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Cenozoic extension in coastal Dhofar (southern Oman): implications on the oblique rifting of the Gulf of Aden

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Abstract

A detailed analysis of fault populations that affect the Paleocene to early Miocene sedimentary succession of southern Dhofar allows the definition of a time-sequence of paleostresses and the reconstruction of the rifting history of the eastern Gulf of Aden. Two distinct phases of N20°- and N160°-trending extensions took place during the deposition of the synrift Dhofar Group from late Priabonian (35 Ma) to middle Burdigalian (18 Ma). A period of tectonic instability preceded these events, marked by normal and strike–slip faulting as early as the mid-Eocene. The two main directions of extension, also recorded in southern Yemen, developed respectively oblique and normal to the N75E trend of the Gulf of Aden. An anticlockwise succession of the two episodes from N20 to N160, only established in Yemen, accounts for the observed synrift fault pattern, which is consistent with the type and geometry of faults predicted in analogue models of oblique rifting. A latest phase of NS compression, marked by strike–slip faulting, may represent a far echo of the Arabia–Eurasia collision.

Keywords: Fault; Paleostress; Oblique rifting; Arabia; Oman; Dhofar; Gulf of Aden

1. Introduction

The Gulf of Aden is a type example of an oblique opening rift-basin (Laughton et al., 1970; Girdler and Styles, 1978; Chase, 1978; Cochran, 1981; Withjack and Jamison, 1986). In the eastern part of the gulf, the rifting started during the Oligocene and continued until the early Miocene, then followed by oceanization. The spreading direction, given by the azimuth of the main transform fault, the Alula–Fartak transform (insert in Fig. 1), at 14°N and 51.5°E, is N26°E, oblique to the mean N75°E trend of the gulf.

Coastal Dhofar, in southern Oman, faces the Arabian Sea at the eastern entrance of the Gulf of Aden (Fig. 1). As southern Yemen and northern Somalia, the area has been the site of an Oligo–Miocene extension, in relation with the rifting of the Gulf of Aden. Equivalent rift-related deposits are exposed along these two conjugate margins.

Until now, except the study of Platel and Roger (1989), very few investigations have concerned the structural environment and the geodynamic evolution of Dhofar. In this paper, we present the results of a detailed fault–slip field survey, which has been con-

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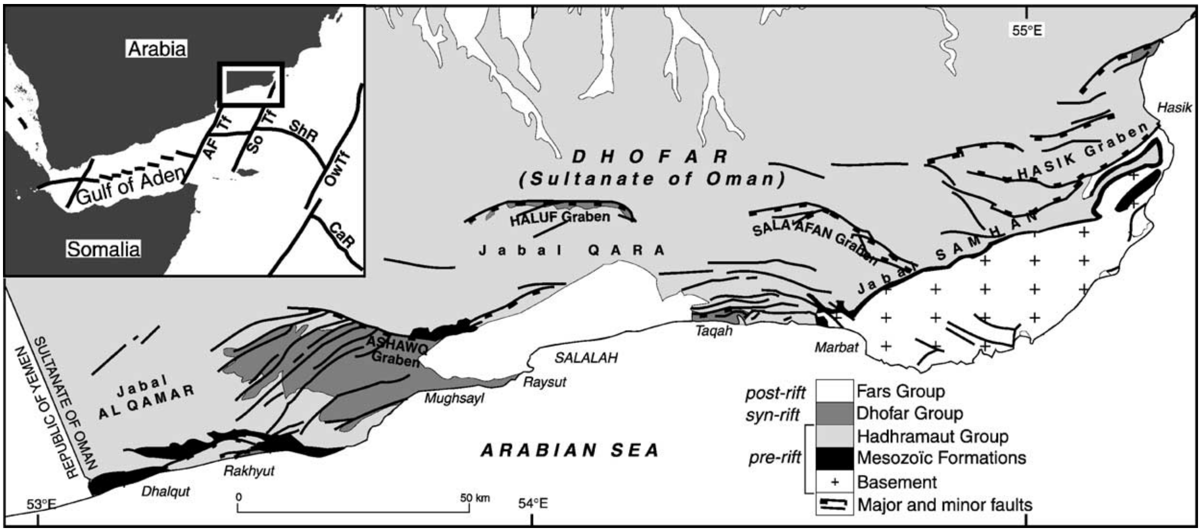

Fig. 1. Structural map and sedimentary units of Southern Dhofar, Sultanate of Oman, derived and simplified from the 1/250 000 geological maps of Salalah and Hawf (Platel et al., 1992; Roger et al., 1992); insert represents the main structures of the Gulf of Aden and the onland study area. Abbreviations are as follows: AF Tf: Alula–Fartak Transform Fault; So Tr: Socotra Transform Fault; Ow Tr: Owen Transform Fault; ShR: Sheba Ridge; CaR: Carslsberg Ridge.

ducted in the Tertiary sedimentary succession, with a special interest for syn-sedimentary faulting. The investigated area from the east to the west of Salalah corresponds in the Gulf of Aden to the E–W trending segment of the Sheba Ridge, between the Alula–Fartak and Socotra transform faults (Fig. 1). This analysis allows us to define a succession of paleostresses. Regional correlations, with recent stratigraphic and tectonic data obtained in Yemen and Somalia (Huchon et al., 1991; Fantozzi, 1996; Fantozzi and Sgavetti, 1998; Watchorn et al., 1998), are established. Geodynamic implications on the rifting and opening of the Gulf of Aden are discussed and compared with analogue experiments (Withjack and Jamison, 1986; Tron and Brun, 1991).

2. Tertiary sedimentary succession

In Dhofar, preliminary explorations were essentially devoted to the establishment of a lithostratigraphic succession in the scope of petroleum investigations (Beydoun, 1964, 1966). Recent systematic mapping, at 1/100 000 and 1/250 000 scale, has been completed by the French BRGM, which led to a significant refinement of the stratigraphy (Roger et al., 1989).

A thick, up to 2000 m, and essentially carbonate marine-dominated succession, including the specific late Eocene to early Miocene Dhofar Group, largely crops out in Southern Dhofar. A northward tilted monoclinal plateau, rising at about 1400 m and bounded by the south-facing escarpments of Jabal al Qamar, Jabal Qara and Jabal Samhan, marks the northern shoulder of the rift (Fig. 1). Good exposures are found in the downfaulted zone separating the interior plateau and the collapsed coastal plain of Salalah-Taqah, as well as in the coastal cliffs of the western area between Mughsayl and Rakhyut.

