

Rotation of the syn-rift stress field of the northern Gulf of Aden margin, Yemen

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Abstract

Remote sensing and field studies of several extensional basins along the northern margin of the Gulf of Aden in Yemen show that Oligocene–Miocene syn-rift extension trends N20°E on average, in agreement with the E–W to N120°E strike of main rift-related normal faults, but oblique to the main trend of the Gulf (N70°E). These faults show a systematic reactivation under a 160°E extensional stress that we interpret also as syn-rift. The occurrence of these two successive phases of extension over more than 1000 km along the continental margin suggests a common origin linked to the rifting process. After discussing other possible mechanisms such as a change in plate motion, far-field effects of Arabia–Eurasia collision, and stress rotations in transfer zones, we present a working hypothesis that relates the 160°E extension to the westward propagation since about 20 Ma of the N70°E-trending, obliquely spreading, Gulf of Aden oceanic rift. The late 160°E extension, perpendicular to the direction of rift propagation, could result from crack-induced extension associated with the strain localization that characterises the rift-to-drift transition.

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1. Introduction

The propagation of an oceanic rift into a continent is a fundamental process leading to continental break-up (Courtilot, 1982; Courtilot and Vink, 1983; Martin, 1984). Recent studies on the active Woodlark basin have shed new light on how rifts propagate with time (Taylor et al., 1995, 1999). Other studies,

for example in the South China Sea (Briais et al., 1993; Huchon et al., 1998, 2001) and in the Gulf of Aden (Manighetti et al., 1997), suggest that rift propagation is controlled not only by plate kinematics (or far-field forces) but also by the rheological structure of continental lithosphere undergoing extension.

The Gulf of Aden is a typical example of such a rift (Courtilot, 1980). It is a young and active ocean basin formed by rifting of Arabia away from Africa (Nubia) and Somalia since the Oligocene (Fig. 1). Two striking characteristics of the Gulf of Aden are (1) its obliquity with respect to the relative plate motion (Manighetti et al., 1997; Dauteuil et al., 2001) and

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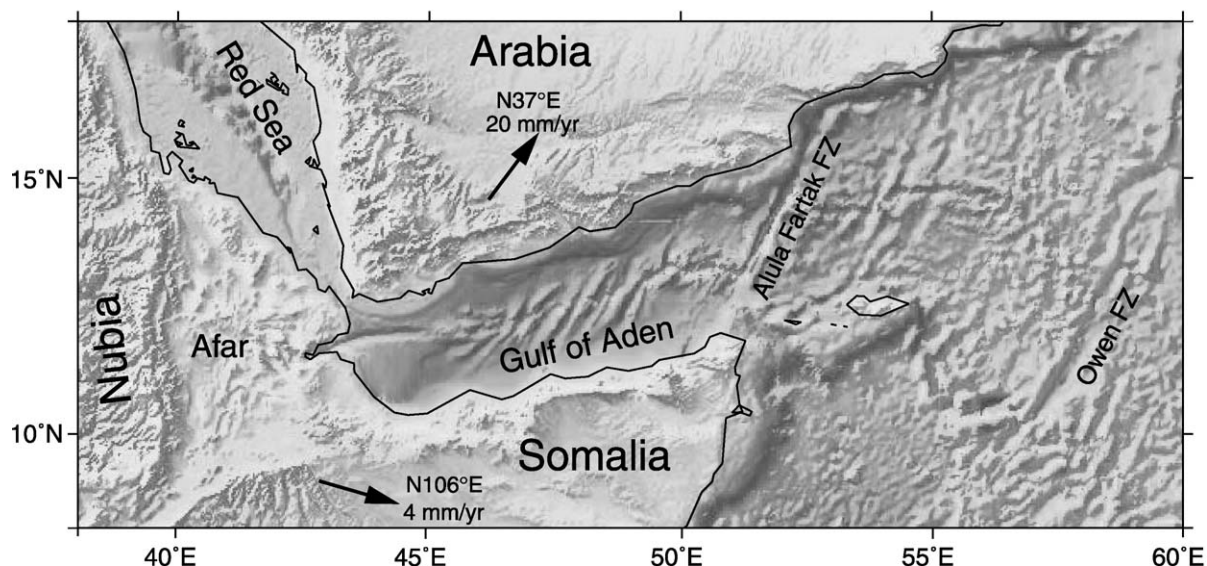


Fig. 1. Topographic and bathymetric map of the Gulf of Aden and surrounding regions. Direction and rate of motion of Arabia and Somalia with respect to Africa (Nubia) from [Jestin et al. \(1994\)](#). FZ: fracture zone.

(2) the presence of the Afar hot spot at its western extremity. The oceanic rift initiated from the Carlsberg ridge in the Indian Ocean and progressed westwards into the Afar region ([Laughton et al., 1970](#); [Manighetti et al., 1997](#)), cutting through several Jurassic and/or Cretaceous basins ([Beydoun, 1964](#); [Bosence, 1997](#)), which have a predominant NW–SE and E–W orientation (Fig. 2). The Oligocene–Miocene stretching of the Arabia–Somalia plate caused a re-activation of the pre-existing structures of these Mesozoic basins, however, without influence on the direction of propagation of the rift toward the west–southwest. It is thus likely that the presence of the hot spot beneath the western part of Yemen and Afar has controlled the direction of propagation of the Gulf of Aden ([Courtilot et al., 1999](#)).

Several hypotheses have been proposed to explain the trend of the Gulf of Aden. Following [Courtilot et al. \(1987\)](#) who consider that the Red Sea and Ethiopian continental rifts pre-existed to the formation of the Gulf of Aden, [Manighetti \(1993\)](#) and [Manighetti et al. \(1997\)](#) noticed that the present location of the Gulf of Aden is the shortest path from the Carlsberg Ridge to the Red Sea and Ethiopian rifts and therefore interpret it as the locus of stress concentration within the Arabo–Somalian plate submitted to extension.

Numerical computations based on a Coulomb failure criteria allowed [Hubert-Ferrari et al. \(in press\)](#) to realistically model the path of the Aden rift, starting from the Carlsberg ridge to the east and reaching the bend in the Ethiopian rift–Red Sea rift system in the Afar region to the west. With a different assumption on the timing of the three branches forming the Afar triple junction, [Malkin and Shemenda \(1991\)](#) pointed out that the Red Sea and Gulf of Aden make a 110° angle whose bisector coincides with the direction of relative motion of Arabia with respect to Africa–Somalia, a situation simulated by analogue models of rifting using a plastic material with a zone of weakness representing the Afar hot spot. In this explanation, the rifting and subsequent spreading of the Red Sea and Gulf of Aden are synchronous, as argued for instance by [Le Pichon and Gaulier \(1988\)](#) and the Ethiopian rift does not play a major role. In this model, the rift directions are controlled by the mechanical properties of the plate while their locations are forced to converge toward the weakness zone, i.e. the Afar hot spot ([Courtilot et al., 1999](#)).

In this paper, we show, on the basis of field surveys in Yemen, along the northern coast of the Gulf of Aden ([Khanbari, 2000](#)), that the general phase of NNE-trending syn-rift extension is overprinted by a

