreading center (N90°E). In addition to several small (<30 km) transform offsets, at least two major transform-fracture zones offset the Gulf of Aden axial rift zone, that is, the Socotra FZ at 55°E (offset ~50 km) and the Alula-Fartak FZ at 52°E (offset 180 km) (Tamsett and Searle 1990). Both these transforms have a strong topographic signature, including "nodal deeps"; their extension merges with offsets of the Somali and Arabian continental margins, suggesting that they were active already

Fig. 2 Map of the Red Sea region, taken from Fig. 50 of Alfred Wegener "Origin of Continents and Oceans", 4° edition (1929)

during the initial opening. The oldest conjugate magnetic anomaly of the eastern part of the Gulf of Aden (east of the Alula-Fartak F.Z.) has been identified as anomaly 5d, suggesting that seafloor spreading in this part of the Gulf of Aden started already at 17.6 Ma (Leroy et al. 2004). Spreading in the eastern Gulf of Aden has been strongly asymmetric (Leroy et al. 2004), faster on the northern (Arabian) side (11–13 mm yr^{-1}) than on the southern (Somalia) side (8 mm yr^{-1}) (d'Acremont et al. 2006). The oldest anomalies become progressively younger moving from east to west, indicating that the initial emplacement of oceanic crust propagated westward. Moving west from the Alula-Fartak FZ, the oldest magnetic anomalies are ~10 Ma, while west of about 45°E the zone of oceanic crust accretion becomes limited to a narrow axial strip. West of ~44°E regular magnetic stripes have not been clearly identified; axial emplacement of oceanic crust may have just started (Hébert et al. 2001).

The Gulf of Aden rift propagates then into the Gulf of Tadjoura and penetrates into the Afar region in the Goubet-Asal rift (Fig. 4), a ~40 km long, highly seismic segment, with intense axial basaltic volcanism and a system of extensional fissures and faults (Fig. 5) flanking the axial neovolcanic zone (Harrison et al. 1975; Manighetti et al. 1997, 1998; Pinzuti et al. 2013). The Goubet-Asal rift opens at a rate of 1.6 cm yr^{-1} in a N40°E direction, and terminates in Lake Asal, a saline lake whose surface is below sea level.

Afar Rift

The Afar region is the locus of a "textbook" triple junction, where the East African Rift, the Gulf of Aden Rift, and the Red Sea Rift converge and meet (Fig. 1). The entire region is covered by fissure basalts, scattered central volcanic cones, and major volcanic ranges, located particularly in the northern part of the region.

The northern part of Afar is a depression (with wide areas below present-day sea level) located between the Ethiopian–Eritrean plateau to the west and the Danakil Alps to the east. The Danakil Block consists of units of Precambrian continental lithosphere overlain by a pre-rift sedimentary sequence including Mesozoic sandstones and limestones. The Danakil Block rotated anticlockwise by about 23° since its separation from the Ethiopian Plateau, being pinned to Africa near the Gulf of Zula and to Arabia in the Bab-al-Mandab area. En échélon elongated volcanic ranges oriented parallel to the Red Sea rift occupy the axial zone of northern Afar. The northernmost and largest is the Erta Ale range, first described by Barberi and Varet (1977), made of recent basalts, and displaying a permanent lava lake on its summit (Fig. 6). An unusually shallow (~1 km) magma chamber has been identified below the summit of the Erta Ale (Pagli et al. 2012). South of the Erta Ale we find two other parallel axial basaltic ranges, that is, Tat Ali and Alayta (Figs. 4 and 6). The basaltic floor of the depression is dissected by extensional faults and fissures oriented parallel to the Red Sea axis; it is affected by widespread fissural basaltic volcanism (Fig. 7a, b) and intense hydrothermal activity. A relatively large lake, lake Afrera (Fig. 6b), lies south of Erta Ale; it is fed by hydrothermal springs and its salinity reaches 158 g/l (Martini 1969). The surface of the lake lies about 100 m below sea level. Unpublished bathymetric lines revealed a >60 m deep trench oriented NNE in the lake's southern basin; thus, the lake's floor may include the lowest point of the entire Afar region. NW of Erta Ale, close to the scarp of the Ethiopian Plateau, iron-manganese deposits have been described; they were probably formed by submarine hydrothermal activity (Bonatti et al. 1972). North of the Erta Ale range the axial part of the rift is covered by a flat salt plain (Fig. 8a); the thickness of the evaporites is >1 km. These evaporites may be related to various episodes of marine invasion and desiccation of northern Afar. The evaporites are uplifted and metamorphosed by hydrothermal activity in a limited area (called Dallol) located near the center of the salt plain (Fig. 8b, c).

Dozens of small (few hundred meters high, up to 1 km in diameter) circular volcanoes are scattered in the northern/central Afar region. They are characterized by a low (<0.5)

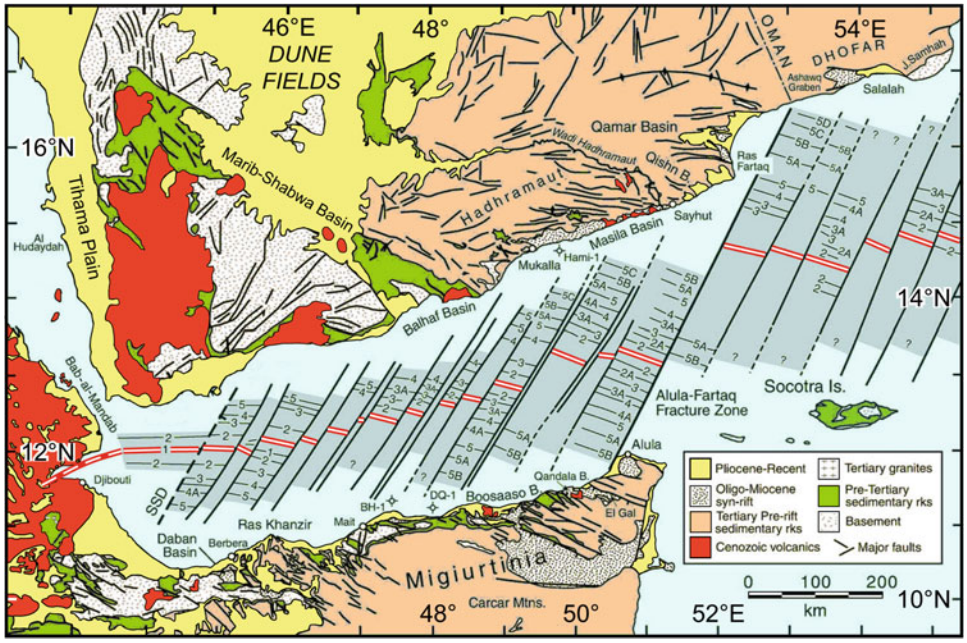

Fig. 3 Gulf of Aden spreading centers, transform faults and magnetic anomalies (modified from Bosworth et al. 2005)