The series involves three sedimentary groups (Platel and Roger, 1989; Roger et al., 1989) which correspond to prerift, synrift and postrift stages of deposition (Figs. 1 and 2): the Hadhramaut, Dhofar and Fars groups, respectively.

• The Hadhramaut Group, Paleocene (Thanetian) to late Eocene (Priabonian) in age, rests unconformably upon Cretaceous strata, itself overlying a crystalline and metamorphic basement, exposed East of Marbat (Fig. 1), and a Paleozoic sedimentary cover. This Group consists of two thick, shallow-marine,

		Ma	Groups	Formations	Members	Ma	sequences
Upper Middle Miocene		16	FARS	Adawnib		18	POSTRIFT
Miocene Lower	Burdigalian						
	Aquitanian	20	DHOFAR	Mughsayl			SYNRIFT
Oligocene	Chattian	28					
	Rupelian			Ashawq	Nakhlit		
Eocene	Priabonian	34		Zalumah		35	
	Bartonian		HADHRAMAUT	Aydim			PRERIFT
	Lutetian	40		Dammam			
	Cuisian			Rus			
	Ilerdian			Umm Er Radhuma			
Paleocene	Thanetian	53					
	Danian						
Upper Cretaceous	Senonian	65					
	Turonian						
	Cenomanian		DHALQUT	Sarfait			

Fig. 2. Mesozoic and Cenozoic stratigraphic units and rift-related sequences in Southern Dhofar (from Roger et al., 1989).

carbonate shelf units. The late Thanetian–middle Ilerdian limestones with shale intercalations and chert nodules of the Umm er Radhuma Formation (Beydoun, 1964) is up to 600 m thick. The latest early Lutetian to Bartonian Damman Formation and Bartonian to Priabonian Aydim Formation reach more than 400 m. The thin (60 m) dolomitic and evaporitic tidal-flat deposits of the Rus Formation (late Ilerdian to Cuisian) develop in between.

- The Dhofar Group, which follows the late Eocene emergence of the Arabian platform and overlies unconformably the Hadhramaut Group, is only confined on the southern edge of the Arabian plate. It is made of two limestones units: the late Priabonian to Rupelian Zalumah Formation, showing continental lacustrine conditions, and the shallow-marine Rupelian Ashawq Formation (more than 600 m thick). The latter passes laterally at top to the overlying, thin-bedded chalky calci-turbidic deposits (more than 700 m thick), of the latest early Oligocene to early Miocene (middle Burdigalian) Mughsayl Formation.
- The Fars Group is restricted to a narrow zone, inland the present coast line, and is represented by the unconformable Adawnib Formation, early Miocene in age, made of proximal carbonate and conglomeratic marine deposits.

In terms of paleo-environments, the deposits of the Hadhramaut Group characterize two complete transgressive–regressive cycles (Platel and Roger, 1989; Roger et al., 1989; Le Métour et al., 1995). The first cycle marks the establishment of the extensive Arabian Platform in the late Thanetian and its emergence by the end of the Ypresian, as announced by the restricted conditions during the deposition of the Rus Formation. The second corresponds to the reinvasion of the platform during the Lutetian and Bartonian and its second emergence in late Priabonian, which implies a significant uplift of the shoulder of the rift, prior to the rifting.

Shallow-marine conditions were re-established in Dhofar probably as early as latest Priabonian and in any case by early Oligocene, with the deposition of the Zalumah and Ashawq Formations. They were followed at the end of the early Oligocene, as a result of the collapse and subsidence of the margin, by deeper depositional environments, represented by the calci-turbidite slope deposits of the Mughsayl Formation, including mega-breccia, debris flows and olistolitic material, which were transported from the adjoining shelf. Deeper marine conditions persisted until the early Miocene (middle Burdigalian).

A tectonic readjustement caused at that time the northward tilting and the subsequent emergence of the entire southern Dhofar, which was then subjected to erosion. As a result of this regression, a new change in the type of sedimentation, from open to shallow marine carbonate and detritic deposits, is expressed in the facies of the Fars Group, which unconformably overlies the bathyal sediments. Sedimentary conditions were at that time very similar to the present-day environments.

Equivalent rift-related deposits and depositional sequences are described along the conjugate Yemeni and Somali margins of the Gulf of Aden (Beydoun, 1970, 1982; Bosellini, 1992; Abbate et al., 1988, 1993; Fantozzi, 1996; Fantozzi and Sgavetti, 1998; Watchorn et al., 1998). In Yemen, the Shihr Group, equivalent to the Dhofar Group, is early to middle Oligocene (Rupelian–Chattian) in age (34–28 Ma) at the base of the sequence, while the top is middle Burdigalian (18 Ma). An eastward deepening of the synrift deposits is observed from continental to shallow-marine (Yemen) and deeper-marine (Dhofar) conditions.

3. Tectonic and geodynamic setting

Tertiary southern Dhofar deposits are largely fault-controlled. A pattern of E–W to WNW-trending normal faults, with a left-stepping en echelon arrangement, can be observed, in association with another set of NE to ENE faults. This fault network has a curvolinear shape probably due to the lateral linkage of individual fault segments (Fig. 1).

The normal faults bound tilted blocks and half-graben structures (Fig. 3), from the dominating plateau down to the coastal plain, and delineate graben structures on the plateau itself (Platel and Roger, 1989). Significant displacements, with throws in the order of several hundred meters, have occurred on the major faults. An eastward plunge of the graben axes is generally observed. In the East, the NE–SW Hasik graben and the Sala'afan graben, several tenth of kilometers long, develop north of the basement between Marbat and Hasik (Fig. 1). North of Salalah, the E–W to NE–SW Haluf graben, filled by the Upper Eocene sediments of the Aydim and Zalumah Formations, entrenches the Jabal Qara. In the western zone of Mughsayl–Rakhyut, the Jabal Al Qamar is intensively dissected by a dominant set of NE to ENE faults, which branch to the north on the major N100°E marginal fault of the early Oligocene Ashawq graben (Figs. 1 and 3); to the south, a ENE-trending fault bounds the graben and the Aquabat horst (Platel and Roger, 1989; Robertson and Bamkhalif, submitted for publication).