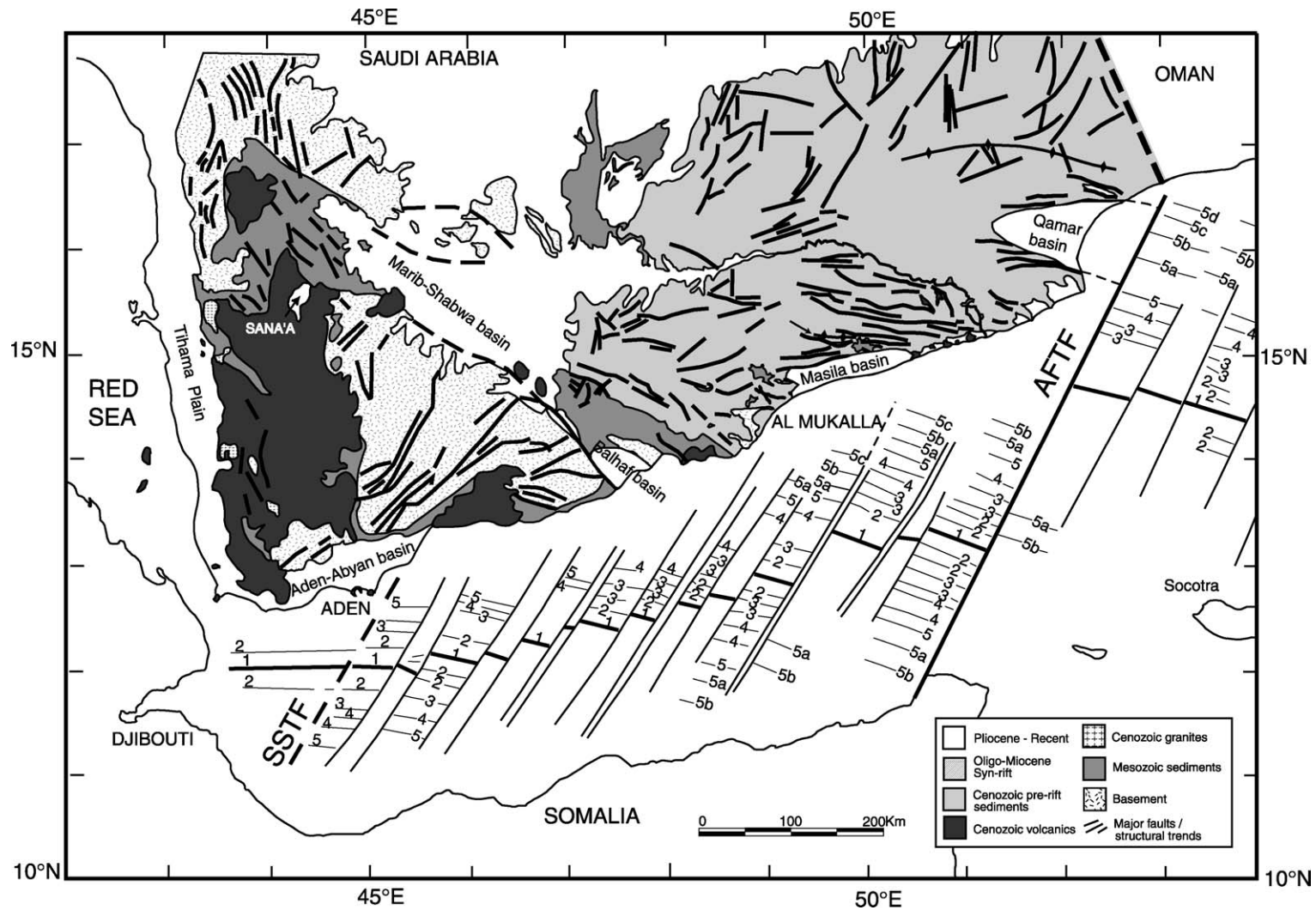


Fig. 2. Simplified geological map of the Republic of Yemen, on northern margin of the Gulf of Aden, and magnetic anomalies from Audin (1999), Cochran (1981) and Sahota (1990). Thick line: oceanic ridge axis. SSTF: Sukra El-Sheikh transform fault. AFTF: Alula-Fartak transform fault.

late phase of NNW-trending extension. We then discuss possible mechanical reasons for the observed paleostresses and present a working hypothesis that relates the late NNW extension to the propagation of the oceanic crust toward the west during the rift-to-drift transition.

2. Kinematics and structural setting of the Gulf of Aden and its northern margin

The movement of the Arabian plate away from Africa in a NE direction (McKenzie et al., 1970; Chase, 1978; Le Pichon and Francheteau, 1978; Joffe and Garfunkel, 1987; Jestin et al., 1994; Chu and Gordon, 1998) led to the opening of two young oceanic basins: the Red sea, between Africa (Nubia) and Arabia, and the Gulf of Aden, between Somalia and Arabia (Fig. 1). These two oceanic basins are overlapping within a large area called the Afar triangle, with an intervening continental block, the Danakil horst (Sichler, 1980; Souriot and Brun, 1992). The East African (or Ethiopian) rift, which separates Nubia from Somalia, is still in a continental stage and forms the third branch, although the detail is more complicated, of the Afar R–R–R-type triple junction (McKenzie and Morgan, 1969). In the following, we summarize the kinematics and the timing of rifting and spreading in the Gulf of Aden, which form the basis for interpreting the syn-rift deformations. We then briefly describe the geology of the onshore northern margin of the Gulf of Aden, in Yemen.

2.1. Kinematics and age of rifting and spreading in the Gulf of Aden

The Gulf of Aden extends from 58°E to the east, where the Owen fracture zone connects it to the Carlsberg Ridge, to 43°E to the west, where it enters into Afar through the Gulf of Tadjoura (Fig. 1). Its general trend is WSW–ENE (N70°E) while the present-day spreading direction ranges between N25°E to the east and N35°E to the west (Jestin et al., 1994). The Gulf of Aden is thus highly oblique to the movement of Arabia toward the northeast. The bathymetric and topographic map shows that the Gulf of Aden can be divided from east to west into three

different segments separated by major discontinuities (Manighetti, 1993; Manighetti et al., 1997) (Fig. 1). The eastern ridge (also called the Sheba ridge) and the central one are separated by the Alula–Fartak fracture zone (Tamsett and Searle, 1990), which is the largest one in the Gulf of Aden, with a 200-km offset. The central part of the Aden ridge shows numerous transform faults, on the contrary to the westernmost part, west of 45°E, which is much shallower, devoid of transform faults and which enters into Afar through the Gulf of Tadjura (Manighetti et al., 1997; Dauteuil et al., 2001).

Oceanic crust has been identified in the Gulf of Aden from the interpretation of magnetic anomalies (Fig. 2). In the eastern Gulf of Aden, the oceanic spreading has started about 18–19 Ma ago (anomaly 5D–5E) to the east of Alula–Fartak transform fault, and 16 Ma ago (anomaly 5C) to the west (Sahota, 1990; Sahota et al., 1995). In the western Gulf of Aden, the oceanic spreading started later, about 10 Ma ago (anomaly 5) to the east of the Shukra El Sheik discontinuity (Cochran, 1981; Audin, 1999). Finally, only anomalies younger than about 2–3 Ma are observed to the west of the Shukra El Sheik discontinuity (Audin, 1999). The age of the oceanic crust is thus progressively younger westwards, which reflects its propagation toward Afar. However, the propagation is not a continuous process. It occurs by steps, with the oceanic axis stalling for a few million years to the east of each of the major discontinuities (Manighetti et al., 1997). It is worth noting that the westernmost discontinuity, the Sukra–El Sheik “transform fault”, coincides with the boundary of the Afar hot spot and thus corresponds to a major change in rheology of the lithosphere (Manighetti, 1993; Manighetti et al., 1997; Hébert et al., 2001; Dauteuil et al., 2001).

While the age of the onset of spreading is fairly well constrained, that of the onset of continental rifting is more difficult to assess because it mostly relies on the age of the oldest syn-rift sediments, often made of clastic sediments and tricky to date. Onshore southern Yemen, the oldest syn-rift sediments of the Shir Group (Beydoun, 1964) have been dated as Rupelian (ca. 35 Ma; Watchorn et al., 1998), in good agreement with estimates of the beginning of uplift based on fission tracks data in Yemen (Menzies et al., 1992, 1997). Offshore Somalia and southern Yemen, wells have revealed the presence of marine sediments of Middle

Oligocene age resting on sabkha-type evaporitic beds and brackish marginal marine sands and clays (Hughes et al., 1991). Farther east in Dhofar (Oman), the first syn-rift deposits are also dated as Early Oligocene (Roger et al., 1989; Platel and Roger, 1989). The onset of rifting thus seems to be synchronous with the emplacement of the Afar hot spot (Manighetti et al., 1997) whose age is constrained at about 30 Ma by Ar/Ar dating and magneto-stratigraphy of the basaltic trap series both in Ethiopia (Hoffmann et al., 1997; Rochette et al., 1997; Ukstins et al., 2002) and in Yemen (Baker et al., 1996).