height/diameter ratio, lower than that of subaerial pyroclastic cones. They are made prevalently of shattered basaltic glass fragments (hyaloclastites), frequently well stratified (Figs. 9 and 10), containing also dispersed crystallized basalt blocks. These volcanoes were probably formed by submarine basaltic eruptions. One of them, located close to the northern shore of Lake Afrera, is capped by shallow water marine carbonates (Fig. 10b). Facies analysis as well ^{14}C and U-Th dating of these carbonates suggest they were deposited roughly 30 ka, before the last desiccation of northern Afar (Bonatti et al. 1971). At least one of these small volcanoes has a flat top (Fig. 9b–d) and resembles a “mini-guyot”. The flat top is not due to erosion and truncation at sea level, as in classical Pacific guyots, but rather to horizontal deposition of basaltic pyroclastics injected into sea water by explosive submarine eruptions (Bonatti and Tazieff 1970). Another volcano has flanks consisting of stratified hyaloclastites due to submarine eruptions, capped by dark massive basalts that were probably erupted subaerially (Fig. 10a).

The axial basaltic ranges of northern Afar are oriented NNW, parallel to the Red Sea axis; however, they are offset in a few places along NNE lineaments (Barberi et al. 1974) that may correspond to offsets in the scarps of the Ethiopian Plateau. Small volcanic cones have been observed aligned NNE, at an angle to the direction of the axial rift. In contrast to the axial ranges, they are composed of alkali basalts, occasionally containing ultramafic xenoliths.

The axial zone of northern Afar marks probably an incipient plate boundary between the Nubian and Arabian plates. Thus, although geographically part of Africa, the eastern portion of northern Afar, including the Danakil Alps, belongs to the Arabian plate. The distribution of seismic events suggests that the accretionary plate boundary is displaced at around 14°N from the northern tip of Afar to the Red Sea axis, along what is probably an embryonic transform system (Fig. 1).

A series of seismic-magmatic events starting in September 2005 might clarify how extension and rupturing of the crust may occur in Afar (Wright et al. 2006; Ebinger et al. 2008; Keir et al. 2009). A large number of seismic events clustered in a limited area between the Gabbo and Dabbahu volcanic systems of Central Afar (Fig. 1). Seismicity reached a maximum from September 24–26, with magnitudes up to 5.6. At the same time, small basaltic eruptions took place along fissures close to the Dabbahu volcano, and a number of fractures opened along a 60 km segment between the two volcanoes (Fig. 7c, d). Magma intruded along this 60 km long segment formed a megadyke located between 2 and 9 km below the surface, that weakened the lithosphere leading to extension and breaking of the crust (Keir et al. 2009). Additional intrusive-volcanic events followed (Ferguson et al. 2010, 2013a, b), suggesting that opening of a rift can be “active”, that is, determined initially by magmatic events at depth, that can result in breakup of the crust and extensional faulting close to the surface.

Red Sea

The Red Sea fills a long (about 2,250 km) and narrow (up to 350 km wide) depression that separates Africa from Arabia (Fig. 2). Much of the Red Sea is only a few hundred meters

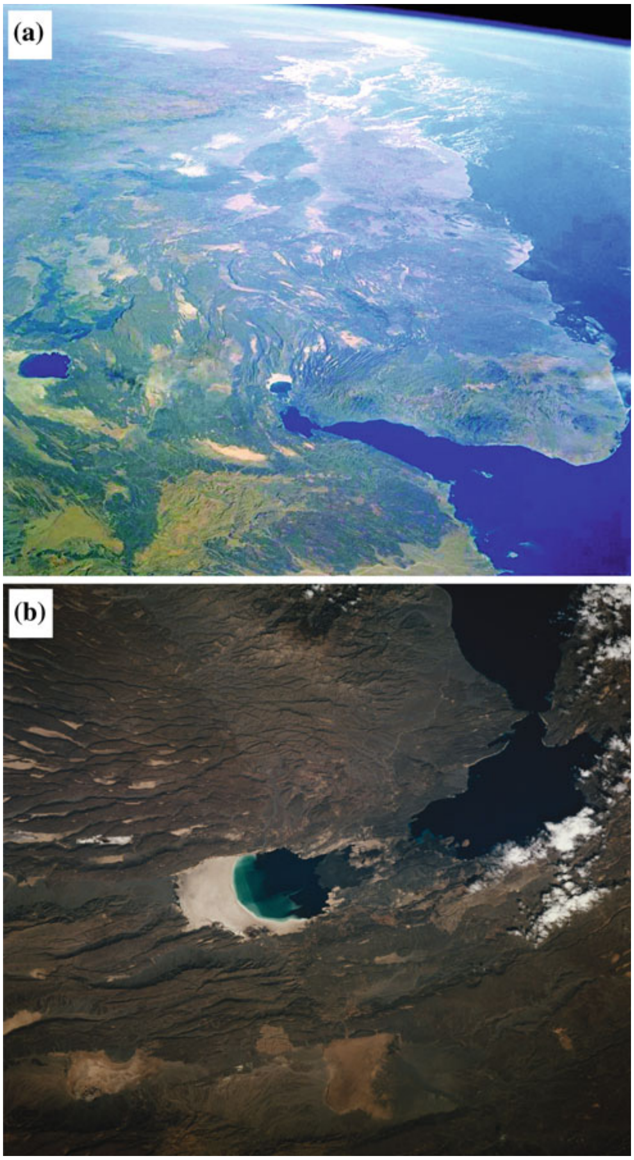

Fig. 4 **a** Satellite image of the Afar region (view toward north), showing the Gulf of Tadjoura and the Ghoubbet–Asal rift, where the Gulf of Aden rift impacts the African continent. **b** Image of the Ghoubbet–Asal rift

deep, except for the floor of a narrow valley that runs almost continuously along its axis, reaching depths of over 2,000 m. The Red Sea connects in the south with the Gulf of Aden–Indian Ocean through the Strait of Bab-al-Mandab, where the seafloor reaches a maximum depth of 120 m. The average strike of the Red Sea from Suez to the Strait of Bab-al-Mandab is N30°W; however, the orientation of the Red Sea axial zone shows a few discontinuities (Crane and Bonatti 1987), with stretches oriented ~5°–10°N, that is, parallel to the Aqaba–Dead Sea transform (Fig. 1), that became active at roughly 14 Ma, causing the deactivation of the Suez rift (Bosworth et al. 2005). The Zabargad Fracture Zone is the most prominent of these discontinuities.