A similar system of WNW–ESE en echelon faults characterizes the neighbouring Hadhramaut zone of Yemen (Watchorn et al., 1998). A comparable geometry is depicted in northeastern Somalia (Fantozzi, 1996; Fantozzi and Sgavetti, 1998). As illustrated on pre-drift reconstructions, the embryonic rift thus consisted in N90°E to N120°E trending grabens, arranged en echelon along the N75°E direction of the gulf; they were separated by NE structural highs interpreted as transfer zones (Tamsett, 1984; Fantozzi, 1996; Fantozzi and Sgavetti, 1998). Rather than NE strike–slip faults, curved normal faults are observed in the connecting zones.

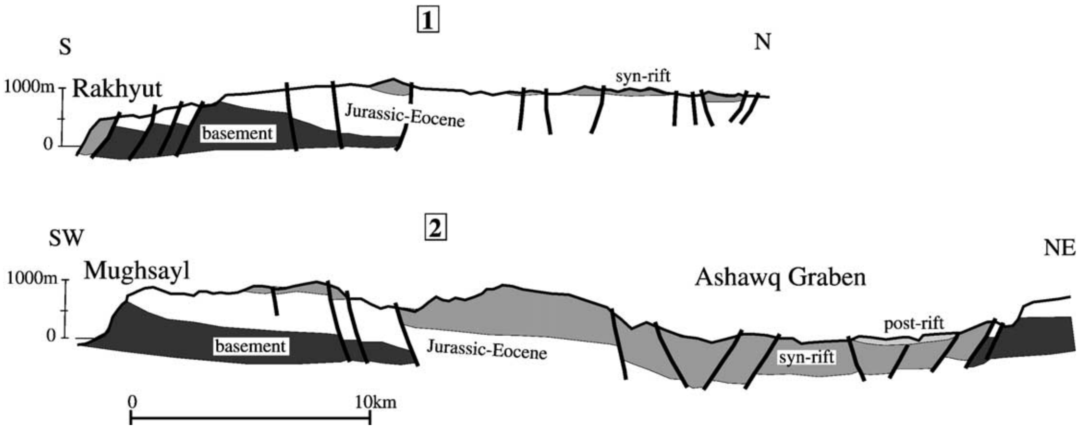

Fig. 3. Generalized cross-sections of the northern margin of the Gulf of Aden in Southern Dhofar, West of Salalah. Simplified from the geological maps of Hawf (Roger et al., 1992) and Salalah (Platel et al., 1992).

To a large extent, the development of the oceanic structures of the Gulf of Aden (Laughton, 1966; Laughton et al., 1970; Cochran, 1981), represented by E–W to WNW–ESE ridge segments (Aden and Sheba median rift Zones) and NE–SW transform faults as the Alula–Fartak (insert Figs. 1 and 8), has been strongly conditioned and guided by the Oligo–Miocene oblique rift trends (Cochran, 1981; Abbate et al., 1988; Bosellini, 1992; Fantozzi 1996). The trace of the transform faults is expressed by lateral offsets in the conjugate margins (Tamsett and Searle, 1988). Similarly, the NE–SW fault-system of the Jabal Al Qamar in the area of Rakhyut (Fig. 1), as well as the faults located East of Ra's Fartaq in Yemen (Fantozzi and Sgavetti, 1998), appear as the direct onland continuation of the Alula–Fartak transform (Platel and Roger, 1989).

Such Oligo–Miocene fault pattern may have been influenced by the Jurassic–Lower Cretaceous rift system, which, in the area, displayed a sub-parallel trend. This older system is known in contiguous Yemen and also in the Socotra area which, prior to the opening of the Gulf of Aden, was lying adjacent to Southern Dhofar (Bosence, 1997; Bott et al., 1992; Birse et al., 1997; Samuel et al., 1997).

4. Fault–slip data and paleostress tensors

Numerous striated fault planes affect the sedimentary pile. The population consists in two sets of W–WNW- and NE–ENE-trending faults, similar to the double system of faults recognised at map scale. Fault–slip data have been collected at various stratigraphic levels. Some of the sites concern the Umm er Radhuma Formation, which gives rise to a well-marked escarpment at the lower part of the sedimentary succession. Some others are located in the Nakhlit Member (Rupelian) at the top of the Ashawq Formation, which is extensively exposed along the asphalt road from Mughsayl to Sarfayt. Many sites have been analysed in the Mughsayl Formation, which crops out widely in the same area. Distinct episodes of brittle tectonics have been recognised, coexisting in the same Formation and in the same site. Within the Mughsayl Formation, syn-sedimentary faulting activity is obvious; soft-sediment deformation also concerns the Rus Formation. After separation on the field of the fault slip data sets, stress tensors has been computed (Table 1), using the direct inversion method (Angelier, 1984, 1990).

Table 1
List of paleostress tensors

Site number		Number of faults	Formation	Member	σ_1 Strike	σ_1 Dip	σ_2 Strike	σ_2 Dip	σ_3 Strike	σ_3 Dip	Φ
1	A	20	MUGHSAYL		139	81	304	8	34	2	0.56
1	B	14	MUGHSAYL		355	4	238	82	86	7	0.39
2	A	21	ASHAWQ	NAKHLIT	113	86	250	3	340	2	0.54
3	A*	6	ASHAWQ	NAKHLIT	53	72	289	10	196	14	0.41
3	B	8	ASHAWQ	NAKHLIT	13	31	171	57	277	10	0.41
3	C	10	ASHAWQ	NAKHLIT	58	35	267	51	159	14	0.39
4	A	9	MUGHSAYL		191	70	291	4	23	19	0.03
7		11	DALQUT	SARFAIT	134	88	294	2	24	1	0.49
8	A	11	DAMMAM	QARA	7	78	274	1	184	11	0.38
8	B	8	DAMMAM	QARA	72	17	289	68	165	12	0.56
9		5	UER		101	78	248	10	339	7	0.38
12		5	ZALUMAH		197	3	80	83	287	6	0.4
13	A	10	UER		290	73	65	12	158	11	0.31
13	B	7	UER		138	81	347	8	257	4	0.26
15		9	UER		182	76	296	6	27	12	0.09
18		14	ASHAWQ	SHIZAR	225	69	78	17	345	10	0.24
20		14	UER		167	81	61	3	331	8	0.36
21		14	ASHAWQ	NAKHLIT	195	81	54	7	323	5	0.36
22		18	MUGHSAYL		354	85	247	1	157	5	0.44

A, B and C refer to the distinct phases found in the same site (without chronological meaning); trend (clockwise from North) and plunge (from the horizontal) of the principal stress axes σ_1, σ_2 and σ_3 are given in degrees; Φ is the stress ellipsoid ratio $(\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$.

