Mass wasting and canyon formation in the light of climate and tectonics: Insights from the Gulf of Aden rifted margin.

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Abstract

The formation of gravity-driven sedimentary systems on continental rifted margins results from the interaction between climate, ocean currents and tectonic activity. During the early stages of margin evolution, the tectonic processes are probably as important as climate for the sedimentary architecture. Therefore, the young margins (ca. 35 Ma) of the Gulf of Aden provide the opportunity to evaluate the respective roles of monsoon and tectonic uplift in the formation of erosional features and gravity-driven deposits (Mass Transport Complexes (MTCs) and deep-sea systems) on the continental slope and in the oceanic basin respectively. Here we present a combined geomorphologic and stratigraphic study along the North-Eastern coast of the Gulf of Aden in which we classified and interpreted the gravity-driven processes, their formation and their evolution. The interpretation of seismic lines reveals the presence of bottom currents since the drift phase, suggesting that the Gulf of Aden was connected to the world oceans at that time. An abrupt depositional change affected the eastern basin of the Gulf of Aden around 10 Ma or thereafter (Chron 5), characterised by the first occurrence of deep sea fans and an increase in the number of MTCs. The first occurrence of MTCs may be explained by the combined 2nd-3rd order fall of the relative sea-level (Serravalian/Tortonian transition). This variation of relative sea level combined with a climatic switch (Asian monsoon onset around 15 Ma and its intensification around 7-8 Ma) control the sediment flux. The youngest unit of the post-rift supersequence is characterised by a second important MTCs occurrence that is restricted to the eastern part of the margin. This is caused by a late uplift of the Eastern part of the margin witnessed onshore by the presence of young stepped marine terraces.

Introduction

Gravity-driven flows are an integrated part of the continental margins evolution that shapes the sedimentary architecture (Posamentier, 2003). The knowledge of sediment transport processes on continental slopes has significantly progressed in the last decades (Nardin et al., 1979; Weimer, 1989, 1990; Mulder and Cochonnat, 1996; Hampton et al., 1996; Canals et al., 2004; Posamentier and Walker, 2006). Gravity-driven transport due to steep continental slopes is dominant in active transform margins (Reis et al., 2010; Silva et al., 2010), but climate can also play a significant influence in monsoonal areas (Ducassou et al., 2009; Paul et al., 2000). The Northern margin of the Gulf of Aden combines a recent Quaternary uplift with a well-established monsoon climate (Prell et al., 1990; Bache et al., 2011) and is therefore a suitable candidate to establish the relative importance of climate and tectonics on thin-sedimented divergent margin.

Here, we present an integrated analysis from erosional features to sediment architecture the Northern margin of the Gulf of Aden, and their possible relations with tectonics and climate. The Gulf of Aden is a young and narrow oceanic basin between the Arabian and African plates resulting from oblique rifting (Fig. 1A; Jestin et al., 1994; Fournier et al., 2001) that started around 35 Ma ago (Roger et al., 1989; Bott et al., 1992) until oceanic spreading started at 17.6 Ma (Leroy et al., 2004; d'Acremont et al., 2006). The onset of the monsoon system in the Western Arabian sea started around the Middle Miocene (ca. 15-16 Ma) and intensified around 8 Ma as the Indian monsoon (Prell et al., 1990; Kroon et al., 1991; Prell and Kutzbach, 1992; Molnar et al., 1993).