Southern Red Sea Region

Seismicity in the Red Sea axial zone is intense between 17°N and 19°N; south of 15°N it is displaced in northern Afar, while north of 20°N seismicity is nearly absent (Fig. 1). The seismic axial zone of the southern Red Sea from about 15°N to 20°N displays a ~300 km long nearly continuous rift valley, the floor of which reaches ~2,200 m below sea level. The floor of the valley is nearly free of sediments, and is covered by basalt with MORB affinity (Juteau et al. 1983; Essien et al. 1989). A detailed magnetic survey (Roeser 1975) revealed a pattern of well-formed, parallel Vine-Matthews magnetic anomalies (Fig. 11a) that allowed the identification of a set of isochrons. The oldest anomalies are about 5 Ma at around 18°N but are younger toward the tips of the axial trough stretch, hinting at the possibility of axial propagation of the zone of oceanic crust accretion. Spreading rates range between 0.6 and 1.0 cm yr^{-1}. Spreading appears to be asymmetric at around 17°N, with rates about 70 % higher on the western, African Side. According to Girdler and Styles (1974) and to LaBrecque and Zitellini (1985), accretion of oceanic crust and sea floor spreading occurred in the southern Red Sea in two stages, the first taking place already at about 30 Ma. This view, based in part on the presence of magnetic anomalies along the margins of the Red Sea, implies that the entire width of the Red Sea is underlain by oceanic crust. Other authors interpret "marginal" magnetic anomalies as caused by basaltic dykes emplaced in the stretched continental crust, similar to those outcropping in the coastal areas of Saudi Arabia. This alternative view implies a southern Red Sea oceanic crust accretion limited to <5 Ma (Cochran 1983; Bonatti 1985).

Multideeps Red Sea Region

Moving north from about 20°N, the axial zone of the Red Sea is characterized by a number of discontinuous deeps with a complex morphology and depths reaching over 2,000 m. The two largest are Atlantis II Deep and Discovery Deep. They became the focus of much interest in the 1960s because it was found that they contain dense, hot brines as well as hydrothermal metalliferous deposits (Degens and Ross 1969). Some of the brines have temperatures >50 °C. This discovery occurred years before hydrothermal activity

Fig. 5 Open fissures in basalts moving progressively away from the axial neo-volcanic zone in the Ghoubbet–Asal rift. Basalts in **a**, **b** display a "polygonal" surface typical of submarine eruptions. **c** Open fissure; **d** fissure with vertical offset

and metallogenesis were observed along mid-ocean ridges. The presence of dense, hot brines in topographic depressions within the deeps may be related to sea water having circulated within evaporite deposits and having acquired a high salinity. In this, Red Sea hydrothermal fluids differ from those observed along mid-ocean ridges that generally are not highly saline. Deposits from the brines include (Fig. 12) abundant Fe-sulfides, often enriched in Zn and Cu, Fe-hydroxides (goethite), Fe-montorillonite, Mn-oxides and hydroxides, manganosiderite and anhydrite (Bischoff 1969).

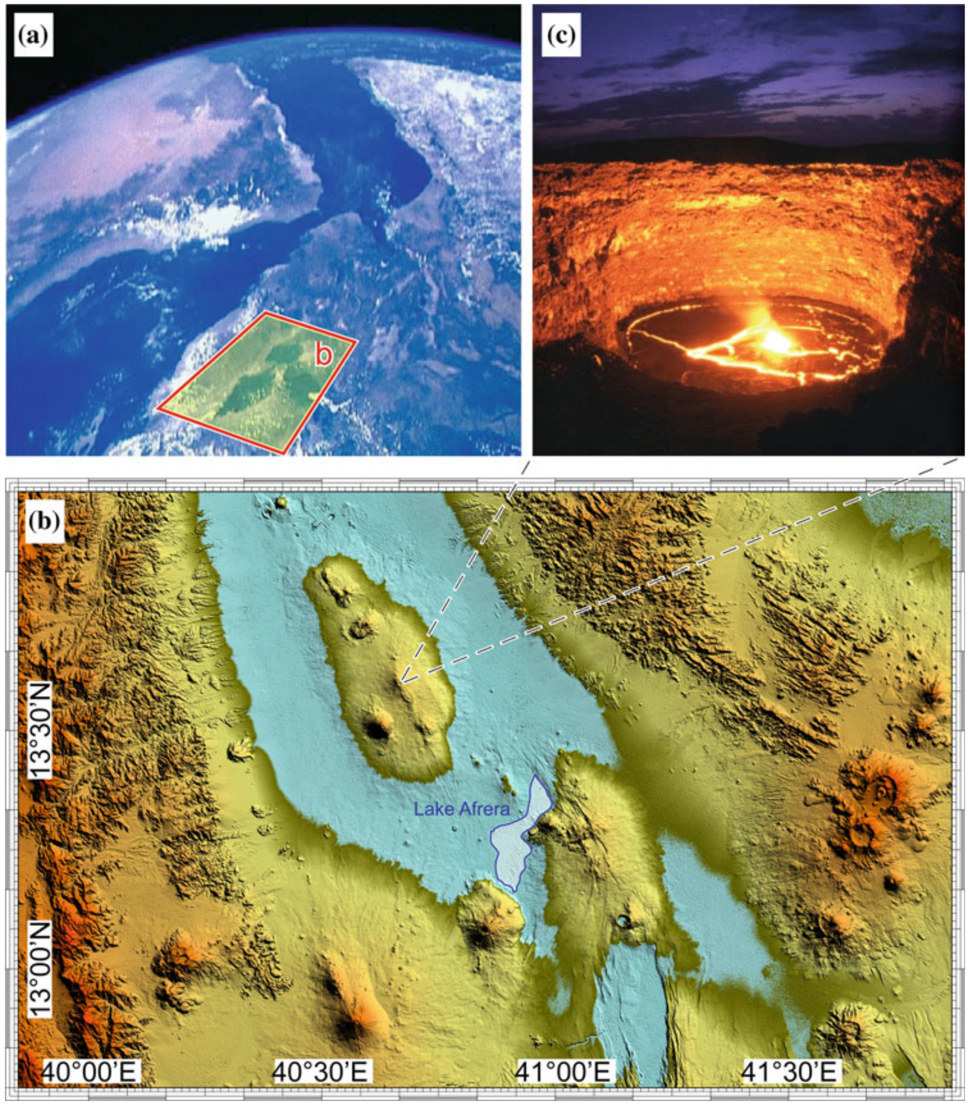

Fig. 6 **a** Satellite image of Afar. The Erta Ale, Tat Ali, and Alayata volcanic systems are clearly visible in the inset. **b** Erta Ale ridge. Zone in the vicinity of the Erta Ale, with areas below sea level in cyan. **c** Lava lake on the summit of Erta Ale