4.1. Extensional faulting events

Three distinct directions of extension have been determined: NNW–SSE, NNE–SSE and ENE–WSW to E–W (Fig. 4). The first two are recorded as early as the Upper Cretaceous and throughout the entire Tertiary succession up to the Mughsayl Formation, Upper Oligocene to Lower Miocene in age. Nevertheless, according to our observations they never coexist in the same site. In some cases, an intermediate sub-meridian direction is obtained (site 8A). In contrast, the E–W extension has been found together with the NNW–SSE to N–S extension in several sites (10, 13, 19) (Figs. 4 and 5).

The Cenomanian upper carbonate sequence of the Dhalqut Formation, which outcrops near Marbat (site 7), has experienced a NNE–SSW extension, manifested on ESE–WNW conjugate normal faults.

The cliff-forming Umm er Radhuma Formation, at the base of the Tertiary strata, displays essentially ENE-trending (N050°E to N080°E) conjugate normal faults (sites 9, 13, 15 and 20), from which a generally NNW direction of the minimum principal stress axis has been determined. In site 13B, a distinct ENE-oriented extension has been evidenced from a set of sub-meridian normal faults. In the following, Rus Formation two sets of approximately N–S and E–W (site 10) or NE–SW (site 19) joints and syn-sedimentary fault planes (generally non-striated) exist, from which E–W, N–S and NW–SE in average directions of extension can be inferred.

In the upper carbonate sequence of the Dammam Formation (site 8), these N–S and E–W directions of extension have also been identified. The latter is only determined from non-striated sub-meridian fault planes.

The upper carbonate sequence (Nakhlit) of the Ashawq Formation is characterized by pinky to reddish limestones with abundant stylolites. It is intensively faulted by a dominant system of NNE to ENE oblique to dip–slip extensional faults. Spectacular fault planes, with up to 5–10 m down-throw, are exposed along the main road which cuts through this plateau-forming unit in the western area. In the cliff

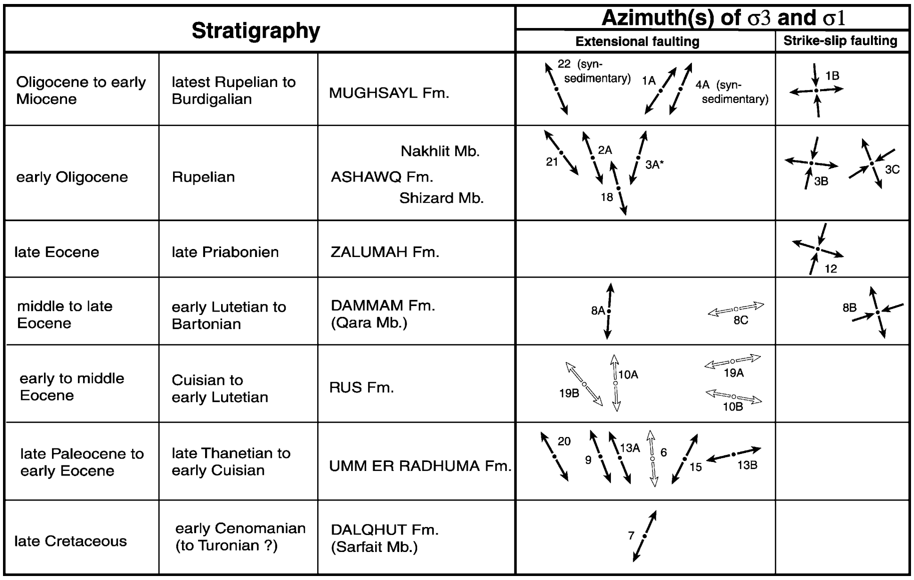

Fig. 4. Summary diagram of the extensional and strike–slip faulting events recorded in the different stratigraphic Formations of Southern Dhofar. Note that local paleostresses, for a given site, are not placed according to their ages but in correspondence with the stratigraphic age of the Formation in which they have been determined (i.e. the same age in case of syn-sedimentary faulting). See in the text (paragraph 4) the discussion related to the time succession of the major regional paleostresses. Site numbers are those in Table 1. Black and white arrows refer respectively to computed or inferred directions of σ_1 and σ_3.

