YOUNG RIFT KINEMATICS IN THE TADJOURA RIFT, WESTERN GULF OF ADEN, REPUBLIC OF DJIBOUTI

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ABSTRACT.

The Tadjoura rift forms the westernmost edge of the westerly-propagating Sheba ridge, between Arabia and Somalia, as it enters into the Afar depression. From structural and remote sensing dataset, the Tadjoura rift is interpreted as an asymmetrical south-facing half-graben, about 40 km-wide, dominated by a large boundary fault zone to the north. It is partially filled up by the 1-3 Ma-old Gulf Basalts which onlapped the older Somali Basalts along its shallower southern flexural margin. The major and trace element analysis of 78 young onshore lavas allows us to distinguish and map four distinct basaltic types, namely the Gulf, Somali, Goumarre and Hayyabley Basalts. These results, together with radiometric age data, lead us to propose a revised volcano-stratigraphic sketch of the two exposed Tadjoura rift margins, and to discriminate and date several distinct fault networks of this oblique rift. Morphological and statistical analyses of onshore extensional fault populations show marked changes in structural styles along-strike, in a direction parallel to the rift axis. These major fault disturbances are assigned to the arrest of axial fault tip propagation against pre-existing discontinuities in the NS-oriented Arta transverse zone. According to our model, the sinistral jump of rifting into the Asal-Ghoubbet rift segment results from structural inheritance, in contrast with the *en échelon* or transform mechanism of propagation that prevailed along the entire length of the Gulf of Aden extensional system.

Keywords: Afar, Tadjoura rift, active/recent extension, faults, basalts, oblique rifting, rift propagation, inherited structures.

INTRODUCTION

The overall architecture of rift/ridge systems is controlled by several physical parameters which interact at various scales of times and space, and usually lead to intricate geometrical configurations. The large-scale spatial architecture of a propagating rift is known to depend merely on the absolute motions of the bounding plates, and on major lateral discontinuities in the strength of either the upper crust (e.g. inherited structures), or the lower crust (e.g. partial melt zones) (*Ziegler and Cloetingh*, 2004; *Wijns et al.*, 2005). At a smaller scale, the segmentation of the spreading axis within the rifted zone itself is commonly assigned to (i) its obliquity to the extension direction, and (ii) the angle between the axis of individual rift segments and the general trend of the rifted zone (*Abelson and Agnon*, 1997). The resulting complex multi-scale rift architecture is typically expressed along the Sheba westerly-propagating rift-drift system (Eastern Afar) by two nearly orthogonal first-order arms that, in turn, display specific segmented axial patterns (Figure 1A-B). Along most of its EW-trending path, the Sheba oceanic ridge is systematically offset to the southwest. This offset occurs through either a left-stepping ridge-transform network (up to the Shukra El Sheikh discontinuity, e.g. *Manighetti et al.* 1997) or oblique transfer zones with onlapping fault networks, up to the Tadjoura rift (TR) to the west (Figure 1B) (*Cochran*, 1981; *Tamsett and Searle*, 1988; *Manighetti et al*., 1997; *Dauteuil et al*., 2001). There, the nearly EW-trending axis veers abruptly counter-clockwise into the N120°E-oriented Ghoubbet rift, which is part of a submeridian, and partly emerged, rifted zone encompassing to the north the Asal and Manda Inakir *en échelon* subrifts (Figure 1B) (*Manighetti et al*., 1998). The structural link between the two sub-orthogonal rift arms in the TR has been variously interpreted, and assigned to either a large-scale dextral fault zone, in the prolongation of the NE-SW Maskali transform fault (Figure 1B) (*Ruegg et al*., 1980; *Arthaud et al.*, 1980; *Gaulier and Huchon*, 1991), or to an overlapping fault zone enclosing a network of *en échelon* structures (Figure 1D) (*Manighetti et al*., 1997).

The main goal of the present work is to address the mechanism of strain transfer between the Tadjoura and Ghoubbet rifts, with emphasis on the structure of the TR. Our study integrates (i) available seismic and bathymetric offshore data, (ii) sampling, geochemical analysis and K/Ar dating of young basalts from the Djibouti Plain, which lead us to propose a new geological map of the southern part of the TR, and (iii) structural analyses based on field studies and remote sensing interpretation.

These new data allow us to demonstrate that the TR typically displays a half-graben structure, which recorded a progressive shift of strain towards its inner part during the last 3 Ma. In addition, we propose that submeridian structural discontinuities, emplaced at an early stage of rifting in the Arta transverse zone (Figure 1B) may have locked the westerly propagation of extension in the TR, hence causing the jump of rift axis southwestwards into the Ghoubbet sub-rift.

