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The Continental Margins of the Gulf of Aden

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Continental Rifted Margins 2,
coordinated by Gwenn PERON-PINVIDIC

1. Introduction

The continental margins of the Gulf of Aden are a good example for illustrating and understanding the formation of rifted margins and the transition to an active oceanic ridge. This exceptional geological object allows us to study continental break-up, both in a magmatic context (under the influence of the Afar mantle plume) and in a low magmatic context (associated with the exhumation of sub-continental mantle).

The Gulf of Aden is an oceanic basin that extends for about 1,400 km between the Red Sea and the Indian Ocean (see Figure 4.1). It is the result of an Oligo-Miocene continental rifting process (34–17.6 Myr) that led to the separation of the Arabian and Somali plates. The result of the rifting is the break-up of the continental lithosphere and the establishment of an oceanic ridge in the center of the basin, here the Aden and Sheba ridges. Currently active, they are a site of intense seismicity (Figure 4.1).

The Gulf of Aden's relatively recent post-rift history (less than 20 Myr) also enables the observation of a continental rift undergoing thermal and compositional rebalancing. Less than 300 km to 650 km apart, the Gulf of Aden's continental margins define a narrow rift, thus promoting correlations between the conjugate segments. The relatively thin sedimentary cover facilitates the observation of the structures by indirect geophysical methods. In addition, the obliquity of the Gulf (the direction of extension is oblique to the general direction of the continental rift, not perpendicular) results in significant segmentation of the margins, which are offset by transfer fault zones that evolve over time to transform fault zones of variable offset (from ~20 to 180 km, see Figure 4.1).

The present-day structure of the Gulf of Aden's continental margins is closely related to the regional geological history.

2. Geological and geodynamic context and heritage

Bordered by the Afar mantle plume to the west and the oceanic lithosphere of the Indian Ocean to the east, the Gulf of Aden opened within the Arabian-African lithosphere, which is made up of terrains of different geological natures (Figure 4.1). These include Neo-Proterozoic bedrock formed by the combination of various arcs and accreted "terranes", and different sedimentary series of Permo-Triassic, Jurassic or Cretaceous ages.

The metamorphic bedrock has undergone several episodes of rifting at different time periods: in the Permo-Triassic, Jurassic and Upper Cretaceous. These extensional episodes were expressed in the

form of grabens and basins distributed on the eastern Afro-Arabic platform in the Permo-Triassic, near the future Gulf of Aden region in the Upper Jurassic and on the Arabian platform in the Upper Cretaceous (see Figure 4.1).

In the Late Eocene (~35 Myr), the extension was localized in the Red Sea-Aden system when the collision started west of the Zagros and the Afar mantle plume was formed (Bellahsen et al. 2003; Koptev et al. 2018). At the paroxysm of activity of the Afar plume (~30 Myr), the rifting of the Gulf of Aden continues. Its expression is clearly volcanic in the west and non-volcanic in the east (Leroy et al. 2012).