2.2. Tectonic setting of the northern margin of the Gulf of Aden

Strata exposed in Yemen span the Archean to the Cenozoic (Geukens, 1960; Beydoun, 1964; Greenwood and Beackley, 1967) (Fig. 2). The Proterozoic metamorphic basement is unconformably overlain by Ordovician ferruginous sandstone, Permian black shales and early Jurassic marls, sandstones and limestones (Kohlman Formation). The late Jurassic is characterized by a generally thick transgressive series of marls and limestones (Amran Group). These platform series are overlain by Cretaceous continental sandstones (Tawilah Group) to the west and marine clastics to the east. Only the western part of Yemen is covered by Cenozoic volcanics (Traps of Yemen) (Civetta et al., 1978; Capaldi et al., 1983; Chiesa et al., 1983, 1989), whereas the eastern part of Yemen is characterized by Paleocene–Eocene limestones, marls and gypsum (Hadramaut Group) and Oligocene–Miocene sediments made of conglomerates, sandstones, marls, gypsum, limestones and shales (Shihir Group) (Beydoun, 1964; Haitham and Nani, 1990; Bott et al., 1992). Late Miocene to Quaternary lavas are also found in various places in Yemen, including along the coast of the Gulf of Aden, but these recent volcanics are volumetrically minor compared to the Oligocene–Miocene traps series (Chazot et al., 1998).

The Mesozoic basins of Yemen have various orientations and ages from west to east (Fig. 2). The interior rifts of the western and central area (Marib–Shabwa basins) are oriented NW–SE (Brannan et al., 1997), following the Najd trend of the Precambrian basement of the Arabian Peninsula (Stern, 1985). To

the east, the Sayun–Al Masila and Jiza–Qamar basins are oriented progressively more east–west (Redfern and Jones, 1995; Beydoun et al., 1996; Bosence, 1997). In the Marib–Shabwa basin, the fill is dominantly Late Jurassic, whilst the eastern Shabwa, Balhaf and Sayun–Al Masila basins exhibit a progressively increased Early Cretaceous fill. Farther east, the main period of fault-related sedimentation in the Jiza–Qamar basin is Cretaceous (Brannan et al., 1997).

These basins have been affected by three successive phases of rifting (Ellis et al., 1996; Brannan et al., 1999; Ziegler, 2001). The first rifting event occurred during the Late Jurassic. It is associated with the fragmentation of Gondwana and the reactivation of the Najd Fault System. The second phase of rifting occurred during Early to mid-Cretaceous. This phase corresponds to the separation of India from Madagascar and led to the deposition of thick Cretaceous sediments in the Balhaf, Masila and Qamar basins. The third phase of rifting, associated with the opening of the Gulf of Aden, occurred during the Cenozoic and caused a reactivation of the pre-existing structures of the Mesozoic basins located along the coast. This reactivation is clearly seen on industrial seismic profiles, on which the main normal faults bounding the Mesozoic basin fill also cut through the Cenozoic formations.

3. Syn-rift extensional deformations

3.1. Methods

We have conducted field surveys in three areas of southern Yemen, extending over more than 600 km, which are from west to east: (1) the Balhaf graben, (2) the Masila basin, east of the city of Mukalla and (3) the Al Gaydah (Qamar) basin, near the border with Oman (Fig. 2). We aimed at characterizing the syn-rift deformations by the observation and measurement of the motion on major normal faults. The field surveys were preceded and complemented by satellite imagery and air photo interpretation and by integration of existing maps and oil industry data, in order to build structural maps. Our field data consist in measurements of faults, including slickenside lineations (striations and grooves). Most of these measurements were performed within the Cenozoic sediments. However,

some outcrops in Jurassic limestones and Cretaceous sandstones were also surveyed in the Balhaf basin where syn-rift sediments poorly outcrop. Data analysis has been conducted using various methods (Angelier, 1984), including stress tensor computation by direct data inversion (Angelier, 1990) for each sufficiently documented site. In most cases, the computation of the principal stress axes could be done with good accuracy owing to the number and distribution of faults. A few sites are less well documented but can be regarded with confidence because of the regional extent of the faults, with throws of several meters to several tens of meters. We paid special attention to the relative chronology between faults and, when observed on the same fault plane, between tectonic indicators with different orientations (such as oblique striations overprinting older grooves or striations).

3.2. Balhaf basin

The Balhaf graben is about 30 km in width, 100 km in length, and trends WNW–ESE (Figs. 3 and 4). The basement, which largely outcrops to the southwest and to the east of the basin, is clearly visible on the satellite images (Fig. 3). It is overlain by the Jurassic Amran Group, the Cretaceous Tawilah Group and the Cenozoic Hadramaut Group. The syn-rift deposits are found only in the centre of the basin, beneath a thin cover of Quaternary sediments. Quaternary volcanics outcrop along the coast, but Quaternary sediments lack evidence of deformation. The basin is bounded by WNW-trending normal faults. In the southwestern part of the basin, these faults bound blocks of Cenozoic sediments tilted toward the northeast (Fig. 5). The basement outcrops along the northern fault scarp (Fig. 5) revealing the asymmetry of the graben. Within the graben, the depth to basement reaches 6 km (Jungwirth and As-Saruri, 1990), but the thickness of Oligocene–Miocene syn-rift deposits does not exceed 800 m. Most of the fill (over 3.5 km) corresponds to the Cretaceous limestones (Qishn Formation) and sandstones (Mukalla Formation) (Beydoun et al., 1993).

Due to the lack of outcropping syn-rift sediments, observation of faults have been done in Jurassic limestones and in the Cenozoic series of the Hadramaut Group, which are composed, in ascending order, of Paleocene limestones (Umm er Radhuma Formation), of lower Eocene shales, marls and limestones

(Jeza Formation), of middle Eocene gypsum and anhydrite (Rus Formation) and of middle Eocene shales, marls and dolomites (Habshiya Formation) (Beydoun, 1964; Schüppel and Wienholz, 1990).

Analysis of faults (Fig. 4) shows that the direction of extension in the southern part of the Balhaf basin is NNE–SSW ($N30^{\circ}E$) (sites BAL-1, BAL-2 and BAL-3, all in Jeza Formation, Early Eocene in age). At site BAL-2, some faults trending ENE–WSW and E–W have an oblique slip corresponding to a $N28^{\circ}E$ direction of extension. The faults at these three sites cut sediments of the Jeza Formation. The corresponding paleostresses are thus post-Eocene. In the northern part, where observations have been made in Jurassic limestones, two directions of extension have been determined: NE–SW to NNE–SSW and NW–SE. Strike-slip faults have been identified cutting Jurassic limestones at sites MAYF-1 and MAYF-2. These strike-slip movements do not affect the overlying Cretaceous and Cenozoic sediments. This event is thus probably Late Jurassic in age and may correspond to the basement uplift that occurred at that time (Jungwirth and As-Saruri, 1990). A poorly recorded E–W direction of extension is also observed in these limestones (site J.MADBI). Other sites in Jurassic limestones show $N30^{\circ}E$ (sites J.BILLUM) and $N150$ – $160^{\circ}E$ (sites J.BAQARW and J.BILLUM) directions of extension, but their ages cannot be constrained. However, at the basin scale, the $N30^{\circ}E$ extension fits well the general trend of the normal faults that affects the Cenozoic sediments.

3.3. Masila basin

Cenozoic sediments dominantly outcrop in the Masila basin, where less abundant Cretaceous sandstones are the oldest outcropping sediments. The Jurassic limestones have been penetrated only in off-shore wells (Haitham and Nani, 1990). The Oligocene–Miocene syn-rift sediments of the Shihr Group outcrop mostly in the coastal area (Bosence et al., 1996; Watchorn et al., 1998). Quaternary volcanics occur in the eastern area of the basin. The simplified geological map of the Masila basin (Fig. 6) shows that most of the normal faults are oriented in an ESE–WNW to ENE–WSW direction. They frequently display a sigmoidal shape. Field observations have been made in Cenozoic sediments, so that the paleo-