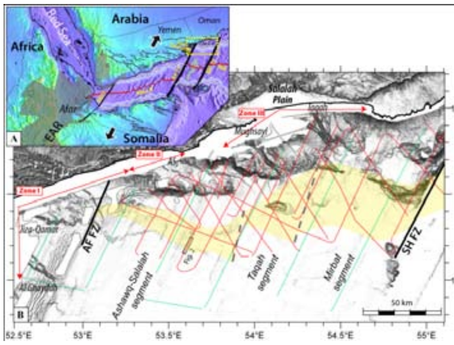

Fig. 1- (A) *Location of the study area (yellow dotted frame) in the regional context of the Red-Sea, Afar and Gulf of Aden opening. Gray shading denotes the Afar-related volcanism. SSTf, Shukra el Sheik transform fault; AFTf, Alula Fartak transform fault; Aden R, Aden ridge; ShR, Sheba ridge; Jiza Qamar b., inherited Jeza Qamar basin. The red line indicates the active oceanic ridge, and blue indicates the spreading axis at Chron 5c (16 Ma) and in the East of AFFZ; the dark blue line indicates Chron 5d (17.6 Ma according to Leroy et al., 2010a,b). The black arrows show relative plate motions.* ***(B)*** *Shaded bathymetric map from multibeam sounding recorded*

during the Encens cruise with the database used in this study and location of seismic lines. The ENCENS-SHEBA survey is represented by green lines (Leroy et al., 2004) and the ENCENS survey by red lines (Leroy et al., 2006). The Ashawq-Salalah, Taqah and Mirbat segments are separated by grey dashed lines (accommodation zones). Yellow shading indicates the extent of the Ocean-Continent Transition (OCT) data coverage. AFFZ, Alula Fartak fracture zone; SHFZ, Socotra Hadbeen fracture zone.

The study area is located offshore Yemen and Oman at the South-Eastern margin of the Arabian plate (Fig. 1B), between the two main fracture zones of Alula-Fartak (AFFZ) and Socotra-Hadbeen (SHFZ). Marine geophysical data (including reflection seismic and multi-beam bathymetry) show evidences for gravity-driven sediment processes (slope failures and associated deposits in the basin). The aim of this study is to interpret the relative importance of the potential control factors (climate, relative sea-level changes and vertical motions).

Method

We combined seismic stratigraphy and geomorphology to provide significant improvement in the understanding of the post-rift evolution of the Northern margin of the Gulf of Aden, from the continental slope to deep basin.

This study is based on the analysis of morphology and seismic data obtained during the Encens-Sheba (Leroy et al., 2004) and Encens (Leroy et al., 2006, 2010b) cruises. Multibeam bathymetry, 3700 km of three-channel seismic-reflection and 5500 km of multi-channel seismic-reflection data were gathered during these two surveys (Fig. 1B).

At first, we have identified and classified the different morphologic features observed on the bathymetry and topography: failure-related scarps, erosional scars, gullies, canyons and channels. We have also established a few quantitative estimates such as stream profiles, slopes or incision values.

Secondly, we interpreted seismic lines up to 4.5 s TWTT and mapped the MTCs and leveed channel in the deep basin on the basis of published criteria (Weimer, 1989; Canals et al., 2004; Posamentier and Walker, 2006). MTCs were also classified according to their stratigraphic position and their estimated volume.

MTCs relations to erosional features

The post-rift megasequence has been divided into three units (U_3, U_4 and U_5) on the basis of tectonic unconformities (Autin et al., 2010). We have redefined and correlated the bounding discontinuities of post-rift sequences throughout the whole study area (D_2, D_3, D_4, Fig. 2) on geometrical basis of the reflection termination patterns and their continuity (Vail et al., 1977; Vail, 1987). The correlation of seismic profiles provides a pseudo-3D mapping of MTCs over the margin. A total of 40 MTCs has been recognised within the post-rift megasequence, at the base of the continental slope and in the oceanic basin: 5 of them are observed in the lower U_3 sequence, 15 in the intermediate U_4 sequence and 21 in the upper U_5 sequence where they are mostly located in the Eastern part of the study area as reported by Bache et al. (2011).