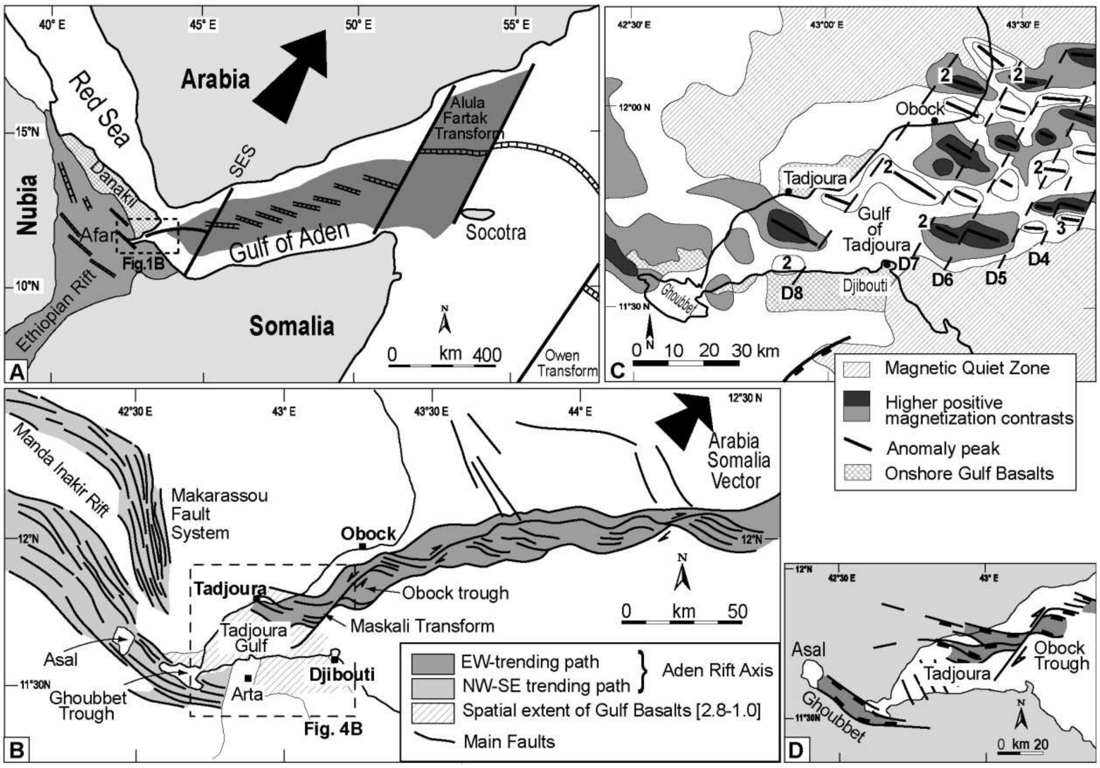

Figure 1: Various types of rift segmentation along the Gulf of Aden plate boundary between Arabia and Somalia. The active EW-trending Gulf of Aden (Sheba) rift-drift system evolves westwards into the sub-orthogonal Ghoubbet-Asal and Manda Inakir rifts. (A). Plate kinematic setting of the Afar Triple Junction. Thick arrows represent plate motion vectors, and the box indicates the study area. (B). Main physiographic features of the western Gulf of Aden rift system, modified from Manighetti et al. (1997). The revised spatial extent of onshore Gulf Basalts, as well as the Arta transverse zone (shown as the white NS domain centered on the Arta locality) are shown. (C). Aeromagnetic map of the Tadjoura Gulf, from Manighetti et al. (1997), with modified onshore parts. Dashed lines (D1-8) represent transform faults offsetting magnetic segments. Numbers refer to specific magnetic anomalies. (D). 'Overlapping subrift' model developed by Manighetti et al. (1997) to account for the relationships between the Tadjoura and Ghoubbet rifts. The inner floors of the rifts are shaded.