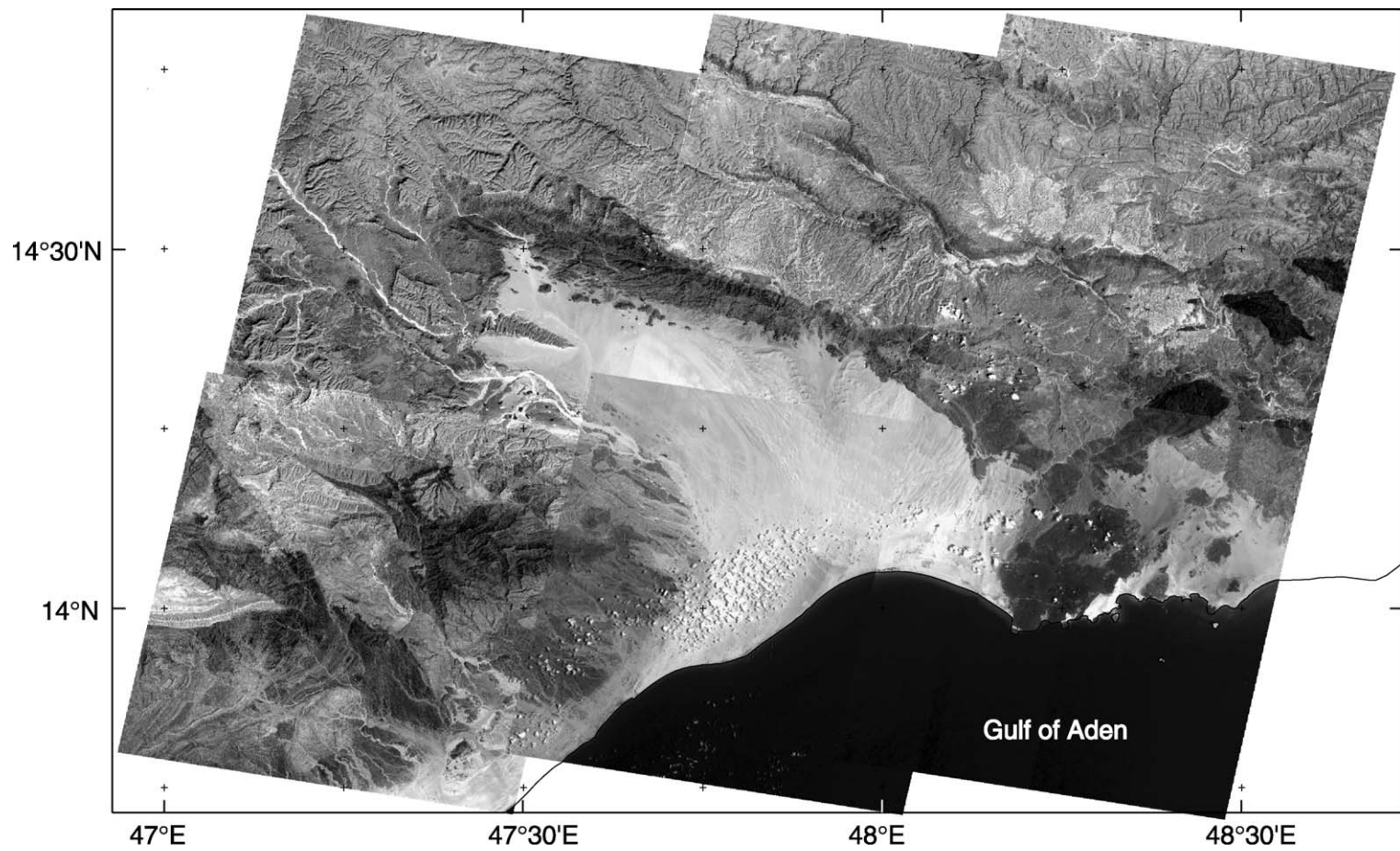


Fig. 3. Mosaic of SPOT panchromatic images of the Balhaf graben. Image numbers: 153-321, 154-321, 155-321, 153-322, 154-322, 155-322.

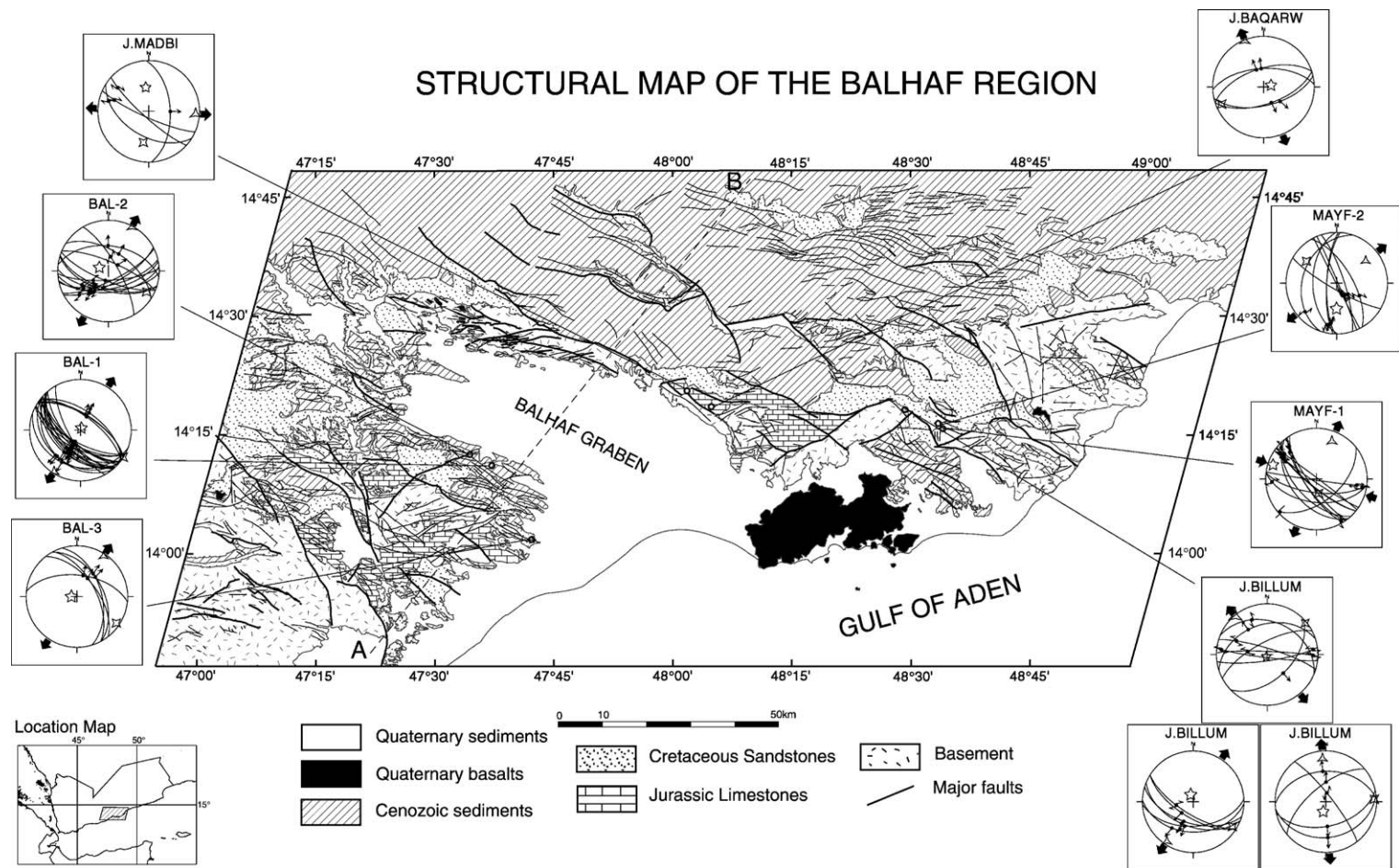


Fig. 4. Simplified geological and structural map of the Balhaf graben and stereographic plots of faults (equal-area, lower hemisphere). Slickenside lineations are shown by small arrows. Principal stress axes σ_1 , σ_2 and σ_3 are shown by five-, four- and three-branch stars, respectively. Black arrows: direction of extension. A–B: cross-section of Fig. 5.

