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The rift to break-up evolution of the Gulf of Aden: Insights from 3D numerical lithospheric-scale modelling

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ABSTRACT

The Gulf of Aden provides an ideal setting to study oblique rifting since numerous structural data are available onshore and offshore. Recent surveys showed that the spatio-temporal evolution of the Gulf of Aden rift system is dominated by three fault orientations: displacement-orthogonal (WSW), rift-parallel (WNW) and an intermediate E–W trend. The oldest parts of the rift that are exposed onshore feature displacement-orthogonal and intermediate directions, whereas the subsequently active necking zone involves mainly rift-parallel faults. The final rift phase recorded at the distal margin is characterised by displacement-orthogonal and intermediate fault orientations. We investigate the evolution of the Gulf of Aden from rift initiation to break-up by means of 3D numerical experiments on lithospheric scale. We apply the finite element model SLIM3D which includes realistic, elasto-visco-plastic rheology and a free surface. Despite recent advances, 3D numerical experiments still require relatively coarse resolution so that individual faults are poorly resolved. We address this issue by proposing a simple post-processing method that uses the surface stress-tensor to evaluate stress regime (extensional, strike-slip, compressional) and preferred fault azimuth. The described method is applicable to any geodynamic model and easy to introduce. Our model reproduces the observed fault pattern of the Gulf of Aden and illustrates how multiple fault directions arise from the interaction of local and far-field tectonic stresses in an evolving rift system. The numerical simulations robustly feature intermediate faults during the initial rift phase, followed by rift-parallel normal faulting at the rift flanks and strike-slip faults in the central part of the rift system. Upon break-up, displacement-orthogonal as well as intermediate faults occur. This study corroborates and extends findings from previous analogue experiments of oblique rifting on lithospheric scale and allows new insights in the timing of fault successions of the Gulf of Aden and continental rifts in general.

1. Introduction

By nature, oblique rifts need to be studied in three dimensions and their understanding depends on the ability to reproduce 3D processes. The Tertiary Gulf of Aden is an ideal area to study oblique rifting. The direction of extension is N025°E but the rift has a N075°E-trend (Fig. 1), resulting in a moderately oblique rift system. The fault pattern is well expressed on the present-day conjugate margins. Moreover, the oceanic basin is young (17.6 My), so the sedimentary cover is thin and the conjugate margins are easily correlated.

The Gulf of Aden rift system formed 34–33 My ago and was active until 20 My ago when break-up took place (Leroy et al., 2012). The Gulf of Aden displays a high degree of segmentation with large fracture zones that delimit three distinct segments (Eastern, Central, and Western Segment, Fig. 1a): The Eastern Gulf of Aden features extremely thin transitional crust at the Ocean–Continent Transition (OCT) (Leroy et al., 2010; Watremez et al., 2011), which most likely involves exhumed serpentinised mantle rocks indicating a magma-poor setting (Leroy et al., 2012). In both the Eastern and the Central Gulf of Aden, margins are thought to be magma-poor as no magmatic structures, such as seaward-dipping reflectors, were recognised in the OCT (e.g. Bosworth et al., 2005). In the Western Gulf of Aden, the margins display volcanic characteristics related to the activity of the Afar hot spot.

Previously, the structural pattern of the Gulf of Aden has been elucidated thanks to field and seismic studies that were conducted onshore and offshore in Oman (Bellahsen et al., 2006; d'Acremont et al., 2005; Fournier et al., 2004) and in Yemen (Huchon and Khanbari, 2003). They allow us to recognise three general fault populations (i) displacement-normal with a fault azimuth of N115°E, (ii) rift-parallel with N075°E and (iii) an orientation that is intermediate between the two former directions (N095°E). The inversion of fault slip data sets permitted the computation of stress tensors corresponding to several local directions of extension (N025°E, N160°E and N–S) in Oman (Bellahsen et al., 2006; Fournier et al., 2004; Lepvrier et al., 2002), in Yemen (Huchon and Khanbari, 2003; Huchon et al., 1991) and at Socotra Island (Fournier et al., 2007). Offshore, near the OCT,