GENERAL RIFT SETTING AND VOLCANO-STRATIGRAPHY OF TADJOURA RIFT VOLCANIC

Geological context

The Sheba accretionary ridge within the Gulf of Aden forms, together with the Red Sea and the Ethiopian rift, one of the three diverging branches of the Afar triple junction (Figure 1A). According to magnetic anomaly data, mid-oceanic ridge segments and fracture zones initiated along its eastern part at 17-18 Ma *(Leroy et al.*, 2004; *d'Acremont et al.*, 2006), or possibly at 20 Ma (*Fournier et al*., in press), and then propagated westwards, obliquely to the N40°E direction of Arabia-Somalia plate separation (*Cochran*, 1981) (Figure 1A). Emplacement of incipient oceanic crust at the western tip of the Sheba ridge is recorded along the ~EW-trending Obock-Tadjoura Gulf by <2 Ma-old paired magnetic anomalies (Figure 1C). The anomalies partly coincide with the 3-1 Ma Gulf basaltic series which floor the Tadjoura Gulf, and outcrop onshore in its northern (Tadjoura) and southern (Djibouti Plain) margins (*Manighetti et al*., 1997) (Figure 1B). The EW-oriented TR-related structures intersect at high angle older tectono-magmatic fabrics displaying a submeridian orientation in the Mablas (15-11 Ma), Somali (7.2-3.6 Ma), and Ribta (3.6 Ma) substratum series, emplaced at an earlier stage of rifting.

The Gulf Basalts are a potentially accurate structural marker of the rift history recorded by the TR in the last 3 Ma, and it is therefore important to determine their spatial and temporal distribution for a better definition of the TR. That has been attempted by using new geochemical and age dataset obtained on basaltic units in the Djibouti Plain, i.e. on the southern margin of the TR. Combined with previously published K-Ar ages, this dataset allows us to discriminate four recent basaltic units, i.e. the Gulf, Somali, Goumarre, and Hayyabley Basalts, hence allowing significant revision of the 2D-map structure of the TR (Figure 2A). Finally, although they are younger than the Gulf and Somali Basalts which they crosscut, the Goumarre basalts were not recognized as a distinct type prior to this study.

NORTHERN MARGIN OF THE TADJOURA RIFT

In the Tadjoura-Obock area, the Gulf Basalts (2.8-1.0 Ma) occur in a 15 x 8 km faulted coastal plateau, less than 300 m high (Figure 3B). The main cartographic unit of the Gulf Basalts (the Roueli unit of *Gasse et al*., 1983, 1985) extends to the north as a 10 x 5 km faulted belt oriented N100°E, which swings to the north-east into a narrower N50°E strip. The Gulf Basalts lie further south as discrete inliers beneath locally faulted Quaternary alluvial fans, possibly as young as Holocene (*Manighetti et al*., 1997). Their rapid disappearance west of longitude 42° 50'E might result from a nearly NS-trending paleo-high, in the northern prolongation of the Arta zone (see below) (Figure 3A).

The southern margin of the TR (Djibouti Plain)

The Gulf Basalts are confined to a 10 x 20 km coastal faulted plateau which uprises southwards, via the EW-trending Ambouli topographic flexure (Figure 3E), to a northerly-tilted surface in the 7.2-3.6 Ma Somali Basalts.