Transitional Red Sea Region

Moving north from about 21°N, we enter a region where a number of discrete axial troughs with high amplitude magnetic anomalies are separated by inter-trough zones that lack an axial rift valley and magnetic anomalies and have a thick continuous sediment cover across the axis. The width and length of the trough segments decrease moving north. From south to north, the axial deeps are known as Hadarba, Thetis, Nereus, and Bannock (Fig. 11b). Ligi et al. (2012, this volume) have described the Thetis and Nereus segments. The Thetis deep originated from the coalescence of three sub-basins that become smaller and shallower moving from south to north. Accretion of oceanic crust started at about 2.2 Ma in the southernmost sub-basin where a ~4 km deep magma chamber has been detected, 1.5 Ma in the central sub-basin, and <0.78 Ma in the northern sub-basin, in a pattern suggesting northward propagation of the axial zone of oceanic crust accretion. Initial oceanic crust accretion occurred at ~2 Ma in the center of the Nereus segment (Ligi et al. 2011, 2012). The Bannock Deep lacks a steep axial rift valley but displays a gentle graben-like morphology with a continuous sediment cover, except for a 500 m high relief protruding from the sediment surface that gives rise to a magnetic anomaly. Basaltic dolerite was sampled from this high, probably a basaltic seamount (Bonatti et al. 1984). The Thetis–Nereus intertrough zone lacks a rift valley and magnetic anomalies and shows a thick sediment cover, while the Thetis–Hadarba intertrough zone is narrower but may

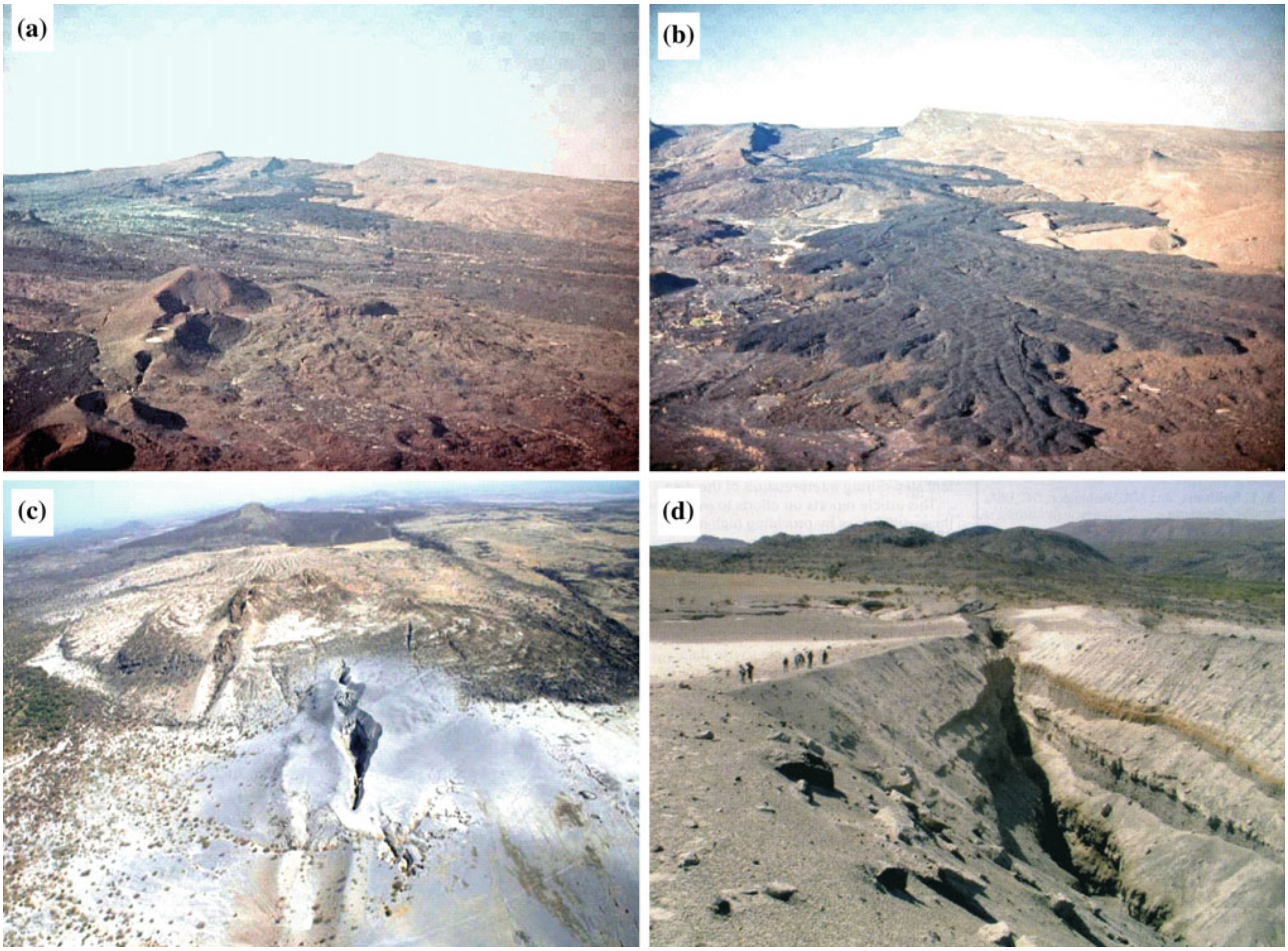

Fig. 7 **a**, **b** Fissure basalt flow in central Afar. **c**, **d** Open fissure resulting from dyke intrusion in 2005, southern Afar (from Keir et al. 2009)

expose fragments of continental basement (Ligi et al. 2012, this volume).

The age and degree of evolution of the axial oceanic cells decrease northward, from Hadarba to Tethis to Nereus to Bannock (Fig. 11b). Note that the axial zone deeper than 1,000 m narrows where the axial "oceanic" segments are present (Fig. 11b), suggesting that the rifting process becomes focused in a narrow axial zone as soon as oceanic crust starts to accrete. Basalt chemistry, distribution of magnetic anomalies and data on crustal thickness suggest an initial "active" burst in each cell (Ligi et al. 2011), with a high degree of mantle melting and rapid seafloor spreading, followed by a steady-state "passive" pattern of spreading (Fig. 13).

The pattern of discrete axial segments of oceanic crust accretion has led to the hypothesis that breakup of the continental crust starts with the evolution of initial cells of mantle upwelling and melting, followed by axial propagation that leads to a nearly continuous axial spreading zone, as observed along mid-oceanic ridges (Bonatti 1985). A possible explanation for the development of initial axial cells of mantle upwelling calls for a subaxial hot low-viscosity mantle zone below a denser, colder, high-viscosity layer, a situation that can be treated as a Raleigh–Taylor instability leading to discrete, equidistant upward injections of the hot, low-density low-viscosity mantle. This mantle-driven pattern may be disrupted by pre-existing lithospheric-tectonic anomalies, such as the Zabargad Fracture Zone.