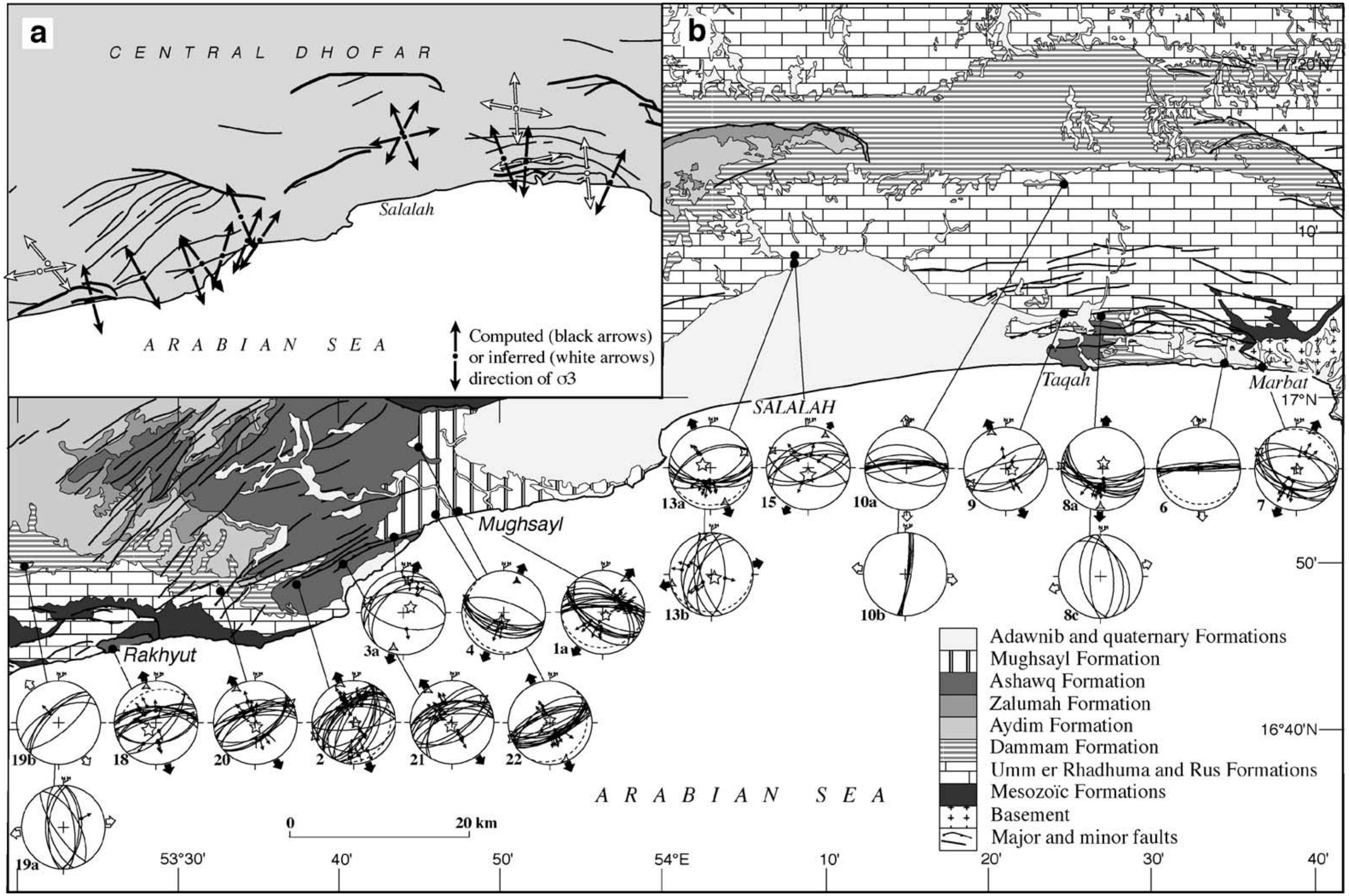

Fig. 5. (a) Main fault structures and directions of Oligo–Miocene extension in Coastal Dhofar. (b) Corresponding stereoplots (equal-area lower hemisphere stereonet) of striated fault planes at different localities and in different formations. Divergent black or white arrows refer to the computed or inferred estimated direction of σ_3; stars correspond to the main stress axis σ_1 (five branches), σ_2 (four branches) and σ_3 (three branches). Numbers refer to the studied sites.

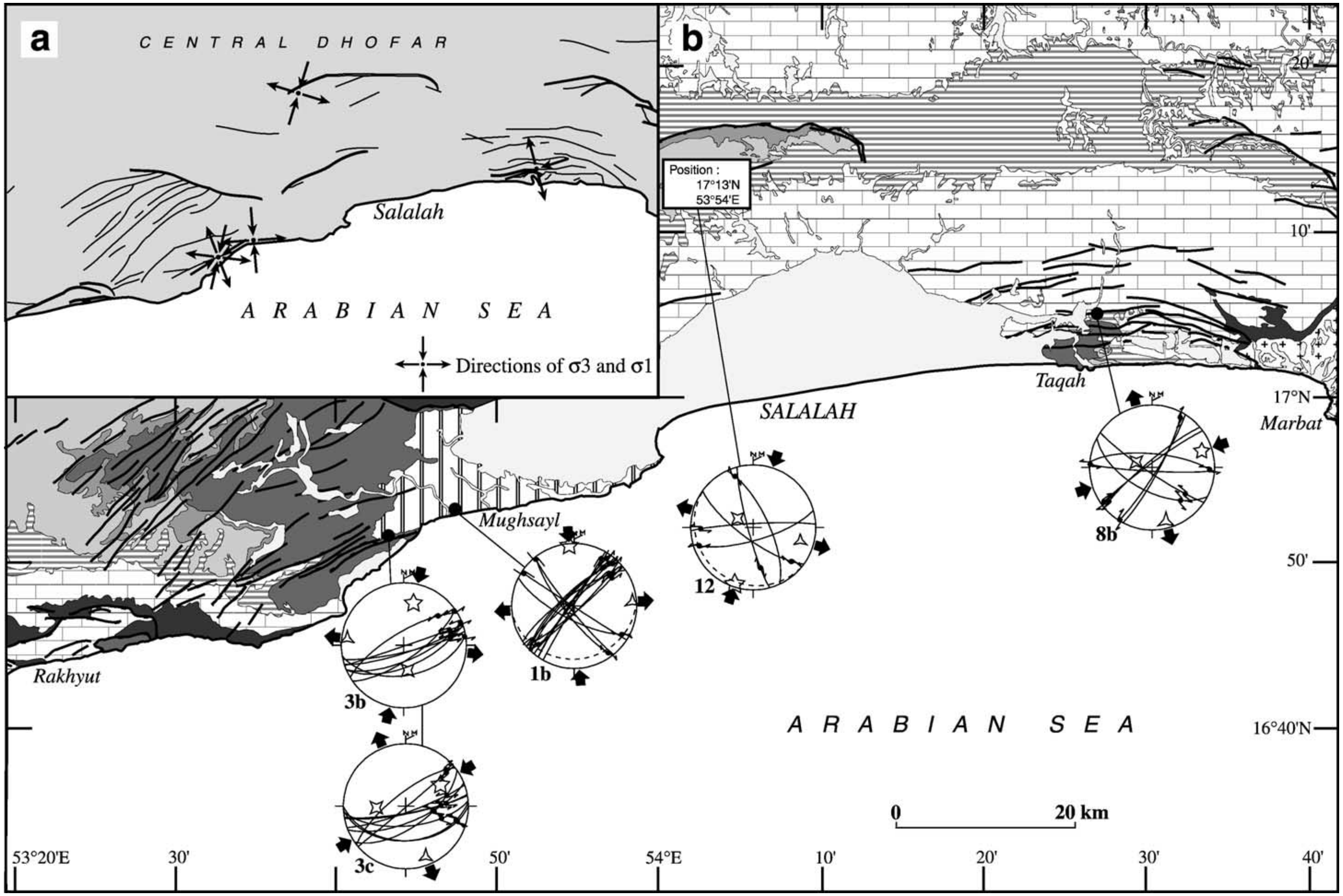

Fig. 6. (a and b) Strike–slip faulting events. Same legends as in Fig. 5a and b.

behind the village of Rakhyut, the lower clay–carbonate sequence of Ashawq Formation is itself affected by a major normal fault and by a lot of other subsidiary ENE- to E-trending faults. The corresponding direction of extension recorded in the Ashawq Formation varies from NW (site 21) to NNW (sites 2A and 18) and to NNE (site 3A).