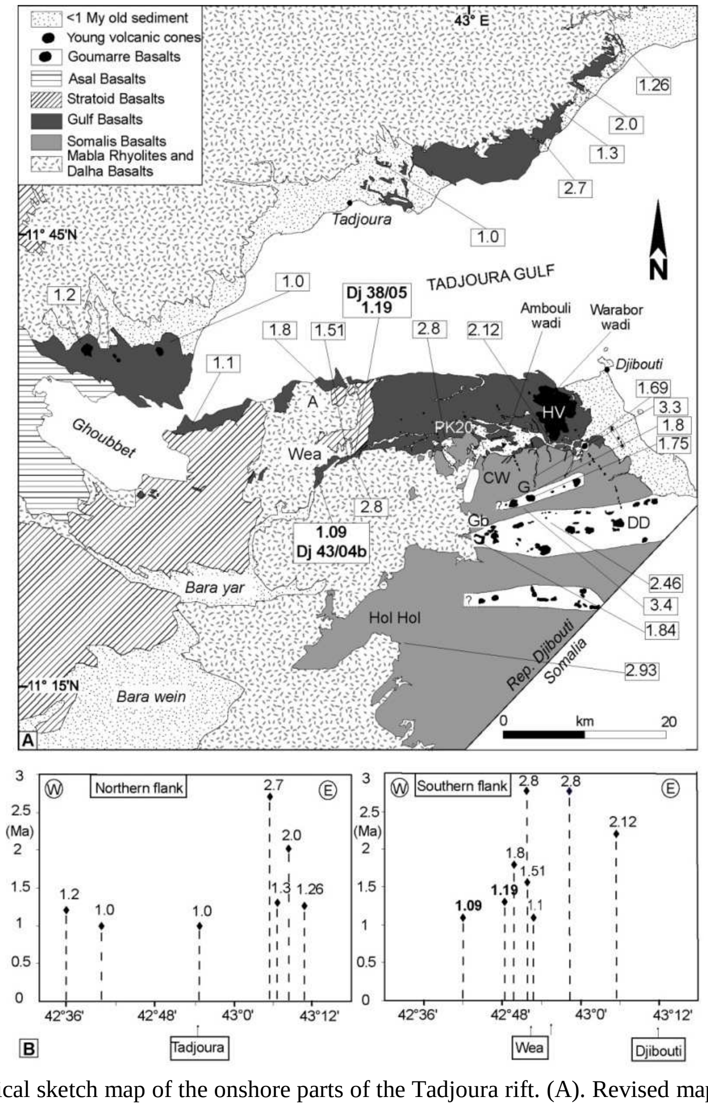

Figure 2: Revised geological sketch map of the onshore parts of the Tadjoura rift. (A). Revised map showing the distribution of the various basalt types and the location of dated basaltic rocks. Ages in Ma (numbers inside the squares) from published (Richard, 1979; Gasse et al., 1983; Zumbo et al., 1995), and new data (this study). Tectonic features are not shown on this simplified map. A, Arta; CW, Chabelley wadi; DD, Dey Dey wadi; HV, Hayyabley volcano; G, Goumarre; Gb, Goubbetto; PK20, "Point kilométrique" 20. (B). Longitude versus age plot for the southern and northern coastal strips of Gulf Basalts. A linear age progression is not clearly observed.

To the east, the Gulf Basalts are overlain by lavas of the ~1 Ma-old Hayyabbley shield volcano (*Gasse et al*., 1983; *Daoud et al*., 2010), the main axis of which follows a major N140°E fault scarp bounding the eastern coastal plain to the southeast. The western limit of the Gulf Basalts abuts against the NS-oriented eastern edge of the Arta reliefs, although they locally fill up the Wea paleo-valley (Figure 2A).

The Goumarre Basalts (2.46-1.69 Ma) forms three N80°E parallel arrays of basaltic vents crosscutting the Somali. These volcanic corridors, each of them a few km-wide, are sharply cut to the east by the N140°E coastal scarp. To the west, their tips remain within the Somali Basalts and do not reach the older substratum series of the Ali Sabieh range. It is therefore suggested that the Goumarre Basalts were emplaced during a relatively short time interval, concomitantly with the Gulf Basalts, but in a more southern, i.e. external, position with respect to the TR framework.

THE HALF-GRABEN STRUCTURE OF THE TADJOURA RIFT

2D-map structure

The TR is a ca. 60 x 40 km EW-trending topographically subdued domain, partly exposed onshore in the northern coastal fault belt (NCFB) and southern coastal fault belt (SCFB), on both sides of the Tadjoura Gulf (Figures 3A-B). Its inner offshore part is dominated to the north by the N120°E-oriented Tadjoura rhomb-shaped trough which is sinistrally offset from the Obock depression by ca. 30 km along the right-lateral Maskali transform fault system (*Arthaud and Choukroune*, 1976). The TR is surrounded by highlands involving older rift-related volcanics of the Mabla (18-11 Ma, in *Gasse et al*., 1985), Dalha (8.6-3.8 Ma), Somali (7.2-3.6 Ma), and Ribta (3.6 Ma) series. It is dissected by an inhomogeneously distributed fault pattern, comprising Gulf-parallel, NW-SE and NE-SW structures. The map-scale sigmoid trace of the entire fault pattern typically evokes an oblique rift setting. Two high-density fault zones occur on the eastern parts of the conjugate margins, in the Tadjoura trough and the NCFB to the north, and in the SCFB to the south. In the intermediate and less deformed zone, the preferred N60°E alignment of shield-like volcanoes might be controlled at depth by Maskali-type transverse structures (Figure 3B). To the west, the TR narrows markedly, north of the Arta transverse zone, where its floor shallows abruptly, up to 100-200 m below sea-level, through a submeridian scarp disrupted by an array of isolated NW-SE faults.

The TR fault system does not extend beyond the Gulf Basalts, e.g. into the substratum series which instead show evidence for earlier deformation (see discussion below).