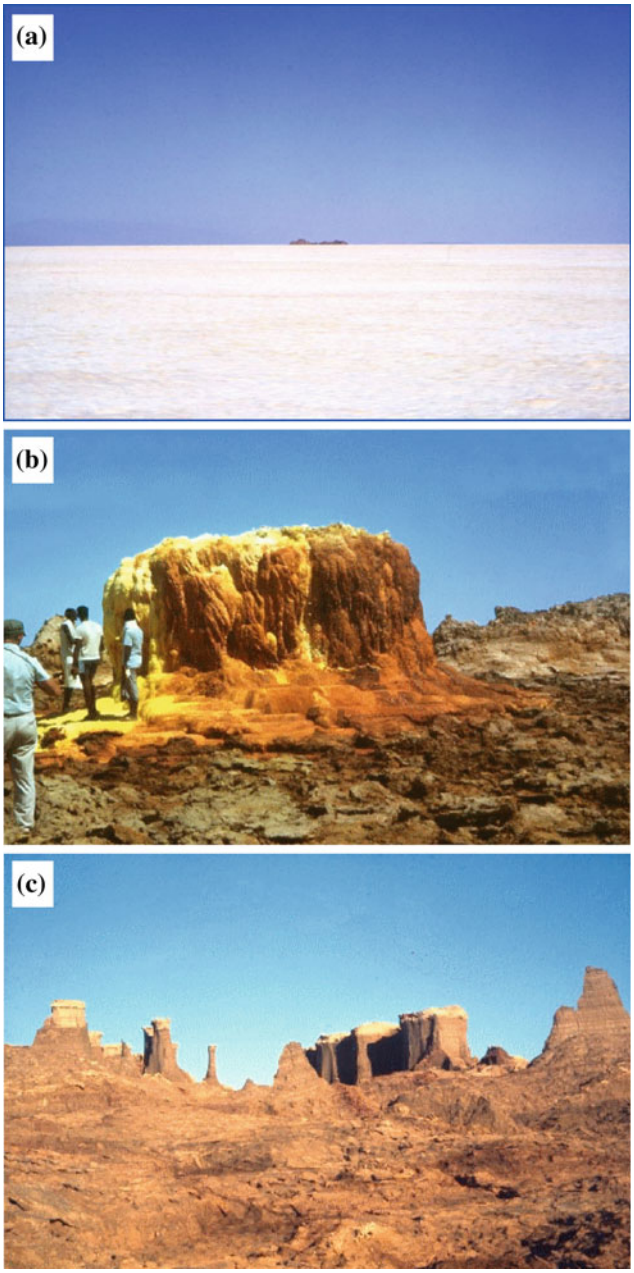

Fig. 8 **a** Salt plain in northern Afar. **b**, **c** Evaporites and hydrothermal mineralizations from the Dallol area, northern Afar

Zabargad Fracture Zone and Northern Red Sea

The orientation of the Red Sea axis, as determined by the axial zone within the 1,000 m isobaths, changes moving N at roughly 24°N from a NNW- to a NNE-direction. It then picks up again its NNW orientation at roughly 26°N (Fig. 1). The NNE-oriented stretch crosses the Red Sea from Zabargad Island at the SSW end to the Mabahiss basin at the NNE end of the fracture zone. NNE-oriented bathymetric and structural elements characterize this stretch, which we call the Zabargad Fracture Zone. The Red Sea axis is displaced laterally by about 100 km along the fracture zone, that can be considered the precursor to a major oceanic transform. The Zabargad F.Z. may act as a "locked zone", as defined by Courtillot (1982), against which the N-propagating axial oceanic rift is impacting (Fig. 11b).

Zabargad Island, located at the SSW end of the Fracture Zone, exposes an uplifted block of sub-Red Sea lithosphere, including three distinct upper mantle peridotite bodies, a gabbro intrusion, and a section of Pan-African continental granitoid gneisses criss-crossed by basaltic dykes, in addition to a probably Lower Cretaceous well stratified sandstone-limestone unit (Fig. 14), an evaporite unit and uplifted Pleistocene reefs (Bonatti et al. 1981, 1986; Bosworth et al. 1996). The dyke-injected continental granitic gneisses probably provide an example of what the Red Sea crust may look like outside the axial oceanic segments (Fig. 14b). The Zabargad mantle peridotites provide an example of "pre-oceanic", rather undepleted mantle bodies (Fig. 14a). The uplift of the island may be due in part to transpression occurring along the SSW side of the fracture zone, while transtension at the NNE-segment may have produced the Mabahiss pull-apart basin, floored by young basalts.

North of the Zabargad FZ we have no clear evidence of an "organized" emplacement of oceanic crust, although a few scattered deeps with basaltic and hydrothermal activity have been identified, such as Shaban Deep, Kebrit Deep, and Oceanographer Deep. Seismic reflection profiles as well as drilling suggest that the northern Red Sea is probably floored by attenuated continental crust dissected by basaltic dykes and intrusions (Cochran 2005; Bosworth et al. 2005), overlain by a several km thick sedimentary sequence ranging from early Tertiary to the present.

Two small islets ("The Brothers") located in the northern Red Sea at around 26°N (Fig. 1) provide interesting hints as to the processes of pre-oceanic rift magmatism. They expose gabbros with elemental and isotopic compositions similar to MORB that crystallized at relatively low pressure (Fig. 13a), suggesting that basaltic melts with oceanic affinity intrude the base of a thinned continental crust before the breakup and the injection at the seafloor of new oceanic crust (Bonatti and Seyler 1987).