In the Upper Oligocene to Lower Miocene Mughsayl Formation, which exhibits well-developed syn-sedimentary faults and gravity-induced features, a well-defined NE-directed extension is deduced from two sets of conjugate E–W to ESE–WNW faults. This can be observed in the outcrops behind Mughsayl village (site 1A) and West of Mughsayl in the cliffs crosscut by the asphalt Road to Rakyut (site 4A). Locally, contractional reverse faults and associated syn-sedimentary folds can also be seen. They are likely formed at the same period of time, and can be interpreted as a result of slumping, then indicating a local and similarly oriented NE–SW direction of local compression. Another episode of syn-sedimentary faulting activity with a NNW–SSE direction of extension is recorded in a Wadi, north of Mughsayl (site 22), through a distinct system of ENE–WSW syn-sedimentary normal faults.

4.2. Strike–slip faulting events

Two episodes of strike–slip faulting have been identified in the Upper part (second half) of the stratigraphic succession, since the middle Eocene (Fig. 4). One is defined by a N–S to NNE–SSW direction of compression and a subsequent E–W extension, with a conjugate set of NE to ENE sinistral faults and NW-trending dextral faults. It affects the different Formations of the Dhofar Group (late Eocene to early Miocene). The other one gives rise in contrary to dextral movements on the NE–SW fault system whereas sinistral movements occur on E–W to ESE–WNW faults. This strike–slip regime, which corresponds to ENE compression and NNW extension, is recorded as early as the upper part of the Dammam Formation (middle to late Eocene). Both are present in the upper part (Nakhlit) of the early Oligocene Ashawq Formation (sites 3B and 3C), where the directions of compression are underlined by two generations of sub-horizontal stylolitic peaks (Figs. 4 and 6).

5. Chronology of tectonic events

The relative chronology of the different phases of brittle deformation has been deduced from field criteria, such as observations of crosscutting and offsetting fault structures, while their age has been constrained by the existence of syn-depositional faults in well-dated rocks.

A chronologic sequence of tectonic events and paleostresses can be proposed, based on the following observations. The two main and distinct NW–SE (N160°E) and N–S to NNE–SSW (N20°E) directions of extension are recorded in the entire sedimentary pile (Fig. 4). These phases of extension correspond to a syn-sedimentary activity during the deposition of the topmost Mughsayl Formation (latest early Oligocene to early Miocene) of the Dhofar Group. Hence, it is reasonable to consider that the normal faults present in the lower part of the succession are due to the same latest early Oligocene to early Miocene period of normal faulting. But it cannot be totally exclude that these extensions were already prevailing by the end of the Bartonian, during the deposition of the Zalumah and Ashawq Formations, prior to the final collapse of the margin and the deposition of the Mughsayl Formation. It has not been possible to establish a relative succession of these two episodes, which have never been observed in the same site and therefore do not exhibit direct crosscutting relationships. They could have been sub-contemporaneous. Possibly also, the minimum horizontal stress switched from N20 to N160 and back again, several times. However, some field evidences in Yemen clearly demonstrate an anticlockwise rotation of the similar extensional trends (Huchon et al., 1991).

The average E–W direction of extension present in the lower part of the Tertiary (Umm er Radhuma, Rus and Dammam Formations) and locally manifested by syn-sedimentary movements represents an earlier event. As pointed out by Platel and Roger (1989), instability, if not a clear tectonic phase, was already present during the Cuisian–early Lutetian. The relative thickness in the area of the Dammam and Aydim Formations is symptomatic, as soon as the middle–late Eocene, of a flexuration of the future margin, which anticipates the Oligo–Miocene rifting.

Considering the strike–slip faulting events, no direct field observations allow to establish their relative timing. But their occurrences with respect to the extensional episodes can be sometimes determined. For example, in the Mughsayl Formation (site 1), as proved by crosscutting relationship, the strike–slip phase, characterized by a N–S and E–W directions of σ_1 and σ_3, post-dates the pure phase of NE extension and therefore can be considered as Miocene in age. In contrast, the strike–slip faulting episode, marked by a ENE direction of σ_1 and a subsequent NNW direction of σ_3, and giving rise to dextral movements on the NE-trending fault set, seems to precede the pure N–S extension in the Dammam Formation. This change could be the result of a permutation between σ_2 and σ_3 stress axes.

6. Regional correlations

6.1. Age of rifting and oceanization

Considering the onset of rifting and the synrift fault development, the data obtained in southern Dhofar are consistent with those documented in contiguous Yemen and in northeastern Somalia.

• In southern Yemen, faulting is inferred to have occurred during three main episodes, with possible local tectonic movements at intervening times (Watchorn et al., 1998). First phase corresponded to the pre-synrift unconformity and took place in the late Eocene between 42 and 35 Ma (Fig. 2). A second event is supposed to correspond to another unconformity around 30 Ma, after an increase of the subsidence rate during the deposition of the synrift Shihr Formation. The third episode occurred prior to the post-rift deposition between 21 and 17, 5 Ma. However the absence of syn-sedimentary deformation within the synrift Shihr Formation tends to indicate that the sediments have infilled passively earlier formed depressions (Watchorn et al., 1998).

• In Somalia, on the opposite conjugate margin, initial phases of rifting occurred in the early Oligocene, (Bosellini, 1992; Fantozzi and Sgavetti, 1998), while another stage has been reported at the Oligo–Miocene boundary (Abbate et al., 1988).

Thus, the period of rifting and active faulting in the central part of Gulf of Aden lasted about 15 Ma, starting 35 Ma ago in the late Eocene–early Oligocene, climaxing around 30 Ma and being completed with the deposition of the post-rift sediments since 18 Ma.

In contrast, the beginning of the accretion is not well constrained. Magnetic anomalies of the oceanic crust have been identified in the basin until the anomaly 5 (11 Ma; Cochran, 1981). Outside of the typical oceanic crust area, a magnetic quiet zone corresponds to a deep sedimentary basin. A slope break in the acoustic basement below a sedimentary scarp seems to delineate the real extent of the oceanic crust (Cochran, 1982). A basalt sample, drilled in this zone at site 231 of the DSDP Leg 24, provided a radiometric age of 13 Ma (Shipboard party, 1974). According to Le Pichon and Gaulier (1988), 13 Ma marks the onset of accretion. Recent work by Bott et al. (1992) and Sahota et al. (1995) indicate that oceanization started as soon as 18 Ma (early Miocene), E of the Allula–Fartak transform, between Dhofar and Socotra.