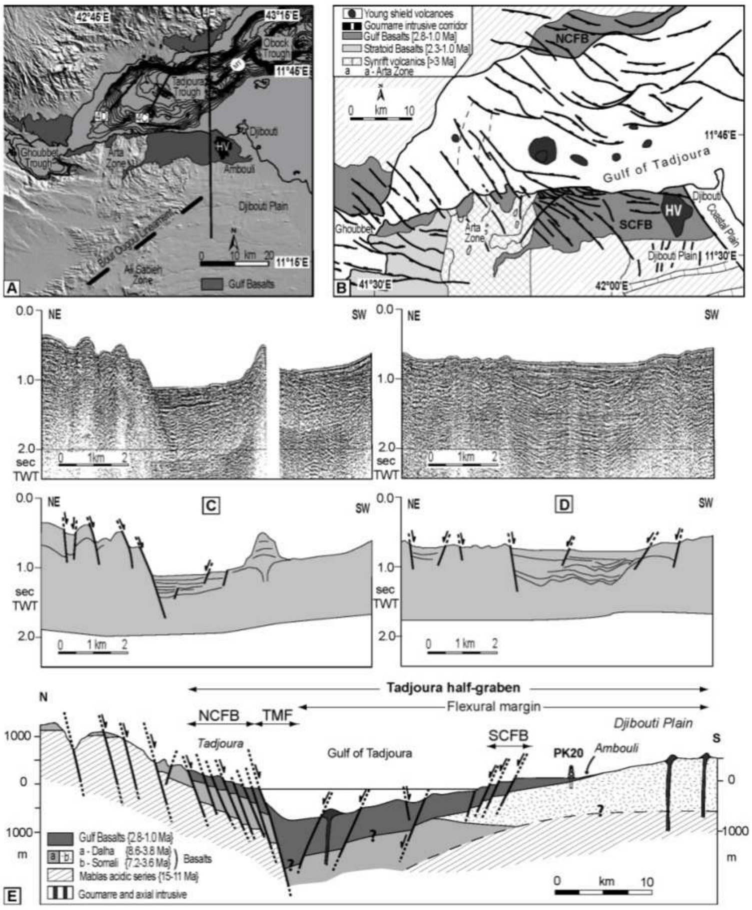

Figure 3: Overall structure of the Tadjoura rift. (A). Topography of the TR drawn from a bathymetric contour map (from *Audin*, 1999, modified) and a SRTM digital elevation model. Dashed lines represent the Maskali transform (MT) and Bour Ougoul transverse fault systems. Note the strong NS-oriented structural grain in the Arta zone. The traces of the structural cross-section in Figure 3E and the two interpreted seismic profiles in Figures 3C and D are shown. HV, Hayyabley volcano. (B). Structural map of the TR obtained (i) by merging onshore geology with offshore bathymetric dataset, and (ii) by using the Gulf Basalts as a rift marker (only drawn onland). ATZ, Arta transverse zone; HV, Hayyabley volcano; NCFB and SCFB, Northern and Southern coastal fault belts, respectively. (C) and (D). Raw (top) and interpreted (bottom) TADJOURADEN offshore seismic profiles (time-sections) perpendicular to the NW-SE-oriented fault-controlled Tadjoura inner trough (see traces in Figure 3A). (E). Interpretative structural cross-section showing the Tadjoura rift as a south-facing half-graben, partly filled up by Gulf Basalts. The elements of the deep structure of the Tadjoura rift are conjectural. The geometrical relationships between the underlying Somali and Dalha basalts are extrapolated from patterns observed onshore along the Bour Ougoul lineament on the NW flank of the Ali Sabieh antiform (see Figure 3A for location).

Half-graben cross-sectional structure

The composite structural cross-section in Figure 3E, drawn at high angle with respect to the dominant N110-120°E fault strike in the TR, is calibrated by TADJOURADEN bathymetric and seismic reflection data which have been merged with onshore geology. It shows a 35-40 km-wide half-graben structure, facing the SSW. Its inner and deeper part is occupied by the Tadjoura trough, which is bounded to the north by a prominent fault system, including the Tadjoura master fault, and its highly faulted footwall block, partly exposed in the NCFB. To the south, a ca. 20 km-long typical flexural margin shallows gradually southwards, up to the Djibouti Plain, where Gulf Basalts are locally dissected by a high density antithetic fault system in the SCFB. The flexure is locally punctuated by shield volcanoes.