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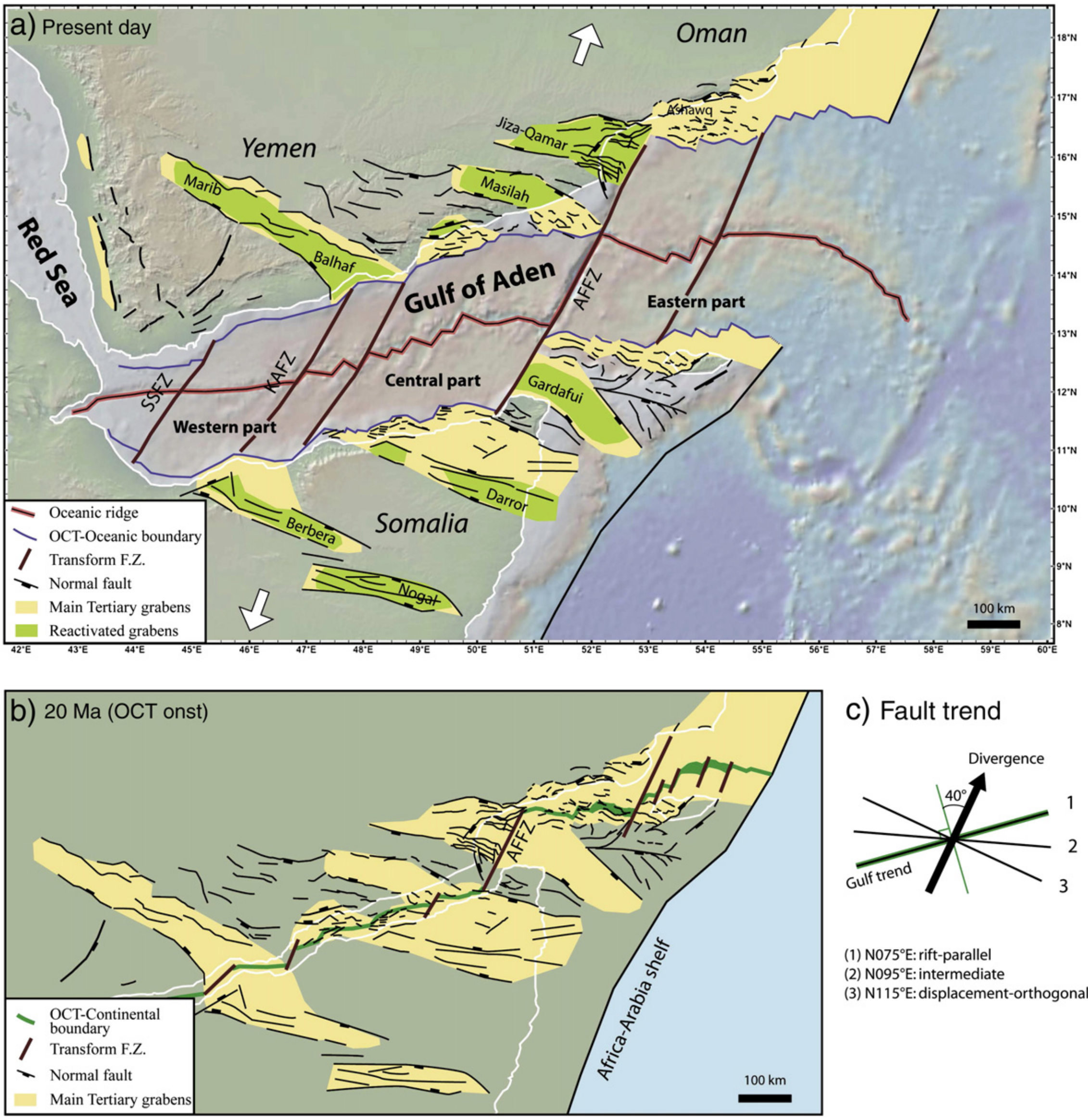

Fig. 1. Gulf of Aden overview map. (a) Structural map of the Gulf of Aden with main Tertiary depocentres and Mesozoic inherited basins (after Bellahsen et al., this volume and Leroy et al., 2012). SSFZ: Shukra El Sheik Fracture Zone, KAFZ: Khanshir Al Irquah Fracture Zone, AFFZ: Alula-Fartak Fracture Zone. (b) Reconstruction of the margins at the onset of the Ocean–Continent Transition (OCT) based on Leroy et al., 2012. (c) Major fault trends observed in the Gulf of Aden.

both the faults and basins mainly strike perpendicular to the Gulf of Aden opening direction (d'Acremont et al., 2005). Bellahsen et al. (2013-this volume) observe that the proximal parts of the margins display intermediate and displacement-orthogonal faults, whereas the OCT displays rift-parallel or displacement-orthogonal faults. The oceanic ridge is orthogonal to the divergence (Dauteuil et al., 2001; Hébert et al., 2001; Tamsett and Searle, 1988). The overall pattern of deformation in the Gulf of Aden shows en-echelon Tertiary sigmoid grabens. This structuration could be linked to Mesozoic inheritance which consists in elongated E–W grabens (Fig. 1b). Previous analogue models of the Arabian plate tend to demonstrate that the obliquity of the Gulf of Aden arises from the interaction between the laterally-evolving subduction of the Tethyan Ocean toward the north and the Afar hot spot in the south-west (Bellahsen et al., 2003).

Fault patterns of oblique rifts have been investigated during the last decades using analogue models on two different levels of complexity: (i) crustal-scale models simplify the rift system to a deforming crust influenced by a basal zone of extension that involves an oblique velocity discontinuity (Clifton et al., 2000; Corti, 2004; Corti et al., 2001, 2003; Mart and Dauteuil, 2000; McClay and White, 1995; Sokoutis et al., 2007; Tron and Brun, 1991; Withjack and Jamison, 1986). The advantage of this setup is that crustal strain patterns can be studied independently of mantle deformation, but this also limits the applicability to the first rift stage where isostatic balancing with the mantle and lithospheric necking can be neglected. Furthermore, the role of the basal discontinuity is overestimated intrinsically. (ii) Analogue experiments on the lithospheric scale have been conducted recently and successfully reproduced lithospheric thinning and its effect on crustal fault patterns (Agostini et al., 2009; Autin et al., 2010; Sokoutis et al., 2007). However, thermal effects or rheological changes that occur during rifting are not modelled in these experiments and their absence remains a significant limitation of such analogue models. They also do not show the progression from oblique rift initiation to plate rupture.

In contrast to analogue models, state-of-the-art geodynamic codes are capable of computing realistic, temperature-dependent viscosity as well as complex elasto-visco-plastic rheologies. Many numerical models include these features and have been used to study diverse aspects of rift dynamics in two dimensions (e.g. Bassi, 1991; Behn et al., 2002; Braun and Beaumont, 1989; Buck, 1991; Buiter et al., 2008; Burov and Cloetingh, 1997; Huismans and Beaumont, 2003, 2011;