6.2. Directions of extension

Direction of extension during the rifting period is not well-established in northeastern Somalia, although a NE-oriented extension is inferred from the existence of down-dip strike on faults striking WNW–ESE (Fantozzi, 1996). In Yemen, a precise kinematic history has been obtained in the area of Aden, at the SW corner of the Arabian Peninsula. A succession of three extensional tectonic movements has been recorded in the volcanic traps (Huchon et al., 1991):

(1) An initial E–W extension coincided with the main period of emplacement of the volcanic pile from the Oligocene (30–25 Ma) until the lower part of the early Miocene (22 Ma) with a possible onset as soon as the Eocene.

(2) A drastic change to an average N–S direction of extension then occurred and remained until the upper part of the early Miocene (18 Ma), as a result of the dominant influence of the proto-Aden Gulf. During this rather short period of time, an anticlockwise rotation of the minimum stress axis from N020°E to N160°E took place.

(3) A third period of NE–SW extension is bracketed between 18 and 10 Ma (mainly Middle Miocene)

which correlates with the transition from continental rifting to sea-floor spreading (around 13 Ma).

These directions of extension, also recorded in southeastern Yemen (Khanbari, 2000), are exactly similar to those obtained in Dhofar but their chronology is somewhat distinct. The N020°E and N160°E directions of extension were prevailing in Dhofar as early as late early Oligocene during the deposition of the Mughsayl Formation. They are manifested in western Yemen only in the upper part of the early Miocene, this diachronism being explained, probably, by the westward migration of the rift. By contrast, the poor record of the preliminary E–W extension in southern Dhofar resulted from its position far from the Afar triple junction and thus out of the influence of the proto-Red Sea and Ethiopian rift.

7. Implications on the rifting of the Gulf of Aden. A discussion

The existence of mechanical or thermal heterogeneities preexisting in the continental lithosphere is generally invoked to explain the localization and development of oblique rifts.

Heterogeneities of lithospheric scale are generated by mantle plumes which impinge on the base of the continental lithosphere. Morgan (1983) pointed out that hot-spot tracks correspond to zones of weakness in the lithosphere as a result of long-term thermal effect and suggested that the Gulf of Aden partly followed the Comoros hot-spot track formed between 180 and 120 Ma. The influence of the Afar hot spot (Morgan, 1971; Schilling et al., 1992) on the development of the Aden–East African–Red Sea rift system appears more obvious since it is located below the Arabia–Nubia–Somalia triple junction. Courtillot et al. (1987) and Manighetti et al. (1997) proposed that the southwestwards propagation of the Aden rift was guided by the existence of a kink in the early East African–Red Sea rift branches of the Afar triangle. In such a configuration, the rift tip tends to reach the nearest point of the plate boundary. Courtillot et al. (1998) suggested that the kink was directly related to the Afar mantle plume.

At crustal scale, the synrift fault pattern of the Gulf of Aden, which consists in N90°E to N120°E trending grabens arranged en echelon along the N75°E direction (Fig. 7) might be explained by a reactivation of the Mesozoic rift system which displayed similar

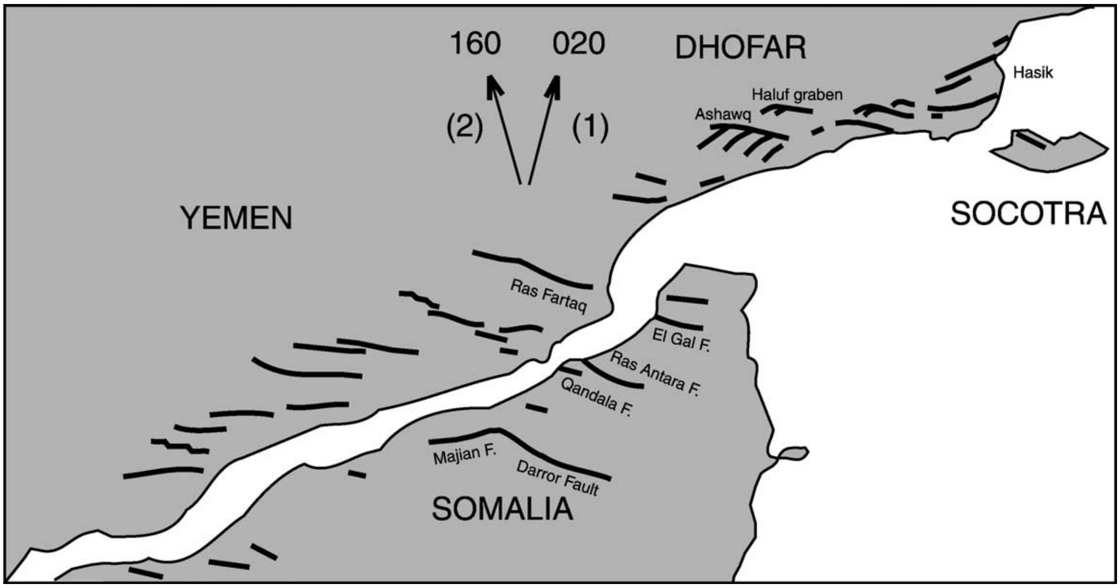

Fig. 7. Sketch map to illustrate the Oligo–Miocene synrift fault pattern of the Gulf of Aden (after Fantozzi and Sgavetti, 1998; Platel and Roger, 1989). The fault geometry resulting of the superposition of successive oblique (N20°E) and normal (N160°E) extension, with respect to the trend of the rift, is consistent with the analogue model of Bonini et al. (1997).

trends. On the other hand, the rift development can be interpreted in the light of results of analytical and analogue models of oblique rifting (Withjack and Jamison, 1986; Tron and Brun, 1991). These experiments show that the trend of the en echelon normal faults, which accommodate oblique rifting in clay and sand-silicone models, are not perpendicular to the displacement direction but depends on the rifting obliquity, i.e. the angle between the normal to the rift trend and the displacement direction. In the Gulf of Aden case study, the mean azimuth of the Arabia–Somalia relative motion is currently N25°E and probably had not change significantly since the beginning of the rifting about 30 Ma ago (McKenzie et al., 1970; Cochran, 1981). As the mean trend of the Gulf of Aden is N75°E, the rifting obliquity, with respect to the spreading direction, is 40°. With such a geometry, the analogue models predict that the normal faults would strike about 20° clockwise from the rift trend, i.e. N90°E–N100°E. Moreover, the azimuth of the extensional principal strain σ_3 would be nearly perpendicular to the normal fault trend, that means N10°E or so. In addition, the expected faults would be sigmoidal, tending to parallel the rift margins, as also shown in analogue two-stage models, which consist in the succession and superposition of oblique and normal extension, at less than 45° from each other. In such a case, the early oblique faults with en echelon pattern, which are produced, continue to develop but tend to progressively connect, giving rise to a sigmoidal fault geometry (Bonini et al., 1997).