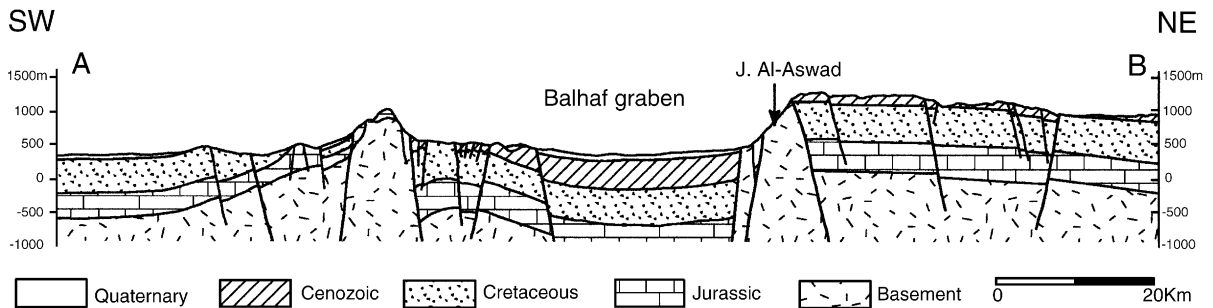


Fig. 5. Geological cross-section of the Balhaf graben. Location on Fig. 4.

stresses we reconstructed can be confidently attributed to the Oligocene–Miocene rifting. Undeformed Quaternary deposits rest unconformably on the syn-rift sediments (Plate 1, top). The tectonic analysis of data (Al Kotbah, 1996, 2000; and this study) shows the existence of two extensional phases: NNE ($N20^{\circ}E$) and NNW ($N160^{\circ}E$) (Fig. 6). The site SHIR28 is the only one in the syn-rift sediments (Plate 1, bottom). This site shows clear syn-sedimentary faults, oriented WNW–ESE and corresponding to a $N10^{\circ}E$ extension. Only one fault is oriented ENE–WSW with an oblique slip. At sites MAS32 (wadi Kharid) and MAS34 (wadi Bidish), two sets of normal faults have been recognized in Paleocene limestones (Umm er Radhuma Formation), corresponding to extensions trending NNE ($N25^{\circ}E$ and $N15^{\circ}E$, respectively) and NNW ($N155^{\circ}E$ and $N160^{\circ}E$, respectively). Other sites show either nearly N–S extension (MAS28, MAS29 and MAS33, in the basement, in the Early Cretaceous Qishn Formation and in the Early Eocene Jeza Formation, respectively) or NNW extension (MAS31, MAS33, in the Umm er Radhuma Formation and in the Jeza Formation, respectively). As at sites MAS32 and MAS34, site MAS33 (wadi Assad) also shows two sets of faults with N–S and NNW extensions, but the distinction is less clear. However, this tectonic analysis reveals that two extension directions have occurred after the Eocene, thus syn-rift, an observation that is confirmed in the Qamar basin presented below.

3.4. Qamar basin

The simplified geological map of the Qamar basin (Fig. 7) shows that Cenozoic sediments of the Hadra-

maut Group outcrop within and outside the basin while the syn-rift sediments (Shihr Group) are restricted to the depression. The major normal faults which bound the basin are oriented E–W to WNW–ESE. Toward the east, they have been identified offshore with the same trend (Brannan et al., 1997). Although most of the fill of the basin is Cretaceous (Brannan et al., 1997), the amount of extension related to the Oligocene–Miocene rifting is large, as shown by the tilt of the pre-rift series that locally reaches 45° (Plate 2, top).

Two directions of extension have been identified. All the faults observed and measured affect Eocene sediments of the Hadramaut Group (excepted for the site QISHN-26, see below). At sites QISHN-26, in the Early Cretaceous limestones of the Qishn Formation, NASH-19, TIN-20, HAUF-14 and HAUF-16, all in the Middle Eocene Rus and Habshiya Formations, a NNE-trending ($\sim N20^{\circ}E$) extension has been computed from fault sets, while at sites FARTK-25, TIN-20 and FATK-23, also in Rus and Habshiya Formations, the faults correspond to a NNW-trending ($N160^{\circ}E$) extension. At site TIN-20 (wadi Tinhalin), both directions of extension have been identified. The temporal relationship between these extensions has been deduced from field observations: on the same E–W trending fault plane, we observed that the oblique striations corresponding to the NNW extension cut dip slip grooves of the NNE extension. The NNW extension is thus younger than the NNE one. An intermediate, N–S trending direction of extension has been also observed in some sites (FARTK-25, TIN-21 and TIN-22). At site TIN-11 (Fig. 7 and Plate 2, bottom), where most of the faults trend E–W, oblique striations corresponding to a NW–SE extension have been observed overprinting older dip-slip

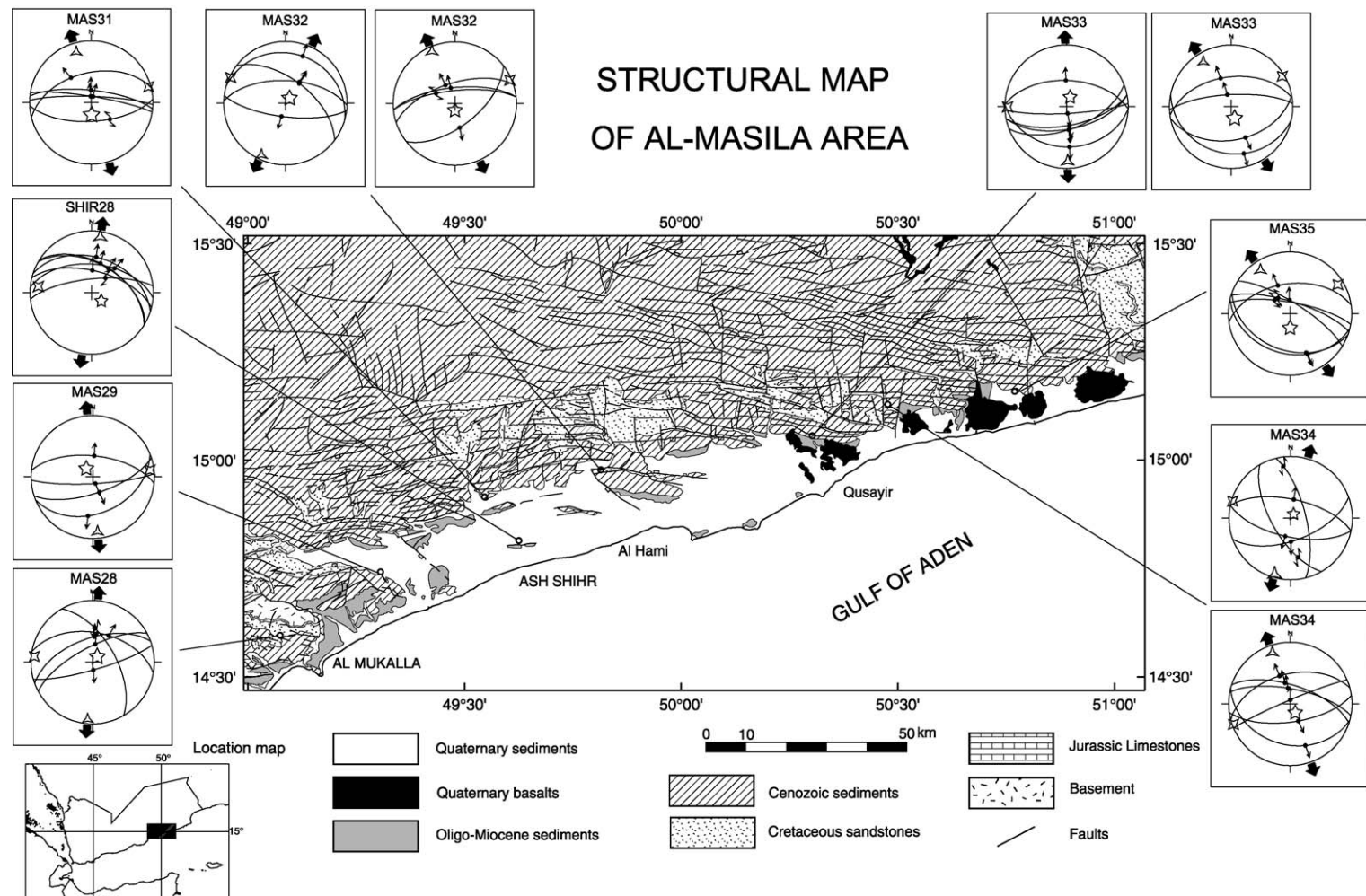


Fig. 6. Simplified geological and structural map of the Masila area and stereographic plots of faults (equal-area, lower hemisphere). Slickenside lineations are shown by small arrows. Principal stress axes σ_1 , σ_2 and σ_3 are shown by five-, four- and three-branch stars, respectively. Black arrows: direction of extension.