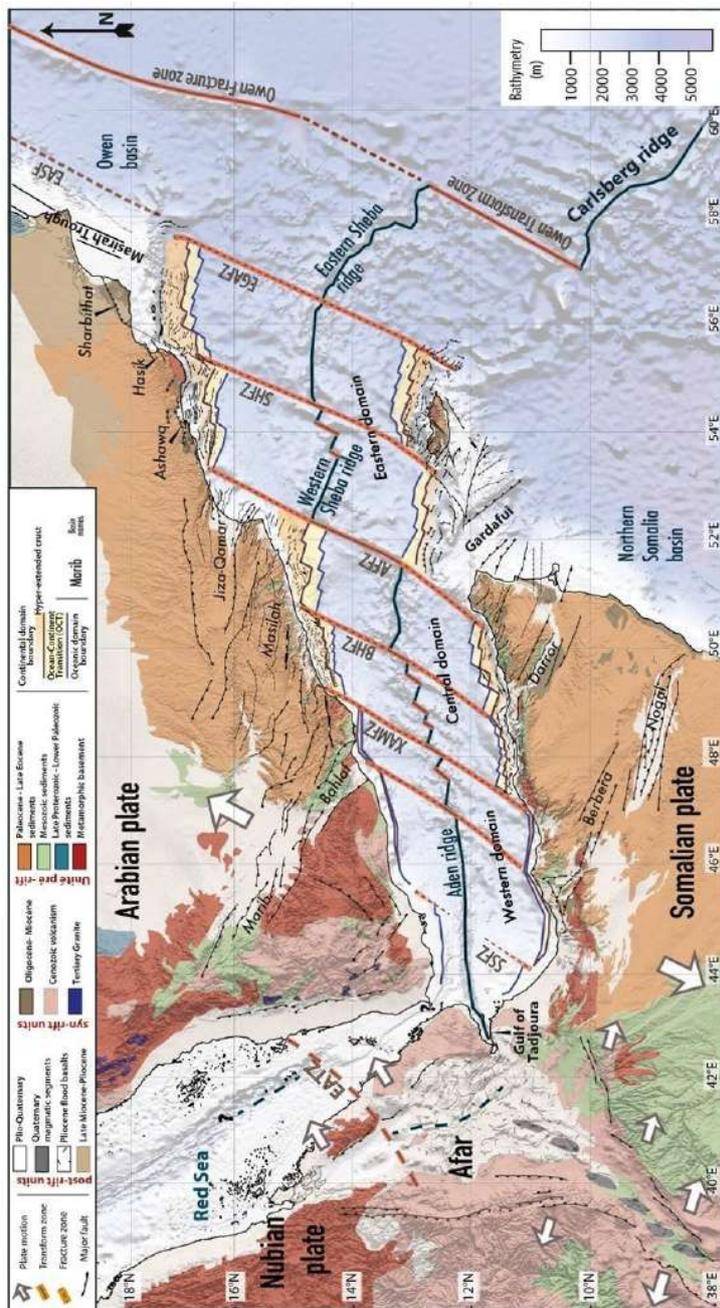


Figure 4.1. Simplified geological map of the Gulf of Aden (source: adapted from Leroy et al. 2012)

FIGURE 4.1.– The bathymetric and topographic data are from the GEBCO global database (GEBCO_2014 Grid). The Mesozoic basin names are noted onshore in black (Leroy et al. 2012). AFFZ: Alula Fartak Fracture Zone. AFTF: Alula Fartak Transform Fault. b: basin. BHFZ: Bosaso Hami Fracture Zone. EGAFZ: Eastern Gulf of Aden Fracture Zone. SHFZ: Socotra-Hadbeen Fracture Zone. SSFZ: Shukra El Sheik Fracture Zone. XAMFZ: Xiis Al Mukalla Fracture Zone. The location of the Ocean-Continent Transition and the hyper-stretched continental crust zone are from Leroy et al. (2010) and Nonn et al. (2017, 2019).

3. Continental rifting timing, initiation and depositional environments

In the different sedimentary basins, the Tertiary series outcrop, notably in Sayhut-al Masilah and Qamar in Yemen, Ashawq-Salalah and Sharbithat in Oman, and in the southern part, on Socotra Island and in Somalia (Berbera, Darror and Gardafui) (Figure 4.1). In the area of Aden City in the western Gulf of Aden, the Tertiary series are volcanic and outcrop as remarkable Seaward Dipping Reflectors (SDRs) sequences from at least the early Oligocene (34 Myr) to 16 Myr (Burdigalian) (Tard et al. 1991).