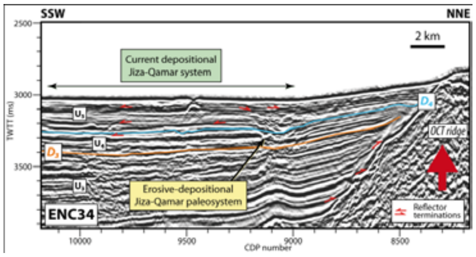

***Fig. 2-** Dip-oriented Encens 34 seismic-reflection profile (see Fig. 1B for location) across the Jiza-Qamar channel-levee system, showing the time evolution of the considered system from erosive to levees deposits.*

The multibeam bathymetry and the seismic lines on the Western part of the Taqah and Mirbat domain show the juxtaposition of many overlapping gravitational structures, from failure-related scarps to a mature canyon displaying an axial incision (*a, b, c, d, e, a'* on Fig. 3A). The tight network of erosional features reveals the strong instability of this part of the margin.

The rough sea floor observed near the Mughsayl canyon mouth (delimited by a purple line in Fig. 3A) is associated with a superficial Mass-Transport Deposit (hereafter MTD) on the seismic section (Fig. 3B), with thrust faults resulting from the flow motion. This superficial MTD surface area and volume are estimated to be ca. 560 km^2 and 95 km^3, respectively. The strike of these syn-depositional thrusts suggests that transport was mainly directed Southward (Fig. 3). Strong basal and lateral erosion shows that reworked material was incorporated during the mass-transport flow (cannibalization phenomenon).

Results

The northern Gulf of Aden's seascape shows a variety of depositional elements, including failure-related scarps, erosional scars, gullies, canyons on the continental slope; leveed channels and MTCs in the oceanic basin. In the first part of this study, we propose a classification based on the mapping of slope failures and associated deposits: this will provide the spatial and temporal context for the formation of the deep-sea deposits (MTCs and deep-sea fans). Based on its morphology, the study area can be classified in three domains, mostly controlled by the structural segmentation of the margin.

The Jiza-Qamar domain (Zone I) is located in the offshore part of Jiza-Qamar graben, along the AFFZ (Fig. 1B) and is characterized by the large number of failure-related scarps and two canyons, Jiza-Qmar at the North and Al-Ghaydah at the South. The Jiza-Qamar canyon connects at its down-dip end to a Z-shaped fan channel that extends Eastward (Fig. 1B). We can assume that the Jiza-Qamar system was connected to a large onshore river. The lateral migration of the Jiza-Qamar deep-sea

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fan is controlled by the tilt and uplift of the OCT ridge that finally create its characteristic Z-shaped morphology (Fig. 2).

Zone II is located on the Ashawq-Salalah second-order segment (Fig. 1B), and is characterized by a small number of erosional features (only few scars and scarps, no canyon). The sea-floor is shaped by the rift structures as described by Autin et al. (2010), a transverse WNW-ESE shallow horst and a deep "perched graben". Three linear channels (AS_1, AS_2 and AS_3) extend from the perched graben to the deep basin with a WNW-ESE direction. The time-evolution of the AS_3 channel from a depositional system characterized by levees to the current erosive-depositional one is mainly controlled by the normal fault delimiting the "perched graben".