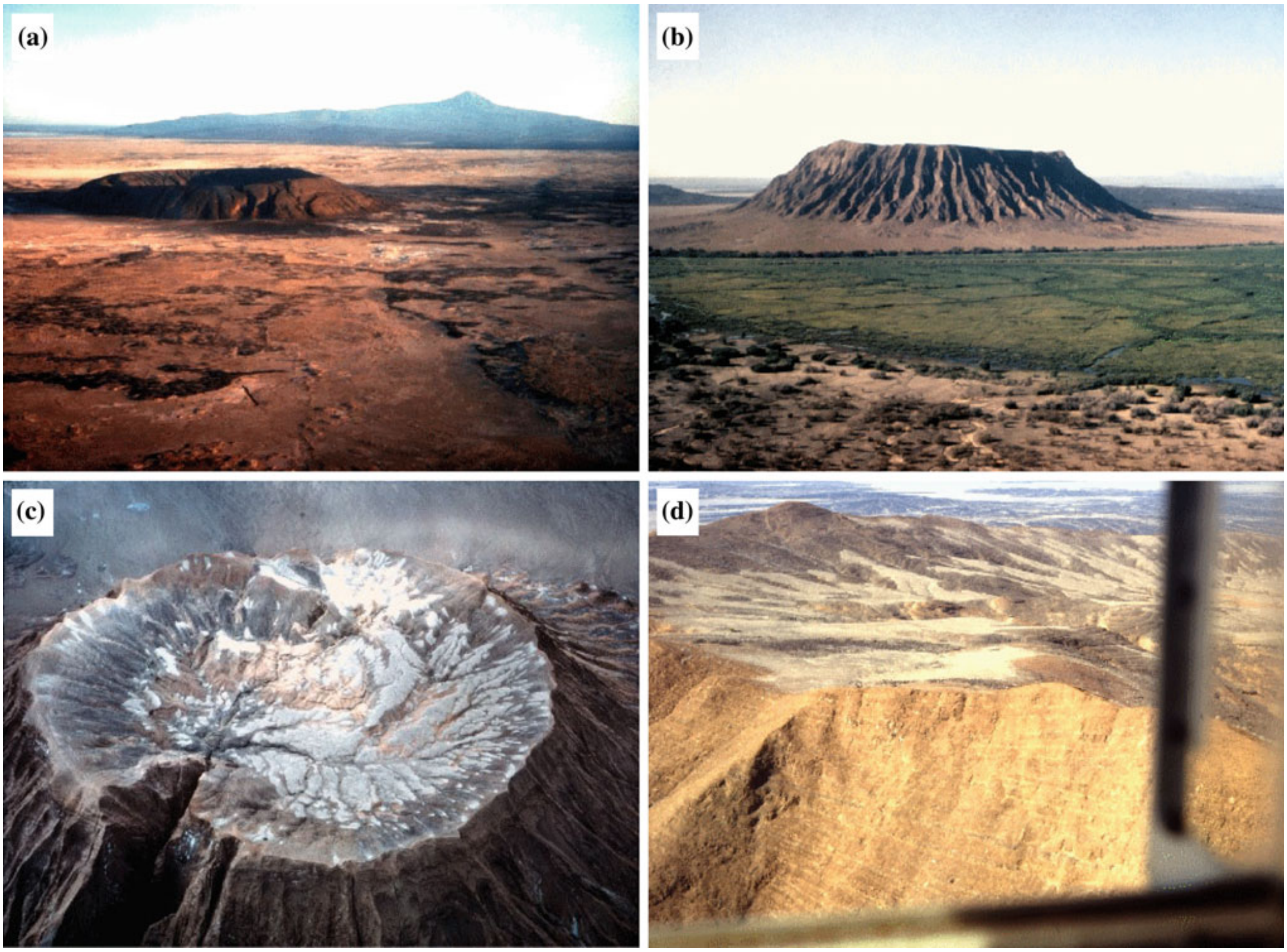

Fig. 9 **a** Submarine volcano made by basaltic hyaloclastites, central Afar. **b–d** Flat-top guyot made of stratified basaltic hyaloclastites, central Afar

Magmatism Along the Red Sea

^{8}Na and ^{8}Fe concentrations in the Red Sea axial rift basalts (i.e., Na and Fe contents corrected for the effects of differentiation according to Klein and Langmuir, 1987), imply: (1) south to north decreasing degree of partial melting, from about 18 % at 18°N to less than 10 % at 26°N (Haase et al. 2000), and (2) crossing of the solidus at pressures decreasing from about 2.5 to less than 1.5 GPa going from south to north. The northward decreasing degree of partial melting correlates with a decreasing spreading rate from 17 to 10 mm y^{-1} (Reilinger et al. this volume). Thus, the ranges of magma composition are comparable to those of slow spreading oceanic ridges. Shallowing of the solidus toward the north suggests a cooler mantle beneath the zone of late-stage continental rifting than beneath the zone of active spreading.

Basalt ^{87}Sr/^{86}Sr and ^{3}He/^{4}He ratios decrease and the ^{143}Nd/^{144}Nd ratio increases moving along the axis from south to north (Altherr et al. 1988; Moreira et al. 1996), possibly due to a decreasing influence of the Afar plume.

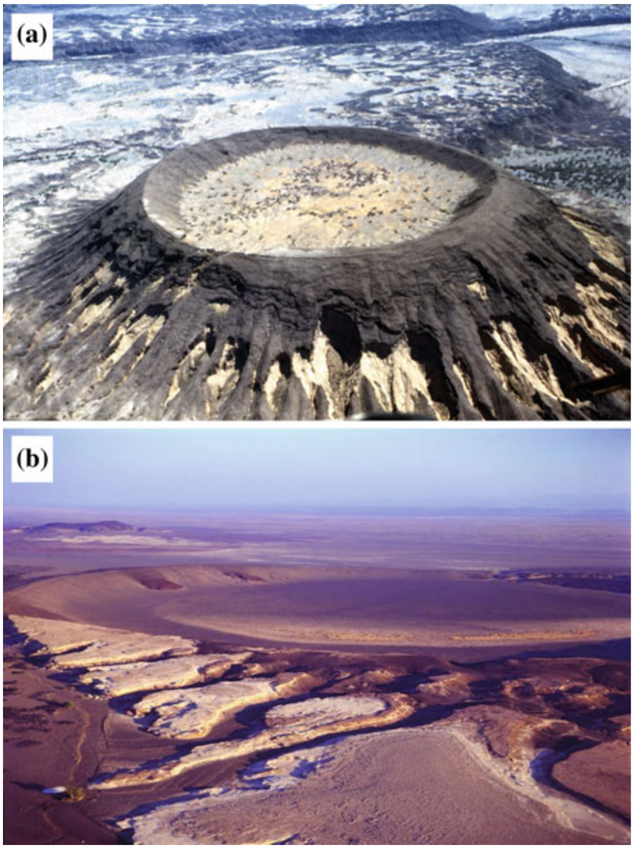

Fig. 10 **a** Volcano made of submarine basaltic hyaloclastites (*yellowish*) capped and mantled by subaerial basalt (*black*). **b** Submarine basaltic volcano capped by marine carbonates (northern Afar)

Moreover, the elemental and isotopic composition even of those basaltic melts emplaced in the attenuated crust of the northern Red Sea through, for instance in the Shaban and Mabahiss Deeps (Haase et al. 2000), do not show contamination by continental lithosphere components. The cooler mantle temperatures in the north are probably due to the fact that relatively shallow mantle from beneath the extending continental lithosphere is melting while relatively hot material from greater depths in the upper mantle is ascending beneath the spreading axis in the south.