The detailed observation of sedimentary facies has allowed us to compare the depositional environments during the rifting process in the western and eastern parts of the northern margin of the Gulf of Aden (see Figure 4.2; (Leroy et al. 2012; Robinet et al. 2013)). Thus, it appears that the western domain underwent uplift and erosion from the beginning of the rifting (from the Aden City area to the Al Mukalla City area), while a more continuous sedimentation characterizes the eastern domain. During the Oligocene, tectonic subsidence of the entire domain promoted the preservation of syn-rift sedimentary series, showing a clear palaeogeographic differentiation: continental terrigenous and evaporitic systems in the central part of the Gulf, and carbonate platform systems and turbiditic basins in its eastern part. The increase in the rate of subsidence during rifting is recorded in the western part of the central Gulf by the development of evaporitic, lacustrine and marine facies, and in the east by the development of turbiditic basins (Mughsayl Formation). The Lower Miocene series constitute the maximum marine inundation in the central domain, and in the eastern domain the deep facies persist (Figure 4.2).

The continental margins of both domains underwent major uplift at the transition between syn-rift and post-rift stages.

Syn-rift series have the same age throughout the Gulf, whether volcanic in the western domain of the Gulf or sedimentary in the central and eastern part (Nonn et al. 2019). Continental rifting thus appears synchronous across the Gulf of Aden since 34 Myr. The uplift phases of the western domain that drive erosions and clastic inflows are assumed to be related to the dynamics of the Afar mantle plume.