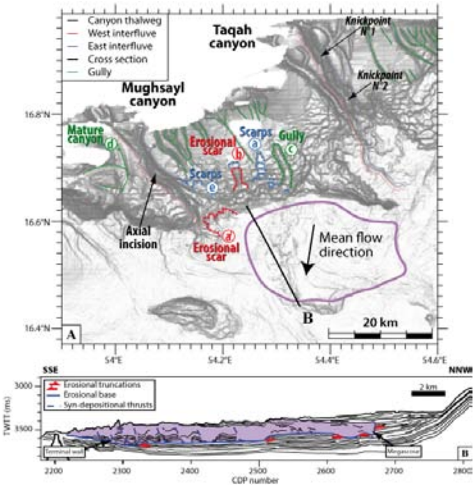

Fig. 3- (A) *Close-up view of shaded bathymetry where some of the various observed gravity-driven structures from scarps to mature canyon have been emphasized on the steep continental-slope of the Taqah domain (Eastern part of zone III). Numerous scarps (a) are generally juxtaposed to bigger sized erosional scars (b). A detailed observation of gullies (c) shows that they display little sub-circular depressions arranged in steps inside them, reminding the scarps morphology. The Mughsayl canyon (d), displaying some tributaries at the top of slope, is affected along its interfluves by landslides (e) and its axial incision is cut by an erosional scar ca. 5,5 km wide (a'). The purple line delimits the superficial MTD ca. 95* km^3 *and ca. 560*km^2*).* ***(B)*** *Seismic-reflection section (located on A) though the superficial MTD. The syn-depositional thrusts are caused by the mass flow abutting against terminal walls. It is very erosive at its base and is probably cannibalizing autochtonous material during mass flow transport. One the main controlling factor for the superficial structure observed on this part of the margin seems to be the slope gradient that produce different instability features ranging from gravity driven failure (simple and complex slides) to gravity flow (MTD, MTC).*

Zone III is located on the Taqah and Mirbat segments, the offshore domain of the Salalah plain (Fig. 1B) and is characterized by a large number of erosional features (failure-related scarps and erosional scars, gullies and two broad canyons, called Taqah and Mughsayl). The continental slope is steep, varying from ca. 4° to 4.6° in the west. The Taqah canyon is formed by a network of tributaries incising the continental slope (Fig. 3A). The stream profile is perturbed by two knickpoints. The first one is located at the intersection with a tributary that could also be related to one of the numerous normal faults identified by d'Acremont et al. (2005) in this area. The second one coincides with an erosional scar, which truncates the Taqah canyon and prevents the canyon from reaching its equilibrium (Fig. 3A).

The most important control parameter for the development of canyons and instabilities is obviously the steepness of the continental slope, which is induced by the structural segmentation (Leroy et al., 2010b).

The generalized occurrence of MTCs along the margin occurs for the first time at 10 Ma (base of the U_4 that overlies oceanic Chron 5 after Bache et al., 2011). Slope instabilities are generally triggered by the presence of a mechanically weak strata, an excess pore pressure generation or a combination of them (Sultan et al., 2004a,b; Huhn et al., 2006).

Sudden and important sea-level variations are one of the causes for high pore-pressure (Garziglia et al., 2008).

In the Gulf of Aden, the regional apparition of MTCs at 10 Ma have been attributed to three control parameters identified at this time (Bache et al., 2011):

- the onset of the monsoon system in the Western Arabian Sea around 15-16 Ma (Prell et al., 1990)
- a rapid and substantial short-term sea level fall likely, the Serravalian/Tortonian boundary at a global level (at 11.9 Ma after Haq et al., 1987)
- the Indian monsoon intensification around 8 Ma (Kroon et al., 1991; Prell and Kutzbach, 1992; Molnar et al., 1993).

The second occurrence of MTCs is mainly restricted to the Eastern part of the margin but represents the most important volume (ca. 315km^3) and has been interpreted as a consequence of a significant localized uplift since 10 Ma or thereafter (Bache et al., 2011). This is also attested by the presence of numerous gravitational instabilities and large incisions on the steep continental-slope shown in the present study.

Conclusions

Analyses of the high-resolution geophysical data on the present-day seafloor provide new insights into the post-rift tectono-sedimentary evolution of the Northern margin of the Gulf of Aden, which is a young margin influenced by the monsoon climate.

This study reveals the different factors that successively controlled the post-rift sedimentary history (since 17.6 Ma).

Just after the break-up, the Gulf of Aden opens up to the world ocean attested by the onset of contour currents.

The onset of the monsoon around 15-16 Ma, its intensification around 8 Ma and the eustatic drop during the Serravalian/Tortonian lowstand led to the first occurrence of MTCs and deep-sea fans.

Finally, the recent uplift of the margin caused a concentration of an increased volume of MTCs in the Eastern part.

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