The deep structure of the Tadjoura inner trough is constrained down to about 2 s (two-way travel-time), or depth of 4-5 km, by selected single-channel seismic reflection profiles striking NE-SW, orthogonal to the prominent bathymetric scarps (Figures 3C-D). To the north, the steep bathymetric scarp, >500 m-high and facing the SSW on the seismic line of Figure 3C, is interpreted as the upper part of the master fault. High amplitude reflectors lying, with an apparent gentle dip, in its immediate hangingwall are reliably correlated with Gulf Basalts dredged from the Tadjoura gulf (*Barrat et al*, 1990; 1993). Similar seismic facies present, with a reduced thickness, in the elevated footwall block correlate laterally with onshore Gulf Basalts in the NCFB (Figure 3B), hence confirming our seismo-stratigraphic interpretation. The volcanic infill sequence thickens markedly towards the boundary fault, just like synfaulting deposits, up to a maximum thickness of 7-800 m. This value is obtained by converting the 0.3 s (two-way travel-time) measurement, assuming an average seismic velocity for basalts of 4.5-5.0 km.s^{-1}.

The southwestern edge of the TR and the Arta zone

The sketch structural map in Figure 4A shows that very few transverse and Gulf-parallel TR-related faults crosscut the >3 Ma-old volcanic terranes forming the Arta zone. In this area, the 8.6-3.8 Ma-old Dalha Basalts and the overlying Ribta felsic lavas (3.6 Ma) are involved into a broad, 10 km-wide, upright arched structure, oriented N-S, i.e. nearly orthogonal to the E-W axis of the TR. This Arta anticline is in turn dissected by a dense network of NS-N20°E fault/fractures, parallel to the anticline axis and locally intruded by felsic bodies of the Ribta Fm. Most of these submeridian fractures were later reactivated as strike-slip faults (*Arthaud et al*., 1980).

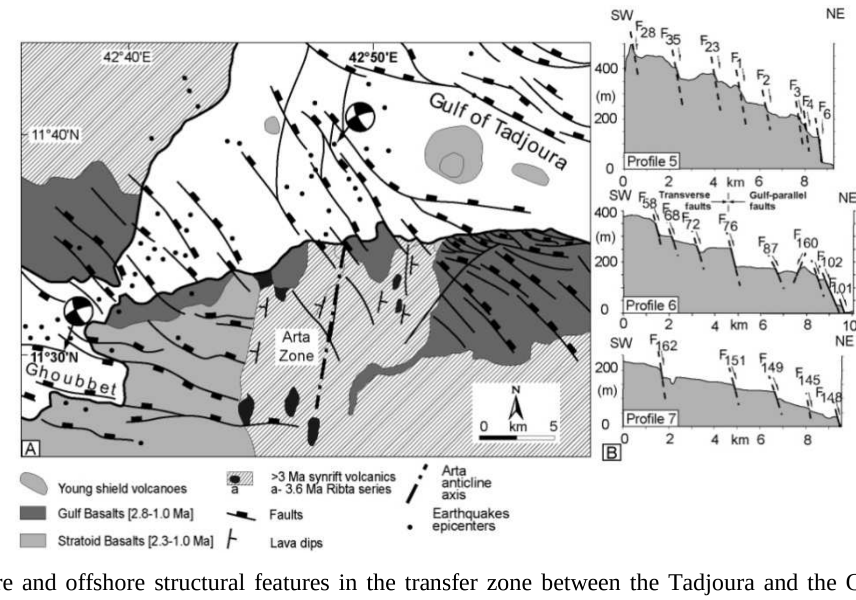

Figure 4: Onshore and offshore structural features in the transfer zone between the Tadjoura and the Ghoubbet rifts. (A) Structural sketch map showing the nearly underformed nature of the Arta transverse zone during recent (<3 Ma) rift stages. Note that most earthquakes and faults cutting through the Stratoid and Gulf basalts avoid the Arta NS-trending zone. The earthquake epicentres are from *Doubre* (2004) and the focal mechanisms of the 1978/21/12 and 1978/08/11 earthquakes, in the Tadjoura Gulf and Ghoubbet trough, respectively, are from *Lépine and Hirn* (1992). (B). Morpho-structural sections crossing the South Coastal Fault Belt, perpendicular to the N140°E transverse fault network.

From these structural relationships, the Arta anticline is inferred to have formed as a magma-driven structure overlying a felsic intrusion emplaced during the 3.6 Ma Ribta event.