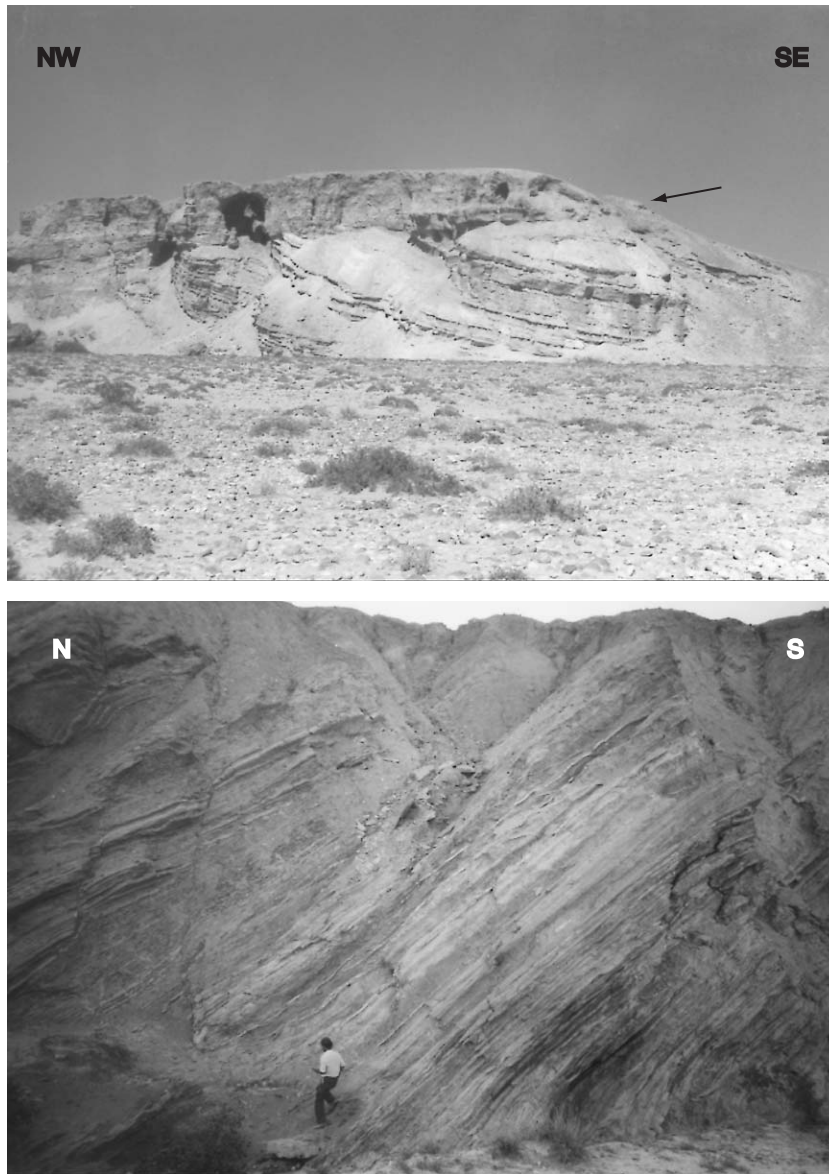


Plate 1. Top: Quaternary deposits unconformably overlying tilted syn-rift sediments (Shihr Group, Oligocene–Miocene formation,), Masila area (latitude $14^{\circ}49'N$, longitude $49^{\circ}37'E$). The arrow shows the unconformity. Bottom: tilted and faulted syn-rift sediments (Shihr Group, Oligocene–Miocene), Masila area, site SHIHR 28 (location on Fig. 6).

grooves. This indicates that the faults, initiated under a N–S to $N20^{\circ}E$ extension, have been reactivated under a younger $N160^{\circ}E$ extensional stress regime. As in the Masila basin, the normal faults reported here affect Cenozoic sediments of the Hadramaut Group, which implies a post-Eocene age of the deformation.

3.5. Chronology and regional extent of the two syn-rift extensional events

The field surveys in the basins along the northern margin of the Gulf of Aden thus suggest the occurrence of two successive Oligocene–Miocene syn-rift

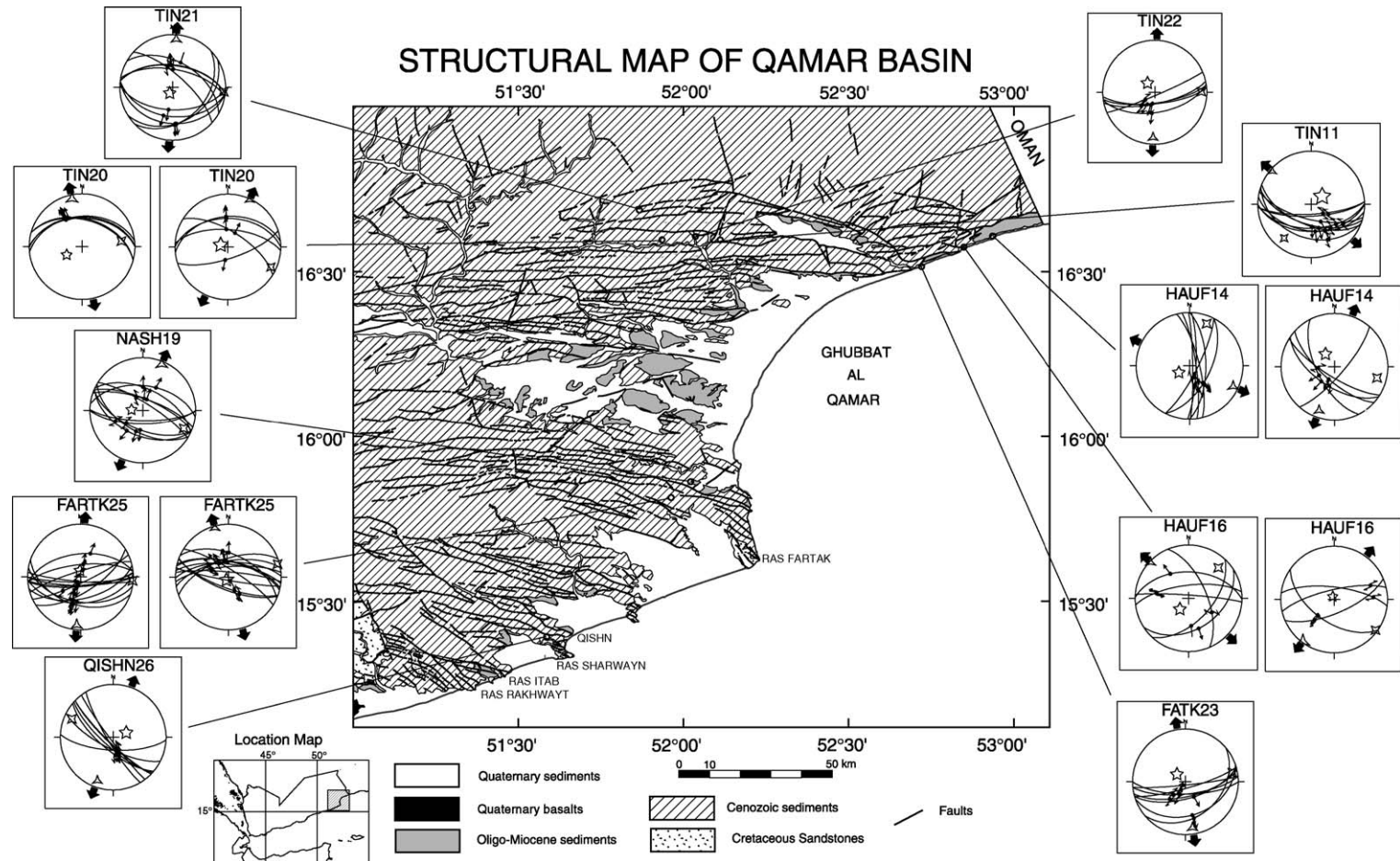


Fig. 7. Simplified geological and structural map of the Qamar basin and stereographic plots of faults (equal-area, lower hemisphere). Slickenside lineations are shown by small arrows. Principal stress axes σ_1 , σ_2 and σ_3 are shown by five-, four- and three-branch stars, respectively. Black arrows: direction of extension.



Plate 2. Top: tilted blocks of pre-rift sediments (Habshiya formation, middle Eocene), southern part of Qamar basin (approximate location: latitude $16^{\circ}2'N$, longitude $51^{\circ}54'E$). Bottom: normal fault (shown by an arrow) in pre-rift sediments (left: Rus Formation; right: Habshiya formation, both Middle Eocene in age), Wadi Tinhalin, northern part of Qamar basin, site TIN11 (location on Fig. 7).

extensions: NNE ($N20^{\circ}E$), then NNW ($N160^{\circ}E$). Except for the Balhaf basin, most of the normal faults have been observed in Paleocene to Eocene pre-rift sediments, while the Plio–Quaternary strata are devoid of deformation, which confirms the Oligocene–Miocene age for the deformation. The relative

chronology of the two extensions, based on field observations, is that the $N20^{\circ}E$ extension predates the $N160^{\circ}E$ one.