Red Sea Stratigraphy

The Red Sea basin contains a thick sedimentary sequence that has been identified by seismic reflection profiling, by drilling for hydrocarbons, by scientific DSDP-ODP drilling and conventional coring. The sequence includes from top-down the following units: (a) Plio–Pleistocene biogenous–terrigenous deposits, that lie above a seismic reflector S, representing the top of an ubiquitous evaporite unit (Ross and Schlee 1973). The thickness of the post-evaporitic deposits reaches more than 100 m; their composition changes with climatic variations that affected sea level, intermittent communication with the Mediterranean and/or the Indian Ocean, biological productivity, and terrigenous input. (b) Evaporite deposition took place throughout the entire Red Sea basin starting at around 14 Ma in the Serravallian and reaching a thickness of thousands of meters (Mitchell et al. 2010; Bosworth this volume). Halite and anhydrite-gypsum were the main mineral phases; they are locally interbedded with sandstones and shales as well as with carbonate platform deposits, indicating intervals of normal marine deposition. The late Miocene was again dominated by evaporite deposition, and in the late Messinian, the Red Sea may have experienced stages of desiccation, similar to basins of the Mediterranean. (c) Pre-evaporitic synrift deposits, widespread throughout the Red Sea basin, include limestones, sandstones, and shales of various thickness, predominantly of shallow-marine origin ranging in age from Neogene to early Miocene. An example of pre-rift deposits is the Lower Cretaceous sandstone/limestone unit exposed on Zabargad Island (Bosworth et al. 1996).

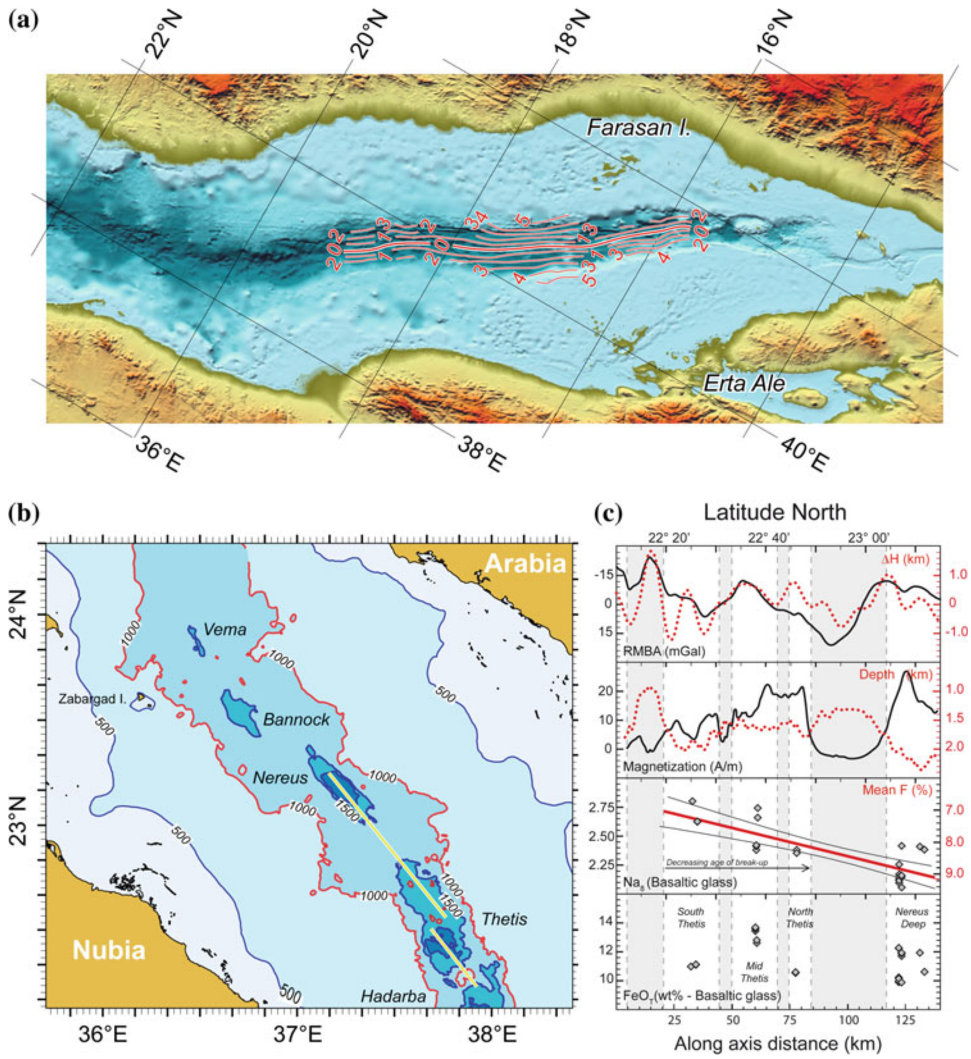

Fig. 11 **a** Axial zone of the southern Red Sea with lineated magnetic anomalies (modified from Cochran 1983). **b** Transitional zone of the Red Sea, with discrete axial rift valley segments separated by intertrough zones. *Note* how the zone limited by the 1,000 m isobath narrows where the axial segments of oceanic crust accretion are present. Contour interval 500 m. *Yellow solid line* indicates along-axis profiles shown in (**c**). **c** Thetis and Nereus along-axis variations of residual mantle Bouguer anomaly (RMBA) and inferred crustal thickness (Δh), rock magnetization and bathymetry, basaltic glasses Na_8 and mean degree of melting, and iron content (modified from Ligi et al. 2012)

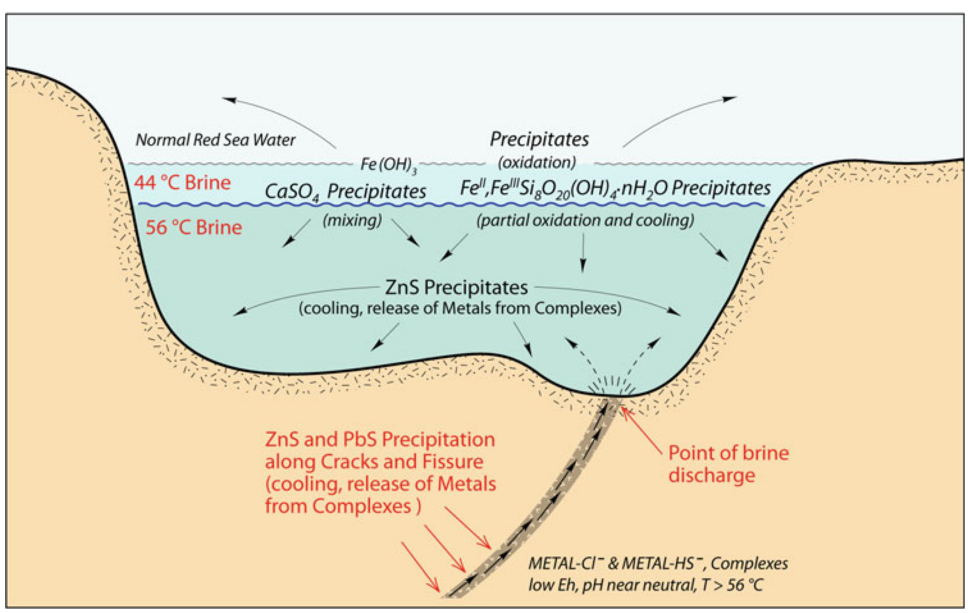

Fig. 12 Hydrothermal activity and metallogenesis at the Atlantis II Deep, central Red Sea (modified from Bischoff 1969)