These predictions can be compared with the active deformation at the ridge on one hand, and the synrift deformation on the margins on the other hand.

At the ridge, the T seismic axis of the tensional earthquake focal mechanisms inform on the direction of extension. This strain orientation depends on the spreading direction and the ridge strike (Withjack and Jamison, 1986; Dauteuil and Brun, 1993). The mean direction of extension along the Aden–Sheba ridges

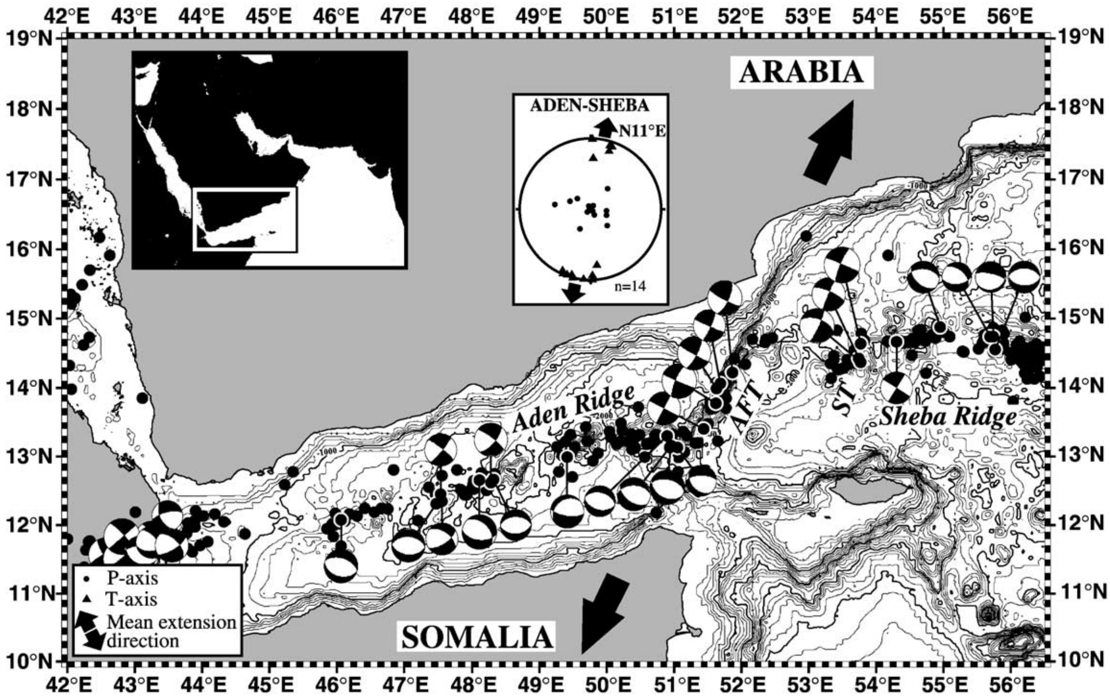

Fig. 8. Bathymetric map, shallow seismicity since 1973 (focal depth < 50 km; magnitude>2; USGS/NEIC Data Base), and all available earthquake focal mechanisms (Harvard CMT; Dziewonski et al., 1999) for the gulf of Aden region. Inserted stereoplot s give the equal-area projections of the P and T axes of the extensional and strike–slip focal mechanisms for the Aden–Sheba ridges and for the Alula–Fartak transform fault (AFT). The mean direction of extension (N11°E) is given by the T axis.

determined from 14 tensional mechanisms (Dziewonski et al., 1999) is N11°E (Fig. 8). Although mechanically wrong, this statistical approach of the distribution of the T axis provides a reliable information, because the focal mechanisms are dip–slip in type. Such a result is in very good agreement with the direction predicted by the analogue models.

The modelling results of oblique rifting fully account also for the Dhofar synrift fault pattern and for the existence of two distinct N20 and N160 extensions, as far as their relative timing would be similar to the succession observed in Yemen. During the initial N20°E extensional stage, N100–120°E normal faults developed, oblique to the rift direction; they displayed an en echelon geometry within an overall dextral shearing setting along the rift borders. While the rift propagates toward the WSW, the subsequent extension becomes orthogonal (N160°E) to the rift trend. As the angle between the two directions of extension is less than 45°, the final fault pattern (Fig. 7) is a curved shape of the initial en echelon oblique faults.

8. Conclusions

During the Cenozoic, southern Dhofar experienced an extensional regime, which led to the rifting and drifting of the Gulf of Aden. Extension, as deduced from the fault–slip data, was dominantly oriented in a NNE to NNW direction. Stretching culminated in the latest early Oligocene to the early Miocene, during the deposition of the Mughsayl Formation, when the margin started to deepen. Thickness variations, symptomatic of differential subsidence and flexuration at the emplacement of the future margin, are reported during this period of time (Platel and Roger, 1989; Roger et al., 1992). Such submeridian extension probably initiated earlier, with the deposition of the late Eocene Aydim and Zalumah Formations and was preceded by a first phase of strike–slip faulting with a similar direction of extension. The E–W extension, poorly expressed by syn-sedimentary movements and instabilities during the deposition of the Eocene Rus and Dammam Formation, thus prior to the establishment of the submeridian extension, could reflect the far influence exerted by the Red Sea branch of the rift system. The second phase of strike–slip faulting with a north to north northeast direction of compression took place later during the Miocene, but the event cannot be temporally constrained. It could represent an echo of the collision of the Arabian and Eurasian plates in the post Middle Miocene.

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