These NNE and NNW extension directions are also recorded in southern Oman (Dhofar region) in the Paleocene to early Miocene sediments (Lepvrier et

al., 2002), as well as in the western part of Yemen. Huchon et al. (1991), Thoué (1993) and Thoué et al. (1997) have shown that during the Oligocene–Miocene the southern margin of western Yemen is affected by two directions of extension: N20°E to N40°E and N160°E to N–S. In the northern part of the Aden–Abyan basin (Fig. 2), Huchon et al. (1991) have reported the succession of N20°E and N160°E extensions affecting the Oligocene–Miocene volcanics.

In Djibouti, at the western end of the Gulf of Aden, Huchon and Gaulier (1989) and Gaulier and Huchon (1991) also identified a N160°E extension in the 9- to 4-Ma-old Dahla basalts. Audin (1999) has shown some paleomagnetic rotations there, which however never exceed 10° and do not change significantly Huchon and Gaulier's results. This NNW-trending extension in Djibouti is thus younger than the one observed in the basins in southern Yemen, where we showed it has occurred syn-rift, thus earlier than 16–19 Ma based on magnetic anomalies. With respect to the propagation of oceanic crust into Afar (Manighetti et al., 1998), the Dahla basalts may be considered as older than the spreading phase, thus syn-rift. From this observation, we can therefore hypothesise that the NNW syn-rift extension that we observed all along the northern margin of the Gulf of Aden is diachronous: in the model we shall envision in the discussion, we will consider, although the evidence is scarce, that the late syn-rift (NNW trending) extension occurred early in the eastern Gulf of Aden and progressively younger moving westwards.

Note that in the Balhaf, Masila and Qamar basins we never observed the early E–W trending phase of extension recognized in western Yemen between 22 and 30 Ma (Huchon et al., 1991). In Djibouti, this early E–W extension occurred during the emplacement of the earliest basalts of the Ali Sabieh block (Huchon and Gaulier, 1989; Gaulier and Huchon, 1991), dated between 27 and 20 Ma (Chessex et al., 1975). It thus appears to be restricted, both in space and time, to the main period of emplacement of the volcanic traps series of the Afar hot spot (30 Ma). At least in western Yemen, the post-22 Ma syn-rift extension is consequently synchronous with the onset of oceanic spreading in the eastern Gulf of Aden at about 19 Ma, a further evidence for diachronous deformation related to the oceanic rift propagation in the Gulf of Aden.

The data presented above emphasize the regional significance of our observations, which is a prerequisite to any interpretation at the scale of the whole Gulf of Aden. The two successive extensions occurred over 1000 km along the Gulf of Aden and has a regional significance. On the other hand, they are not evidenced in the interior basins of Yemen such as the Marib–Shabwa basin. Since this two-phase extension is restricted to the coastal strip, it is intimately linked to the rifting process. Is it related to far-field forces (or relative plate motions) or to the strain localization during the transition, in time, from rifting to spreading, thus to the mechanism of westward propagation? What is the possible role played by the obliquity of rifting? We now discuss these questions before presenting our preferred model.

4. Discussion

4.1. Stress field rotations in the Afro-Arabian region

Before discussing possible causes for the stress field rotation in Yemen, we wish to point out that such rotations are fairly common during the Neogene in the Afro-Arabian region. In the gulfs of Suez and Aqaba, many workers have evidenced changes in the extensional stress direction (Suez: Chorowicz et al., 1987; Bosworth and Taviani, 1996. Aqaba: Chorowicz et al., 1987; Eyal, 1996, among many others). Some of these stress reorientations are Late Quaternary, and thus possibly related to the slowing down of the African and Arabian plates (Sella et al., 2002). In the Gulf of Suez, the direction of extension rotated anticlockwise before 125 ka, becoming N–S at present instead of NE–SW earlier (Bosworth and Strecker, 1997), possibly related to the increasing locking of Africa and Arabia against Eurasia. Stress reorientations also occurred earlier, in the Middle to Late Miocene, probably related to the development of the Gulf of Aqaba–Dead Sea transform fault boundary in response to the collision of Arabia with Anatolia (Turkey).

Interestingly, stress reorientations also occurred during the Quaternary in the Kenyan rift, far to the south of the Red Sea. After 0.4–0.6 Ma, extension rotated clockwise from E–W to NW–SE (Strecker et al., 1990; Bosworth et al., 1992; Bosworth and

Strecker, 1997). An earlier clockwise rotation also occurred by about 2.6 Ma (Bosworth and Strecker, 1997). Similar observations were done in the western branch of the East African rift (Tanganyika–Malawi rift) (Ring et al., 1992; Delvaux, 1993). Although the sense of rotation is opposite to that in the northern Red Sea, Bosworth and Strecker (1997) argued in favor of a common, although unidentified cause. Consequently, there is still a matter of debate about the processes involved in varying stress fields, but above all there is a need for more data covering the whole Afro-Arabian region.

Gravitational collapse is another possible cause for post-rift, or post-rift shoulder uplift, extension differing from the syn-rift regional stress field. This has been shown for the Gulf of Aqaba (Eyal, 1996) and the eastern border of the Ethiopian plateau (Chorowicz et al., 1999). However, we never observed down-to-the-basin faults cutting the post-rift, Plio–Quaternary section, which seems to rule out such an explanation for the N160°E extension observed along the Gulf of Aden northern margin.

4.2. Role of oblique rifting

Deformation in oblique rifting is known to produce a complex pattern of faults, depending on the angle of obliquity (Tron and Brun, 1991; Withjack and Jamison, 1986; Bonini et al., 1997). However, Acocella and Korme (2002) show that the Holocene extension direction across the Main Ethiopian rift very consistently trends about N130°E, over more than 400 km, both in the southern rift, which is perpendicular to extension and in the northern one, oblique by about 15°. It results in a slight component of dextral shear on normal faults in the northern rift. This observation is somewhat contradictory with analogue modelling of oblique rifting (Dauteuil and Brun, 1993; McClay and White, 1995) but however suggests that far-field forces basically control the direction of extension along the Ethiopian rift, whatever the trend of the rift.

An alternative explanation for the N160°E, late syn-rift extension in Yemen would thus be to consider an anticlockwise rotation of the stress field in the transfer zones between right-stepping, en-échelon basins (Fig. 8). Although this would produce a NNW extension in the transfer zone, it would then be difficult to explain that the N160°E extension has been observed (1) as

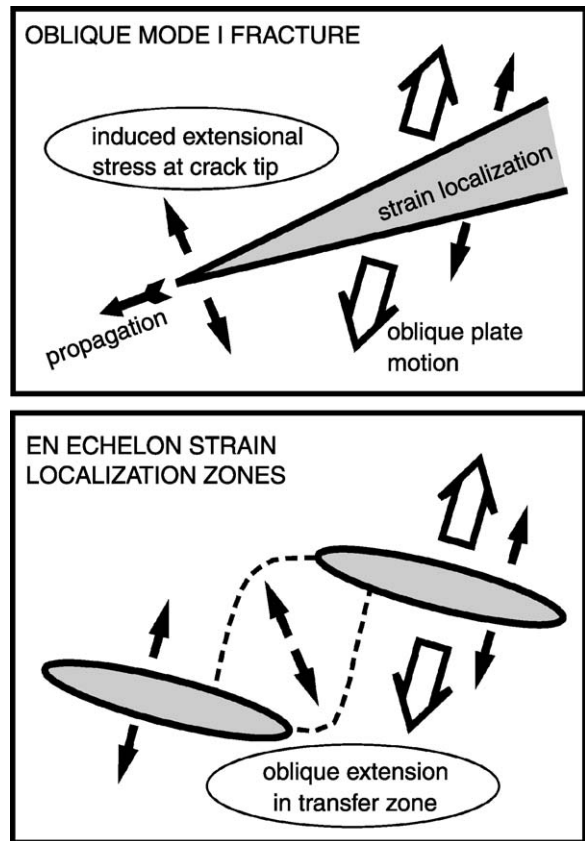


Fig. 8. Sketch of the extensional stresses induced by the oblique propagation of an oceanic rift. Top: lithospheric-scale crack. Bottom: transfer zone between areas of localized strain (onset of oceanic spreading). Open arrows: relative plate motion. Black arrows: extensional stress.

systematically younger than the N20°E one, and (2) not particularly located in zones of relay between the en-échelon basins, but rather within the basins themselves. We consequently rule out such a local explanation, given the fact that the late syn-rift can hardly be perpendicular to the overall trend of the Gulf of Aden just by coincidence.