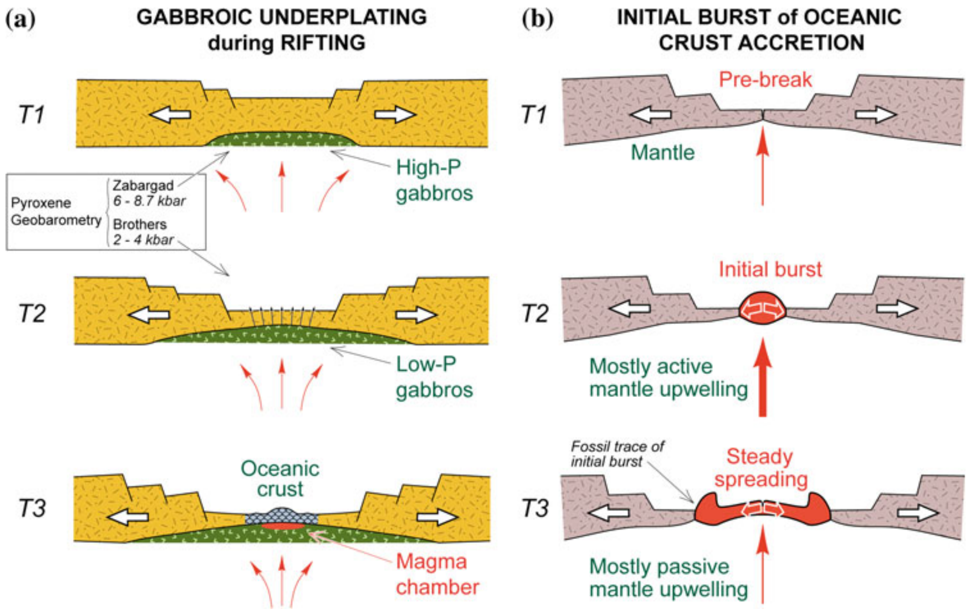

Fig. 13 **a** Progressive underplating of the thinned continental crust by gabbroic, MORB-type melts before initial accretion of oceanic crust (Bonatti and Seyler 1987). **b** Initial "active" burst of oceanic crust accretion, followed by steady-state "passive" sea floor spreading (Ligi et al. 2011)

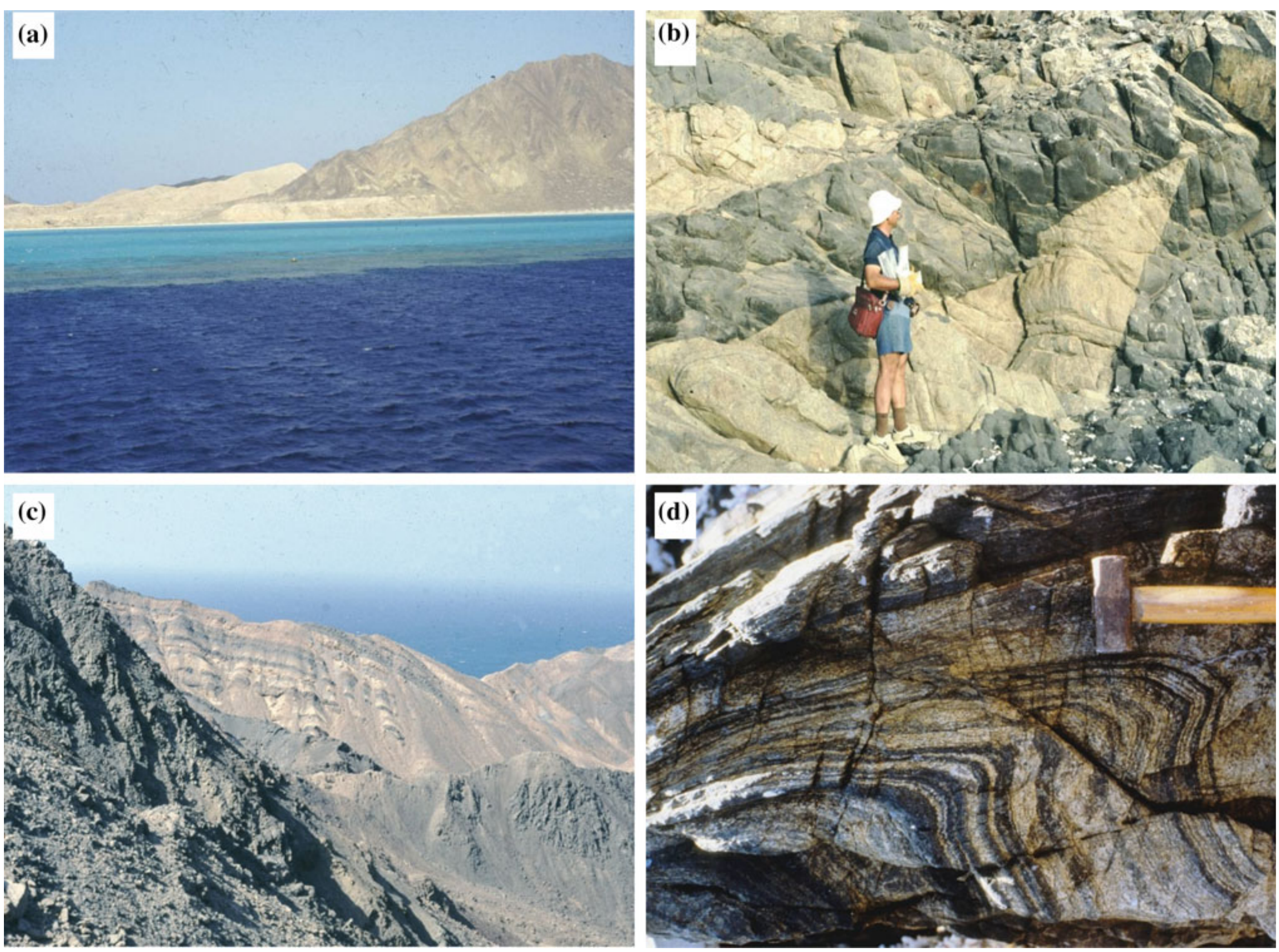

Fig. 14 Zabargad Island (location in Fig. 11b). **a** A portion of the southern peridotite hill; uplifted reef limestones are also visible. **b** Pan-African granitic gneiss criss-crossed by basaltic dykes. **c** Cretaceous sandstone-limestone stratified deposits. **d** Pan-African granitic gneiss

Conclusions

The Gulf of Aden-Afar-Red Sea region displays a spectacular range of geological situations that illustrate different modes and different stages in the processes of splitting of a continent and of birth of a new ocean. This article provides an introduction to the variety of important problems that can be tackled in this unique region of our Planet. Some of these problems have been addressed more in depth in other chapters of this volume.

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