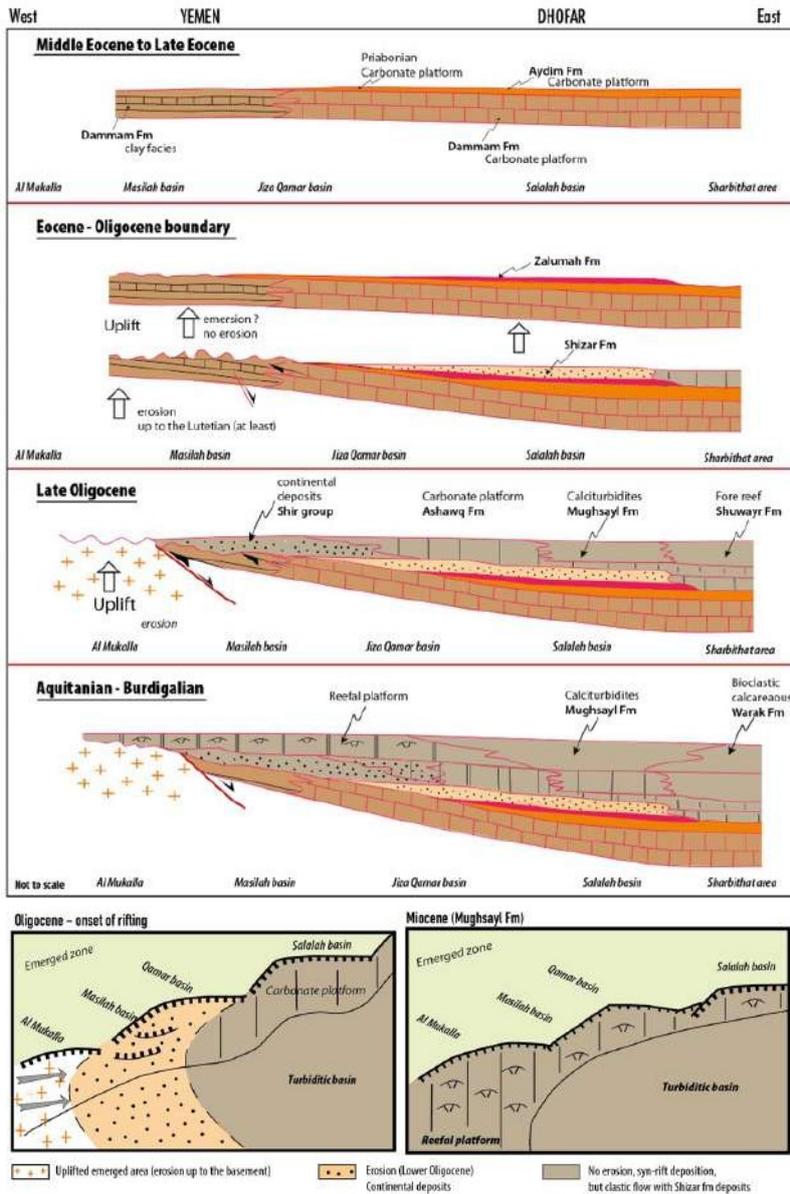


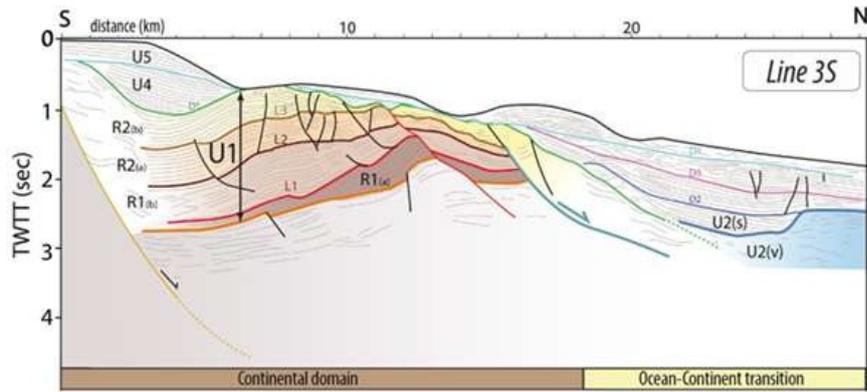
Figure 4.2. Diagram of longitudinal evolution of sedimentary systems and eroding areas along the northern margin of the Gulf of Aden from the central region to the Salalah Basin in the east (between the city of Al Mukalla in Yemen in the west and to Sharbithat in the Sultanate of Oman in the east) (source: adapted from Leroy et al. 2012)

4. Structure of the conjugate margins

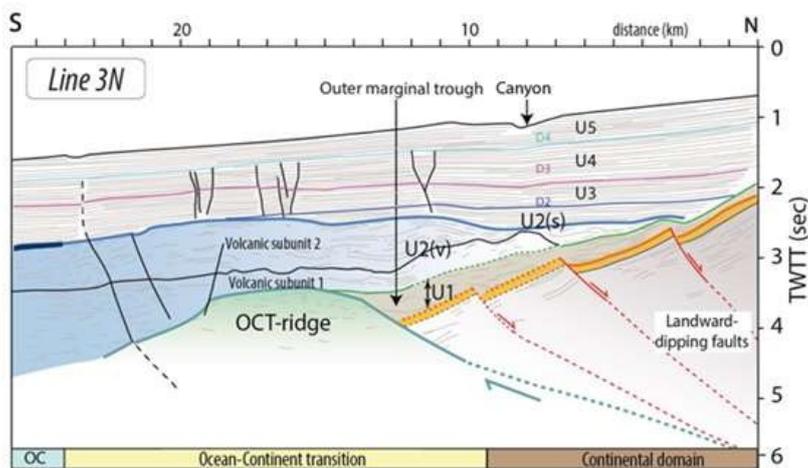
The Gulf of Aden is marked by the significant narrowness and asymmetry of its margins combined with a gradual decrease in magmatic intensity towards the east. The mapping of the different crustal domains can be seen in Figure 4.1.

The continental domain is structured by a succession of tilted blocks (see Figures 4.1 and 4.3). For the conjugate margins of the central Gulf of Aden, crustal thinning is dominated by north-verging normal faults (see Figure 4.3b). The northern margin is characterized by low fault displacements (100–500 m). In contrast, for the southern margin, the accommodation of extensive deformation occurs on faults with larger displacements (~1,000 to 4,000 m, see Figure 4.3a). For the margins of the eastern Gulf of Aden, thinning of the upper crust occurs along shallowly dipping faults (<30°), some of which were initiated at the onset of rifting on the western part of Socotra Island (Leroy et al. 2012). These faults are present throughout the continental domain, from proximal to distal domains (Figure 4.4).