4.3. Rift propagation or change in plate motion?

The first phase of extension, oriented N20°E on average, is almost parallel to the direction of opening of the Gulf of Aden and to the movement of Arabia toward the northeast, while the second phase (N160°E on average) is perpendicular to the mean trend of the

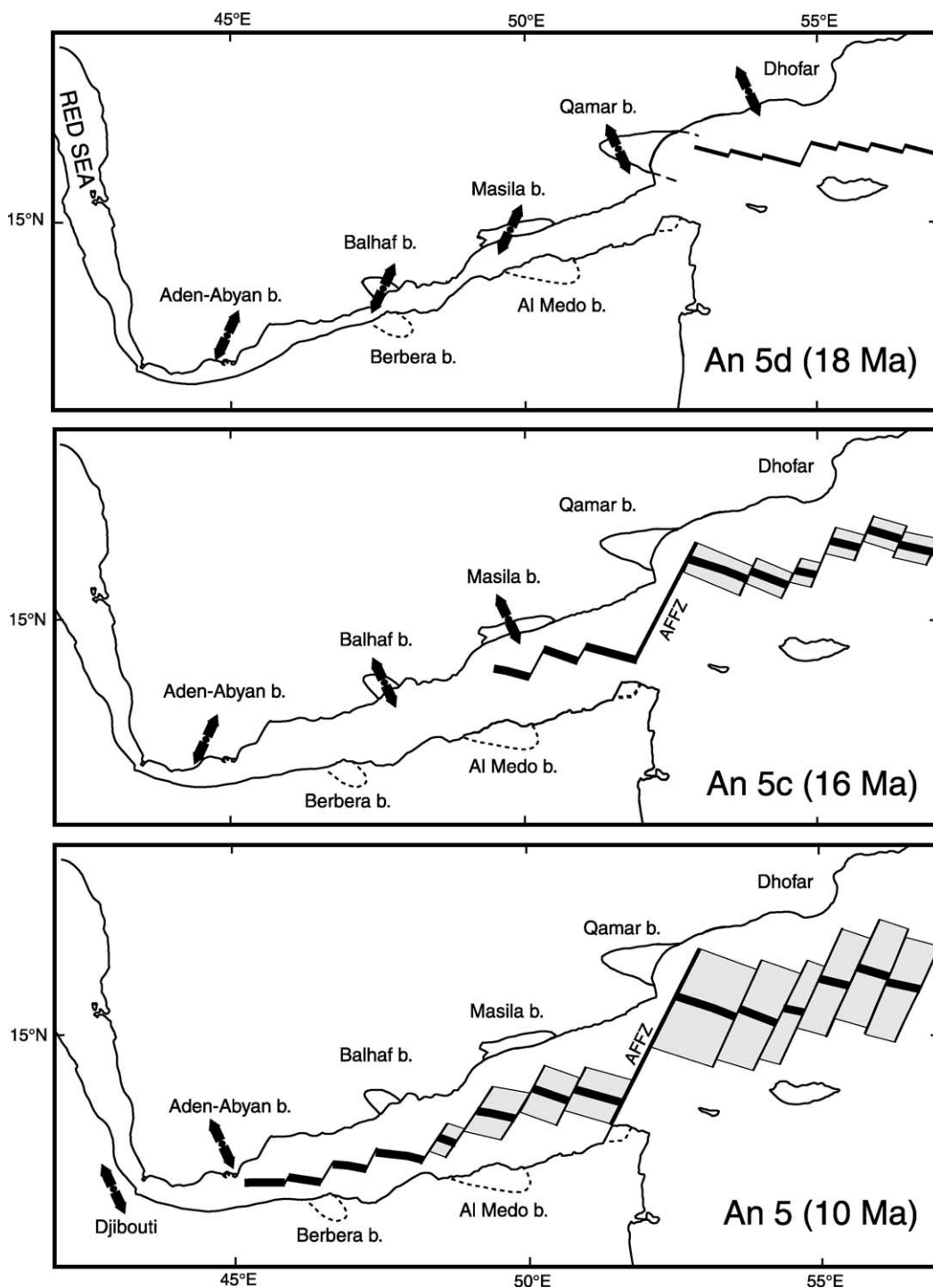


Fig. 9. Reconstructions of the Gulf of Aden at the time of magnetic anomalies 5D (18 Ma), 5C (16 Ma) and 5 (10 Ma) and possible distribution trough time of the syn-rift extension (double arrows) observed in the field (Dhofar: from [Lepvrier et al., 2002](#); Yemen: this work; Djibouti: [Gaulier and Huchon, 1991](#)). AFFZ: Alula–Fartak fracture zone. See discussion in text.

gulf (N70°E). We therefore suppose that the N20°E extension reflects the continental rifting of the Gulf of Aden, starting in the early Oligocene. It is slightly oblique to the present-day motion of Arabia with respect to Somalia but parallel to the inferred motion in Oligocene based on kinematics considerations about the Red Sea–Gulf of Aden–Ethiopian rifts closure (Jestin and Huchon, 1992). When oceanic spreading started to the east of the Alula–Fartak transform fault 19 Ma ago, it did not propagate toward the northeast, perpendicular to the direction of Arabia–Somalia motion, but toward the southwest, toward the Afar hotspot, for reasons summarized in the Introduction. The main point is that fitting the magnetic anomalies in the Gulf of Aden does not require any major change in the direction of plate separation. Consequently, the N160°E extension does not relate to any change in the direction of plate motion, but with the mechanism of propagation itself.

The fact that the late syn-rift extension is perpendicular to the mean trend of Gulf of Aden strongly suggests it occurred in the same way as extensional stresses are generated at the tip of a propagating mode I crack (Jaeger and Cook, 1979) (Fig. 8). This does not affect however the direction of ridge propagation since oblique spreading also implies a component of shear (mode III crack) that stabilizes the propagation direction (Abelson and Agnon, 1997). In this hypothesis, the late NNW extension would have occurred just at the rift-to-drift transition, a timing that is however impossible to demonstrate owing to the scarcity of well-dated syn-rift sediments. In the following, we therefore propose what should be considered only as a working hypothesis.

4.4. A possible scenario for the stress field rotation during rift propagation

Although the stratigraphy is not precise enough to demonstrate it, we envision that the late syn-rift extension becomes younger toward the west, following the progressive westward propagation of the corresponding oceanic crust, from 19 Ma ago to the east of the Alula Fartak fracture zone to a few million years ago to the west of Shukra El-Sheik. Fig. 9 shows three reconstructions of the Gulf of Aden 18 Ma ago (anomaly 5D), 16 Ma ago (anomaly 5C) and 10 Ma ago (anomaly 5). At each step, we show the part of the

Aden ridge that is already spreading and the part where oceanic spreading just initiates, together with the observed directions of extension in the basins of southern Yemen. A straightforward test of this model would be to look for a similar stress reorientation in the basins of northern Somalia, which show a structural pattern similar to that of southern Yemen (Beydoun, 1970; Abbate et al., 1988; Bosellini, 1989; Fantozzi, 1996; Fantozzi and Ali Kassim Mohamed, 2002).

5. Conclusion

Continental stretching and oceanic spreading that led to the formation of the Gulf of Aden between Arabia and Somalia have involved a lithosphere already affected by several phases of extension since the Jurassic. Although the Mesozoic basins are nearly perpendicular to the relative motion between Arabia and Somalia during the Neogene, the Gulf of Aden has cut through these basins in an oblique way. Structural and microtectonic analyses of the basins along the continental margin of Yemen reveal that these basins, formed during the Jurassic and the Cretaceous, have been reactivated from Late Oligocene to Early Miocene with an average stretching direction trending N20°E. However, a late syn-rift, N160°E trending extensional event also occurs along the margin over more than 1000 km between Oman and Djibouti. We interpret this extension, which is perpendicular to the overall trend of the gulf of Aden, as induced by the westward propagation of the oceanic ridge, following a mechanism similar to a tension crack, but of lithospheric scale (Manighetti et al., 1997, 1998; Courtillot et al., 1999).

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