KINEMATIC MODEL FOR THE <3 MA RIFT EVOLUTION OF THE TR

In response to the regional N40°E extension (*Jestin et al.*, 1994; *de Chabelier and Avouac*, 1994; *Vigny et al.*, 2007), the TR developed as a 60 x 40 km south-facing half-graben, filled up by a thick pile of syntectonic fissural Gulf Basalts. In map-view, the TR rhomb-shaped structure involves a composite network of dominantly extensional faults, striking EW (Gulf-parallel) and NW-SE.

The latter trend occurs in the western termination of the TR at the longitude of ca 42° 45’, i.e. in the northern offshore prolongation of the Arta zone. The TR-related faults which exclusively involve the Gulf Basalt-filled half-graben recorded a complex history within an overall westerly migration of tectonic activity (*Manighetti et al.*, 1997). The dating of fault-controlled volcanic activity (Goumarre) across the flexural margin of the TR half-graben suggests that the onset of faulting along the master boundary fault to the north occurred at 1.7 Ma, concomitantly with active extension in the Tadjoura inner trough. At this stage, the master fault might have developed a number of splays into the footwall uplifted block (NCFB), probably coeval with localized antithetic faulting along part of the flexure to the south (SCFB). The long-lived development of the Tadjoura half-graben was accompanied by the temporal migration from old structures, in an external position, towards younger ones, closer to the Gulf axis. A similar evolution is reported from the Kenya rift, where a temporally progressive focus of strain into a narrow and inner trough has been documented (*Baker and Wohlenberg*, 1971; *Cerling and Powers*, 1977; *Vétel and Le Gall*, 2006). In addition to cross-rift migration of faulting, along-strike fault propagation also occurred, and resulted in contrasted fault patterns in the NCFB and SCFB. In the NCFB, the amount of displacement decreased regularly westwards along Gulf-parallel faults, towards a tip line located within the Gulf Basalts. Very few faults extended beyond the Gulf Basalts/substratum boundary, across the Mabla felsic series (Figure 5B). Small-scale (a few hundreds meters wide) jumping rift segments were assumed to occur in the NCFB (*Manighetti et al.*, 1997), where they turned into a network of *en echelon* fault swarms which connected the TR and the Ghoubbet rifted trough to the SW. These small-scale rift structures are here regarded as subsidiary structures on the northern flank of the TR half-graben documented in this work.

A more intricate fault pattern is present in the western part of the SCFB. There, the Gulf-parallel extensional faults deviate clockwise, from N90°E to N140°E, when approaching the Arta transverse zone. This fault map curvature is accompanied by a marked increase of fault density westwards, together with a decrease of individual fault length, hence resulting in over-displaced fault pattern.

Structural data suggest that strong submeridian terranes, including the Arta zone, transect orthogonally the western end of the TR (Figure 5B). To the south, these terranes extend towards the Ali Sabieh anticline (*Le Gall et al.*, 2010). They are bounded to the east by the so-called Arta-Asamo discontinuity, the > 60 km-long map trace of which is outlined by a variety of structures that indicate its long-lived history. To the north, the decrease of vertical motion along the NW offshore course of the N140°E transverse fault network (see Figure 3D) suggests the occurrence of a stronger substratum offshore the Arta zone.