Three crustal subdomains are identified (Figure 4.4) as follows: (1) The proximal domain: this domain corresponds to the outer parts of the rift where crustal thinning is very weak. The crustal thickness varies between ~35 and 40 km. (2) The necking domain: in this domain, crustal thickness decreases from ~35–40 km to 10 km. Crustal thinning is achieved by the interplay of high-displacement faults in the upper crust and shear zones in the lower crust. The necking domain is limited in its distal part by a remarkable point in the architecture of the margins, the Taper Break, which is located at the foot of major faults. It is the closest point to the coast where the crust is less than 10 km thick (Osmundsen and Redfield 2011). Major oceanward dipping faults border the necking domain and form scarps that participate in ~3–4 km of crustal thinning. They root into the mantle at the coupling point (CP) and are responsible for the crustal breakup of the continental margins. (3) The hyper-extended domain: this constitutes the edge of the continental domain. It is formed by continental crust less than ~10 km thick. In the eastern part of the Gulf of Aden, it extends over a width of 90 km cumulated on the conjugate margins and is asymmetric with the northern margin wider (~50–80 km) than the southern margin (~10–40 km). Consisting of a succession of small blocks of continental crust 2–14 km wide on the Omani margin, these blocks are decoupled by a system of major northward dipping detachments. Visible in seismic reflection by a reflector with a very high impedance contrast induced by the juxtaposition of continental crust and underlying exhumed mantle, it resembles the reflector observed in the West Iberian margin (S reflector (Reston et al. 1996), or in the Porcupine basin, P reflector (Reston et al. 2001)).



(i) Southern margin



(ii) Northern margin

Figure 4.3. Seismic interpretation of 3N and 3S conjugate sections in the Ahl Medo-Hami region of the central Gulf of Aden. The different seismic sequences are identified on the seismic profiles, as well as the different crustal domains (continental, oceanic and ocean-continent transition). (source: adapted from Nonn et al. 2019)

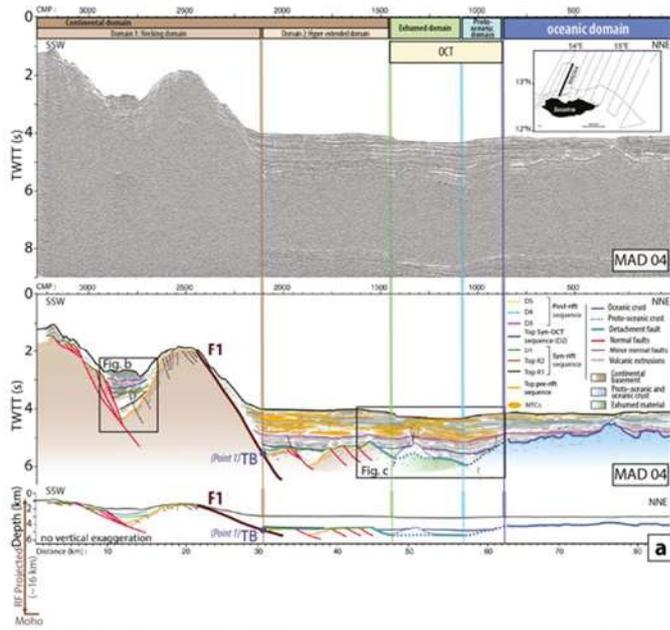
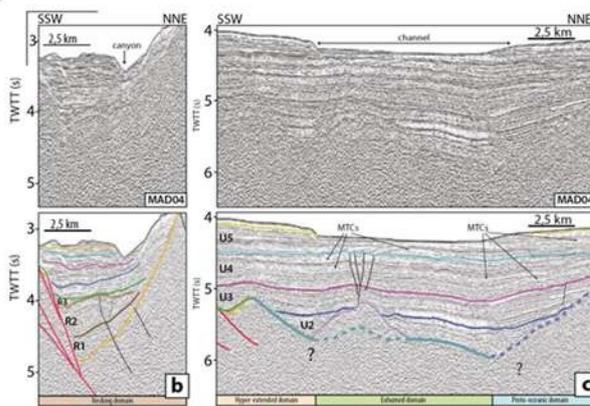


Figure 4.4a. a) Seismic profile of the southern margin and its interpretation with the different sedimentary sequences identified on the conjugate margins and identification of the five crustal domains (continental, necking, hyper-extended, exhumed, proto-oceanic crust and steady-state oceanic domains). The depth of the Moho projected on the interpreted profile is from Ahmed et al. (2014). b) The interpretation of sedimentary sequences in the perched synrift basin. c) Interpretation of seismic bedrock structures and sedimentary units in the ocean-continent transition zone. MTC: Mass-transport deposits. OCT: Ocean-continent transition. TB: Taper Break. (source: adapted from Nonn et al. 2017)



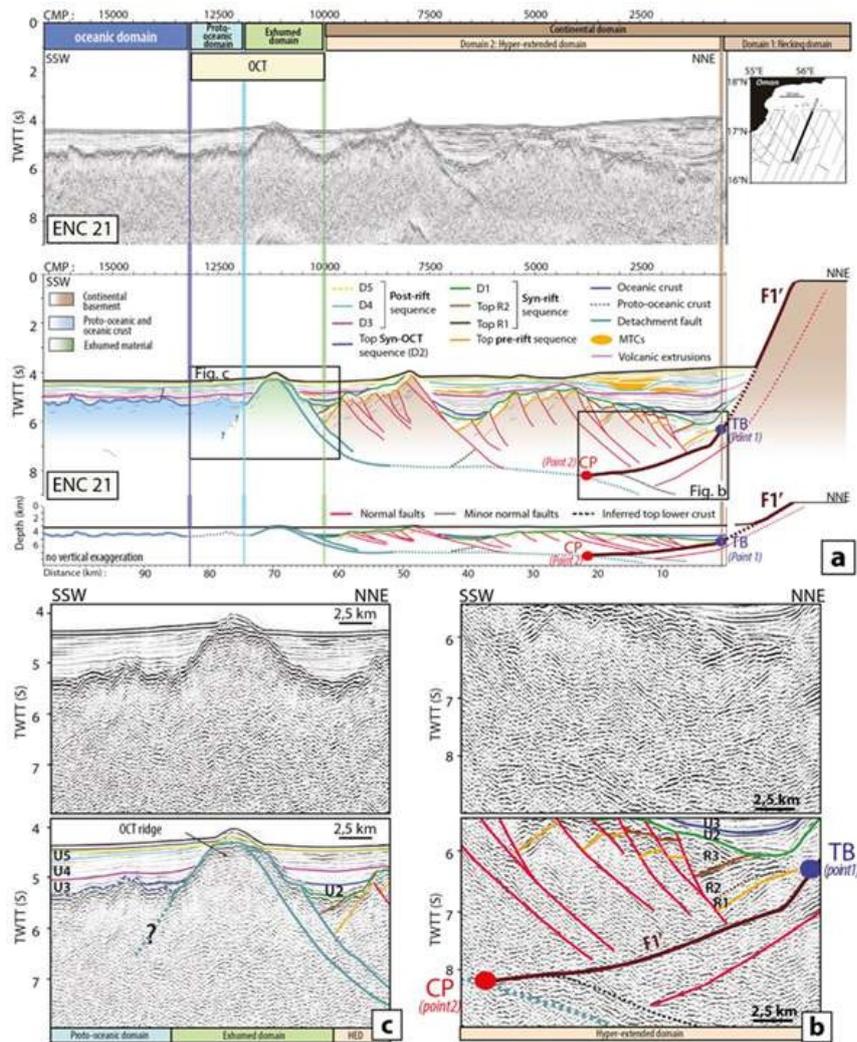


Figure 4.4b. a) Seismic profile of the northern margin and its interpretation with the different sedimentary sequences identified on the conjugate margins and identification of the five crustal domains. b) Interpretation of seismic bedrock structures, location of the Taper Break (TB) and Coupling Point (CP) (see text for definitions). c) Ocean-Continent Transition (OCT) ridge and proto-oceanic crust. HED: Hyper-extended domain. MTC: Mass-transport Complex deposits. OCT: Ocean-continent transition. (source: adapted from Nonn et al. 2017)