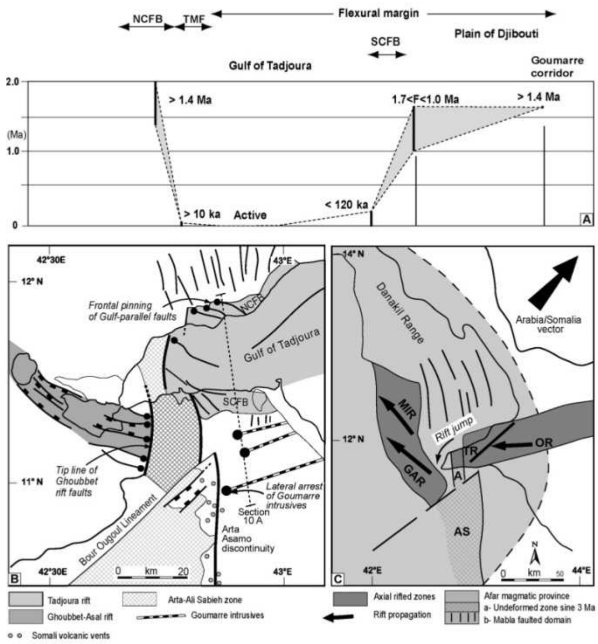

Figure 5: Kinematics of rift propagation throughout the Tadjoura-Ghoubbet connection zone. (A). Timing of faulting along a synthetic cross-section of the Tadjoura Rift. Despite age uncertainties, a pattern of younging of strain is observed from the margins to the inner part of the Tadjoura Rift, indicating progressive axial focusing of extension. NCFB: Northern Coastal Fault Belt; TMF: Tadjoura Master fault; SCFB: Southern Coastal Fault Belt. (B). Rift kinematic model in the Tadjoura-Ghoubbet linkage zone, emphazing the role of inherited submeridian structures in pinning the propagation of the Tadjoura and Ghoubbet rifts. C. Sketch rift pattern showing a major submeridian discontinuity at the transition zone between two variously-trending rift arms of the Aden plate boundary. The shaded area corresponds to the eastern edge of the Afar magmatic province (the initial 30 Ma-old flood basalts of Yemen are not considered). A., Arta zone; AS., Ali Sabieh range; GAR., Ghoubbet-Asal rift; MIR., Manda-Inakir rift; OR. Obock rift; TR., Tadjoura rift.

The strong mechanical behaviour of the Arta transverse zone during recent rifting is also confirmed by (1) the restricted location of earthquakes and aftershocks linked to the 1978 seismic crisis in the Tadjoura gulf (*Lépine et al.*, 1980; *Lépine and Hirn*, 1992; *Doubre*, 2004) (Figure 4A), and (2) the abrupt arrest of the EW-trending Ghoubbet rift fault network against its NS-trending western edge (Figure 5B).

Further south, the continuation of the Arta-Asamo discontinuity along the eastern flank of the Ali Sabieh anticline is deduced from the restricted distribution of the N80°E Goumarre fault-dyke corridors which do not penetrate westwards into the Ali Sabieh substratum series (Figure 5B). The inherited and deep-seated origin of the Arta-Asamo discontinuity is suggested by the NS alignment of Somali (7.2-3.6 Ma) volcanic vents along its inferred map trace (Figure 5B). This discontinuity might have been guided at depth by a large-scale Proterozoic fracture zone belonging to the Marda system (Boccaletti et al., 1991).

During the recent SE Afar rift history, the Arta preexisting submeridian structures are therefore assumed to have provoked the frontal pinning of axial fault growth in the TR, and then the lateral jump of rifting in the Ghoubbet area, in response to inferred higher strength contrast, together with their orthogonal orientation to rift propagation. This abrupt change in rift kinematics probably occurred at ca. 900 ka, when diffuse volcanism and associated faulting started in the Asal-Ghoubbet rift (*Manighetti et al*., 1998; *Audin et al*., 2001).

CONCLUSIONS

The major and trace element analysis of young basalts collected from onland Tadjoura Rift units (especially from the Djibouti Plain) allows us to distinguish four distinct types, namely the Gulf, Somali, Goumarre and Hayyabley Basalts. These results, together with new and previously published radiometric age data, lead us to propose a revised volcano-stratigraphic sketch map of the southern (SCFB) and northern (NCFB) margins of the TR. With respect to former studies (*Richard*, 1979; *Gasse et al.*, 1983, 1985, 1986), the Goumarre Basalts (2.46-1.69 Ma) are recognized as a distinct unit and the southern limit of the Gulf basalts in the Djibouti Plain is shifted ca. 10 km northwards. A consequence of this revision is that the progressive westerly younging of the Gulf Basalts suggested by previous authors (*Richard*, 1979; *Manighetti et al*., 2001; *Audin et al*., 2004) for the southern and northern borders of the TR is no more supported by the new longitude *versus* age trends for these basalts.

New structural data based on fieldwork and remote sensing analysis allow us to interpret the overall structure of the TR as an asymmetrical south-facing half-graben, about 35 km-wide, dominated by a large boundary fault zone to the north and extending southwards as a >20 km-long shallower flexural margin, partially exposed in the Djibouti Plain. There, it is locally disrupted by an antithetic southern coastal fault belt, and by the Goumarre transverse fault-dike corridors close to the inflexion point of the Somali Basalts monocline. Recent faulting is spatially restricted to the Gulf Basalts which form two narrow strips on the northern and southern margins of the TR.

The temporal change of the location of normal faults towards the inner trough of the half-graben indicates the progressive focusing of strain with time within the axial part of the rift. The geometrical and statistical analysis of onshore fault networks in the southern fault belt shows a westeryl increase of strain that is mechanically assigned to the frontal locking of axial fault tip propagation against sub-meridian discontinuities in the Arta zone. The arrest of fault propagation in the TR lastly resulted in the jump of rifting into the Ghoubbet-Asal trough system.

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