5. Ocean-continent transition (OCT) and the birth of an oceanic ridge

Combined academic and industrial marine geophysical data provide a high-resolution magnetic coverage, associated with seismic profiles essential for locating the ocean-continent transition (Figure 4.1). The asymmetry of the margins and the observation of detachment surfaces in the hyper-extended continental domain of the northern margins support the hypothesis of the existence of north-verging exhumation systems (Figure 4.4). In our model (Figure 4.5), the northern margins in Yemen and Oman belong to the upper plate and are located in the hanging-wall of the main detachment. The margins located in the south (Somalia and Socotra Island) are the lower plates and are located in the footwall, in agreement with the model proposed by Lister et al. (1986).

Detachment systems are initiated at the end of the thinning phase and at the beginning of the exhumation phase, but the duration of their activity remains difficult to determine. For the central and eastern Gulf of Aden margins, exhumation faults are likely to have initiated the emplacement of the serpentinized subcontinental mantle in the OCT (Figures 4.4 and 4.5) (d'Acremont et al. 2006; Autin et al. 2010; Leroy et al. 2010, 2012; Watremez et al. 2011; Nonn et al. 2017, 2019).

In the central Gulf of Aden, the formation of the OCT is associated with significant volcanism related to the increasing westward influence of the Afar plume (Nonn et al. 2019).

The OCT in the eastern part of the Gulf is subdivided into two crustal subdomains: the exhumation domain consisting of serpentinized mantle and the proto-oceanic crustal domain, which is characterized here by serpentinized mantle strongly affected by volcanic intrusions and extrusions. The general morphology of the OCT is different on the upper and lower plate margins.

For margins located on the upper plate, the exhumation domain is characterized by an OCT ridge (also called a peridotite ridge (Sibuet et al. 2007; Davy et al. 2016)) that borders the hyper-extended domain. Several generations of detachment faults are identified; deformation delocalizes into the wall of the previous fault and causes the emplacement of a new exhumation fault (Sauter et al. 2013). Therefore, the duration of exhumation-initiating fault activity is time limited. For margins located on the lower plate, the OCT exhibits a basin-like morphology. The basement is

probably locally composed of very thinned lower crust. In the eastern Gulf of Aden, the basement of the exhumed domain is affected by local volcanism. The significant increase in magmatic production occurs at the time of emplacement of the proto-oceanic domain and corresponds to the 5D magnetic anomaly (17.6 Myr; (Nonn et al. 2017)).

The oceanic domain is characterized by steady-state oceanic crust, emplaced around ~17 Myr (Leroy et al. 2012). The final lithospheric breakup occurs when active volcanism and asthenospheric dynamics take over lithospheric dynamics. Thus, oceanic crust formation occurs during a period of intense magmatic production that localizes deformation and creates a stable oceanic ridge (Jagoutz et al. 2007; Cannat et al. 2009; Bronner et al. 2011).

6. Opening of the Gulf of Aden

The interpretation of the data allows us to reconstruct the history of the opening of the Gulf of Aden without propagation within the African continent from the edge of this craton to the Afar region (Figure 4.1) since 34 Myr. This was followed by an oceanic opening that initiated around 17.6 Myr, with the emplacement of the proto-oceanic crust corresponding to the 5D magnetic anomaly identifiable from the edge of the Arabian-African craton in the east to the Shukra el Sheik fracture zone in the west (Figure 4.1).

The influence of the Afar mantle plume, as a lithospheric weakness (Bellahsen et al. 2003), is probably considerable in this ultrafast opening over the 700 km forming the Gulf of Aden. In the west, the influence of buoyancy forces (Afar mantle plume) are thus dominant, while in the east, plate boundary forces appear to drive extension throughout the rifting process (Bellahsen et al. 2013).

In the extreme east of the area, east of the Eastern Gulf of Aden Fracture Zone (EGAFZ), the oceanic ridge was initiated 20 Myr ago (Fournier et al. 2010) in an oceanic lithosphere of probably Late Cretaceous age, with a different rheology than the Afro-Arabian craton. This region would thus rather belong to the Carlsberg Ridge system than to the Gulf of Aden system, which starts west of the EGAFZ (Leroy et al. 2012) proper.

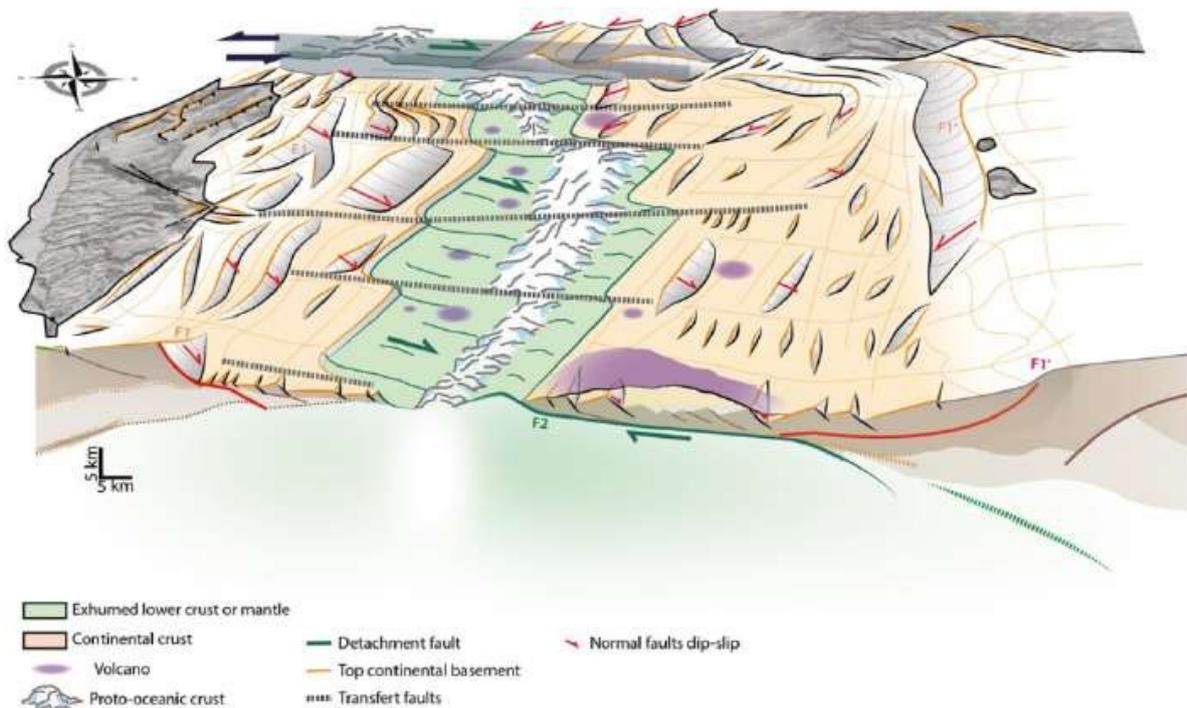


Figure 4.5. 3D block representing a bedrock scarp at the end of the ocean-continent transition period (Middle to Upper Burdigalian). This reconstruction takes into account the 3D morphology of the conjugate margins from the seismic interpretation of structures currently observed on seismic profiles (bedrock morphology, faults, nature of the crust). (source: adapted from Nonn et al. 2017)

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